The responsive reply chain: the influence of the positioning of decoupling points

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THE RESPONSIVE SUPPLY CHAIN: THE INFLUENCE OF THE POSITIONING OF DECOUPLING POINTS

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ABSTRACT

Manufacturing supply chains have been challenged by high competition, dynamic, and stochastic conditions. They have to be constantly responsive in today's ever-changing manufacturing environment. The proper positioning of decoupling points for material flow and information flow has a significant potential for increasing responsiveness in a supply chain. Positioning the material decoupling point as close to the end consumer as possible whilst the information decoupling point is positioned upstream is the key to the industries' ability to reduce lead time and enhance performance in the dynamic behaviour of the supply chain.

An initial review of literature concerned with agility and supply chain indicated the need to measure agility for improving the agility and performance of the supply chain which has been underdeveloped and has been facing various limitations. It appeared that the responsiveness was the major measure within the supply chain areas. This critical review of the literature also identified that there is a need for a new responsiveness assessment for the supply chain that considers operational measures for all processes and main activities. The decoupling point is the point where the fixed product specification and order information penetrate upstream into the chain. Further upstream of this point, the order information and product characteristics are subject to uncertainty and forecasting systems are used to predict order characteristics and types of products. Two types of decoupling point have been identified where the order information decoupling point should be as upstream as possible while the product characteristics decoupling point should be as downstream as possible. A combination of the responsiveness assessment with the optimum decoupling points positioning of modern supply chains is the main theme of this thesis. This prompted the need to create a new responsiveness assessment methodology combined with the analysis of supply chain through simulation modelling to determine the optimum positioning of the decoupling points.

The impact of positioning the material decoupling point as far downstream as possible, and the information decoupling point as far upstream as possible on responsiveness was then tested using four literature-based case studies. Then, a supply chain responsiveness measurement model was developed. This model was then validated through collecting quantitative data where discrete event simulation (DES) modelling was used to undertake a comparative analysis of different decoupling points' positions, which shows the potentially large effect these positions can have on systems' responsiveness.

Abstract

Results from the literature-based case studies were analysed for each case individually before it was analysed on inter-case basis. This has been done to show the effects of the material and information decoupling point positioning on agility and thereby responsiveness.

Results from the in-depth case study show through the experimentation of the different scenarios of positions of material and information decoupling points that positioning of material decoupling point as downstream as possible and information as upstream as possible produce the best responsiveness. The four dimensions of the information decoupling point (demands, mixes, specifications, and due dates) revealed a significant improvement in the supply chain analysis. It was revealed that by positioning the information decoupling point upstream, different levels and zones can be created for each dimension of the information decoupling point. A novel methodology for analysing positioning of the customer order decoupling point through information and material flows was developed. Four types of information decoupling points were identified, and characterised.

Results from this research indicate that there is a need for manufacturing organisations to analyse and evaluate its supply chains in terms of responsiveness following the material and information decoupling points and the decoupling zones. The study makes an explicit practical contribution for manufacturing organisations in assessing supply chain's responsiveness and contributes substantially to the theory about the decoupling point positioning as well as the utilisation of the DES modelling to the decoupling point concept.

Keywords

Agile supply chain, customer order decoupling point, positioning of the customer order decoupling points, agility, responsiveness, material order decoupling point, information order decoupling point, analysis with simulation modelling, literature-based case studies.

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Table of Contents

Table of Contents

Table of Contents

Table of Contents

List of Figures

Number ***Page***

List of Figures

List of Figures

List of Tables

Number ***Page***

List of Tables

List of Tables

Commonly Used Abbreviations

AHP .... Analytical Hierarchy Process
APO .... Advanced Planner and Optimiser
APICS .... American Production and Inventory Control Society
APICS .... The Association for Operations Management
APIOBPCS .... Automatic Pipeline Inventory Order Based Production Control System
Arena .... Simulation Software by Rockwell Automation
ASC .... Agile Supply Chain
ATO .... Assemble-to-Order
ATP .... Available-to-Promise
AM .... Agile Manufacturing
AS/RS .... Automated Storage/Retrieval System
BTO .... Buy-to-Order
BOM .... Bill of Material
CODP .... Customer Order Decoupling Point
CODZ .... Customer Order Decoupling Zone
CPFR .... Collaborative planning, forecasting, and replenishment
CPRs .... Continuous-Replenishment Program
CS .... Complex System
CSCMP .... The Council of Supply Chain Management Professionals
CTP .... Capable-to-Promise
CVRD .... Brazilian multinational diversified metals and mining corporation (Vale)
DES .... Discrete Event Simulation
DC .... Distribution Centre
DP .... Demand Planning/Decoupling Point
DRI .... Direct Reduction Iron/Direct Reduced Iron
DRP .... Distribution Requirements Planning
DEDS .... Discrete-Event Dynamic Systems
DMDP .... Demand Mediation Decoupling Point
EAF .... Electric Arc Furnaces
ECR .... Efficient Consumer Response
EDI .... Electronic Data Interchange

Commonly Used Abbreviations

ETO..Engineer-to-Order
FMS .... Flexible Manufacturing System
FTO... Finish-to-Order
FAI .... Fuzzy Agility Index
GATP..Global Available-to-Promise
GCC .... the Gulf Cooperation Council
GIIC .... Gulf Industrial Investment Corporation
Hadeed ....Saudi Iron and Steel Company
JTT .... Just-in-Time
IDP ....Information Decoupling Point
IDD .... Independent identically distributed
IOC ....Iron Ore Company of Canada
ISO ....the International Organization for Standardization
IT..Information Technology
LF...Ladle Furnaces
LKAB ....Swedish mining company
LSC ....Lean Supply Chain
LSDG...Cardiff Logistics Systems Dynamics Group
MABS .... Multi-Agent based Simulation
MAS...Multi-Agent System/Multi-Agent Simulation
MC ....Mass Customisation
MDP...Material Decoupling Point
MQ ....Market Qualifier
MS...Manufacturing System
MTO ....Make-to-Order/Manufacture-to-Order
MTS .... Make-to-Stock/Manufacture-to-Stock
MPS ....Master Production Schedule
MRP..Material Requirements Planning/Material Resources Planning
MW ....Market Winner
NPI .... New Product Introduction
OGV..Ocean-Going Vessel
OTD ....Order-To-Delivery
OPP .... Order Penetration Point
OPT..Optimised Production Technology

Commonly Used Abbreviations

PDP .... Point of Product Differentiation
PSDP .... Product Supply Decoupling Point
QC .... Quality Control
QCM .... Quebec Cartier Mining Company
QR .... Quick Response
SABIC .... Saudi Basic Industries Corporation
SAP .... System Analysis and Program Development
SAP R/3 .... The main enterprise resource planning software produced by SAP AG
SBU .... Strategic Business Unit
SC .... Supply Chain
SCM .... Supply Chain Management
SCOR .... Supply Chain Operations Reference Model
SD .... System Dynamics
SKU .... Stock Keeping Unit
SOP .... Sales and Operation Planning
SP .... Steel Plant
STS .... Ship-To-Stock
TPS .... Toyota Production System
TV .... Transfer Vessel
VBTO .... Virtual-Build-to-Order
VMI .... Vendor-Managed Inventory
VC .... Value Chain
WIP .... Work-in-Process

Publications

Refereed Conference Papers

Alkahtani, M., Burns, N. (2008) "An Integrated Methodology for the Design of Agile Supply Chains on the Decoupling Point Using Simulation". Proceedings of the logistics research network, Annual conference 2008, 10th-12th September 2008, University of Liverpool, UK. (Alkahtani & Burns, 2008)

Conference Presentations

Alkahtani, M., Burns, N. (2008) "An Integrated Methodology for the Design of Agile Supply Chains on the Decoupling Point Using Simulation". Proceedings of the logistics research network, Annual conference 2008, 10th-12th September 2008, University of Liverpool, UK. (Alkahtani & Burns, 2008)

Chapter 1

Introduction

The research described in this thesis is concerned with the improvement of responsiveness in the supply chain. It investigates the responsiveness of a supply chain using a simulation model, as a decision aid during the evaluation stage of the system design process.

1.1 Research Background

The steel industry in Saudi Arabia was faced with high competition that resulted in the loss of the local market share for the long products market (the main types of steel products are long and flat products). The main challenge of managing supply chains was to adapt to rapid change to customer demand and market changes. This required a combination of efficiency to fulfil demand with agility to deal with the volatile market and variety of the demand. In order to find a balance between efficiency and agility, the positioning of customer order decoupling points (CODPs) plays a central role in managing the supply chains (Naylor et al., 1999).

Given the limitations of the mass production paradigm in today's competitive environment, the emergence of agile enterprises which develop and exploit capabilities to thrive and prosper in complex and ever uncertain changing business environments is necessary (Kidd & Henbury, 2007). Various authors have highlighted the agility paradigm (Christopher, 2000; Goldman et al., 1995; Harrison et al., 1999; Hormozi, 2001; Kidd, 1996; Nagel & Bhargava, 1994; Nagel et al., 1991; Sharifi & Zhang, 1999; Vokurka & Fliedner, 1998; Yusuf et al., 1999).

Agility is identified as new systems of doing business which have wider scope and could be applied to the entire organisation at the enterprise level (Christopher, 2000). Agility is an umbrella term and has been applicable over a range of related areas that together define an extensive change in the current system of competition (Goldman et al., 1995) at the marketing, production, design, organisation, management, and people levels. Agility will have as intense an effect in the twenty-first century as mass production has had in the twentieth century (Goldman et al., 1995). The first presentation of agility was published by

Lehigh University's Iacocca Institute in 1991: *21st century Manufacturing Enterprise Strategy: An industry-led View* (Nagel et al., 1991).

The research here focuses on the assessment of operational levels that are related mainly to production and design. The production level is characterised by the need for responsiveness - the ability to manufacture goods and produce services to customer order in arbitrary lot sizes, and from a design point of view is characterised by a holistic methodology that integrates supplier relations, production processes, business processes, customer relations, and the product's use and eventual disposal.

Generally speaking, decision-makers need to assess responsiveness in order to understand their capability, which requires comprehensive knowledge of the competitive capabilities. Agility and design of the agile supply chain is not well understood and the conceptual aspects are still being defined due to its fresh development (Kidd & Henbury, 2007).

Among the aspects of agility, the thesis focuses on responsiveness: the concept of agility in the context of supply chain management focuses around "responsiveness" (Christopher & Towill, 2000). The Supply Chain Operations Reference Model (SCOR) promoted responsiveness as one of the main attributes of the performance metrics. The assessment of responsiveness is the focus of this research since it is one of the major capabilities of an agile supply chain. Also, the research focuses on the influence of the customer order decoupling point (CODP) in maximising responsiveness. Two main types of CODP have been considered in this research. First, the material decoupling point which has been introduced in the literature as the physical strategic point to separate parts of the supply chain oriented towards activities for customer orders (order driven activities downstream) from the part of the supply chain based on forecasting and planning of the supply chain (demand driven activities upstream) (Hoekstra & Romme, 1992). The research here included the information decoupling point as the second type of customer order decoupling point, which has been classified in this research under four types of customer order types and its penetrations upstream. The four types of customer order information included information sets related to the demand, mix, specification, and due date which flow upstream separating the information decoupling points into marketplace modified order data upstream and unmodified downstream of the supply chain. The positioning and analysis of the material and information in the supply chain is conducted in this thesis to investigate its impact on the responsiveness of the supply chain.

1.2 Research Aim and Programme

The aim of this research is to investigate the importance of positioning decoupling points in the supply chain system and thereby enhance the capabilities of decisions makers to represent the behaviour and predict the performance and agility of supply chain systems. However, there is no objective measure of the resulting agility and it appears no distinct method of defining the agility. The knowledge gap I will fill is:

1. Responsiveness assessment from an operational perspective:

   In conditions of turbulence, firms must adopt agility, and more importantly must be able to achieve agility. This led to the responsiveness assessment as an aspect of agility because it is the basic element of agility from an operational perspective that is reported in the literature. Components from the measurements methods developed use a number of factors identified from a review of the literature, and an evaluation of the existing methods and techniques.

2. "...to move the material decoupling point as close to the end consumer as possible thereby ensuring the shortest lead-time for the consumer...the further the information decoupling point is moved upstream, the better the improvement in the dynamic behaviour of the supply chain…" (Mason-Jones & Towill, 1999). These statements imply that by positioning the material decoupling point as far downstream as possible, and the information decoupling point as far upstream as possible, maximum agility is achieved. Hence, there is a decoupling zone between these decoupled elements. This research will verify this statement, decoupling zone and measure its characteristics.

"The proper location of decoupling points for material flow and information flow enable a hybrid supply chain to be engineered" (Christopher & Towill, 2000).

"By managing the two decoupling points, material and information decoupling points, a powerful opportunity for agile response can be created" (Christopher, 2000).

The customer order decoupling point (CODP) concept is still limited as it has been viewed as a physical separation point between the order and demand-driven operations in the supply chain. Acknowledging the information order decoupling point and the gradual increase in certainty across the supply chain provides a point for extending the decoupling point to a decoupling zone between these decoupled elements between the information and material decoupling points.

The research develops a novel integration of responsiveness assessment and modelling for an agile supply chain using simulation based on the decoupling point's positioning, which is investigated through the following research questions:

- RQ1: Do actual and successful companies attempt to meet the requirement of agility by positioning the material decoupling point as far downstream as possible?
- RQ2: Do the companies go to some lengths to improve the quality and utility of information which is transmitted upstream?
- RQ3: Do the companies transmit this information as far upstream as possible?
- RQ4: What sort of agility do these companies achieve? Is it mix flexibility, the ability to rapidly reconfigure their production facilities? Is it coping with variable demand? Is it a much wider variety of products they have to provide?
- RQ5: Do they create some disadvantages by moving the decoupling point downstream?
- RQ6: Can they verify the decoupling zonal idea in information penetration and measure its characteristics?

These research questions were developed to understand the effects of the decoupling points' positioning in relation to the agility and responsiveness of the supply chain

The first step undertaken in this research project was to define the research problem through a literature review (Chapter 2) in order to derive a research aim. Figure 1.1 shows the main concept of the research idea.

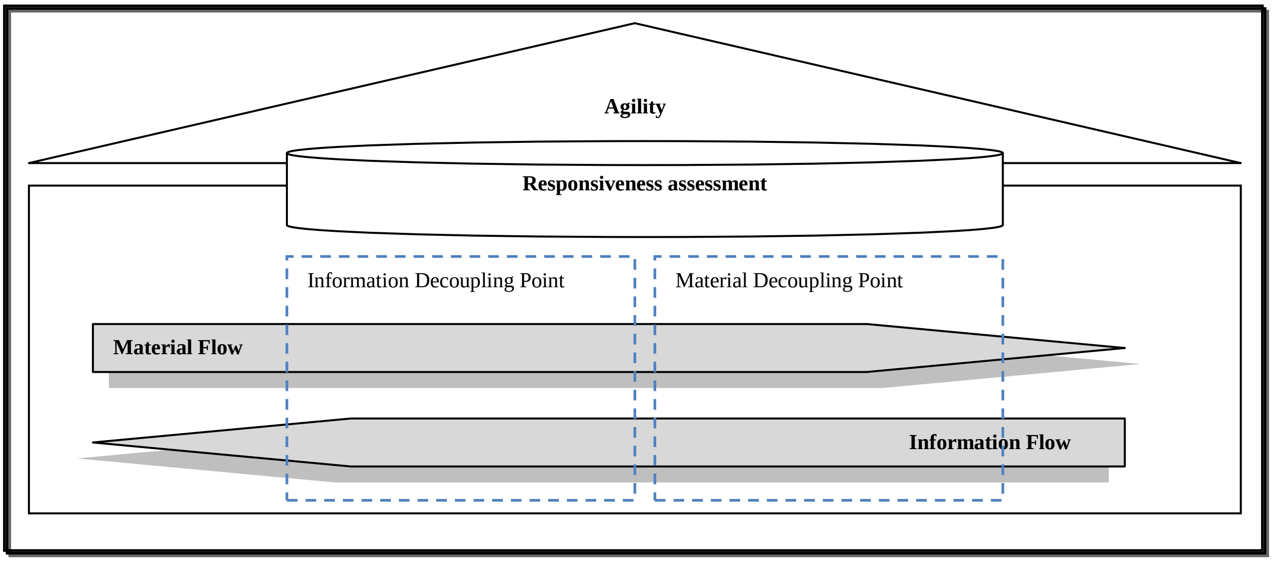

Figure 1.1: Integrating of the responsiveness assessment through material and information flows

The research aim and objectives are detailed in Section 3.2.

1.3 Motivation of Research

The motivation for this research is to provide a valuable tool to developing practitioners who intend to adopt new manufacturing practices/tools in their organisations. The responsiveness assessment with the influence of the decoupling points' positioning through the research would be a valuable aid to help manufacturers gain insights into the choices of practices/tools that could be adopted or adapted to achieve competitive advantage in their businesses.

1.4 Research Methodology

- First phase: Carry out an extensive literature review to determine existing work on agility, decoupling point positions and achieving agility and how these concepts may be integrated through responsiveness.
- Second phase: Develop a design methodology that can accurately and realistically capture the important characteristics of the responsiveness assessment into a balanced supply chain which could compete and change rapidly based on the extended decoupling points.
- Third phase: Test and verify the proposed model for a suitable supply chain using simulation modelling.

1.5 Summary of Contribution to Knowledge

The literature-based case studies as well as the in-depth case study based on simulation have produced a wide range of findings regarding the decoupling points' positioning and their impact on responsiveness through the analysis of the case study and simulation model. This section brings together the key findings of the work, which are discussed in detail in Chapter 9 and summarises the contribution to knowledge.

Section 1.5.1 describes the key findings from the literature-based case studies conducted in order to develop the responsiveness assessment through the decoupling points' positions. Subsequently, Section 1.5.2 describes the key findings derived from the simulation experiments conducted to test the positioning of the decoupling points using the in-depth case study. Finally, Section 1.5.3 presents the contribution to knowledge that this research has made.

1.5.1 Key research findings from the literature-based case studies

Observations from the literature-based case studies suggest that positioning the material decoupling point downstream to the latest point, and information decoupling point to the furthest point upstream, have a significant impact on agility through the responsiveness of the supply chain, through the four types of cases studied and the different types of industries. Furthermore, the material decoupling point was different between the cases ranging between assemble-to-order and make-to-order strategies. It was significantly faster to respond to changes in the market and more flexible when positioning the material decoupling point to the latest point downstream, and positioning the information decoupling point to the further point upstream. The analysis of the cases based on the literature review is detailed in Chapter 4 and summarised in Chapter 9. Finally, it was found that the information types of decoupling point for the case study is consistent with the zonal concept proposed and planned in the objectives and research questions.

1.5.2 Key research findings from the in-depth case study using simulation experiments

The results of the simulation experiments suggest that the impact of positioning the customer order information decoupling point upstream and postponing the material flow at the warehouses scenario has a significant impact on responsiveness and performance measures based on the model of supply chain proposed in Chapter 5. The simulation modelling of the in-depth case study verified the decoupling concept based on the four dimensions of the information decoupling point (demand, mix, specification, and timing) dependent on the considered material decoupling point which was make-to-stock. Chapters 6, 7, and 8 present a simulated in-depth case study and experiments that quantify the responsiveness measure and the performance measures of the supply chain using Arena. This enables the other possible positions of the decoupling points to be tested and shows neither better responsiveness nor performance output than positioning the customer order information decoupling point upstream and postponing the material flow at the warehouses scenario. It has also been found that the information decoupling point with its four classifications represent zones of decoupling points that ease the coordination, modelling, and improve the responsiveness and performance output.

1.5.3 Summary of contribution to knowledge

Advances have been made in understanding the impact of positioning the customer order information decoupling point upstream and postponing the material flow downstream on responsiveness, performance, and thereby agility of supply chains. The literature-based case studies and the in-depth case study are identical in having a significant effect on the responsiveness and agility of the supply chain when positioning the customer order information decoupling point upstream and postponing the material flow downstream. The literature reviews-based cases and modelling supply chain of the in-depth case study have achieved the same conclusion regarding the improved responsiveness and agility with the different methodology used. The zonal concept has been verified and shown in detail in Chapter 9. Dependent on the main material decoupling point as studied in the cases ranging from MTO, ATO, and MTS, the positioning of the information decoupling points are pushed upstream with its dimensions. Chapter 9 discusses and concludes this research.

1.6 Thesis Layout

The thesis contains 9 chapters which are outlined below and in Figure 1.2 at the end of the chapter.

Chapter 1: This chapter introduces this research, and illustrates its background. The research aims and objectives are explored as well as the research methodology selected to fulfil those objectives.

Chapter 2: This chapter reviews the literature in the field of the lean, agile, decoupling point of the supply chain. It focuses on the responsiveness as an aspect of the agility and how it can be accessed from a supply chain perspective. Also, it presents several factors that affect the positioning of the decoupling point and represent the decoupling point methodology in the material and information pipelines. This methodology is linked with the agility paradigm and responsiveness assessment.

Chapter 3: This chapter develops a structured research programme that allows systematic execution of the research. It explores and determines the research methodology and means for the research. It also explores the research method orientation, approach, methodology, qualitative and/or quantitative. Then, a detailed analysis and preparation of the simulation is done followed by the data collection process and a review of the modelling process for analysis.

Chapter 4: This chapter presents case studies based on the literature companies' cases. The purpose of this chapter is to examine some published industrial cases to see if they provide further insights about positioning the material decoupling point downstream and information decoupling point upstream and if it enhances the responsiveness of the supply chain. The four literature-based case studies are Benetton, HP, National Bicycles, and Whirlpool. The objective is to obtain evidence that supports the hypothesis of the decoupling point positioning and its impact on responsiveness for the companies' cases studied.

Chapter 5: This chapter introduces a novel methodology for modelling to demonstrate the importance of finding the best positions of the customer order decoupling points: information and material flows using a discrete event simulation (DES) and its impact on supply chain responsiveness, and thereby enhancing the capability of the supply chain performance. The chapter focuses on modelling supply chain responsiveness generally linked with supply chain performance. The purpose of this chapter is to develop a systematic modelling methodology of supply chain responsiveness that can contribute to the knowledge and ease the analysis of the supply chain using a discrete event simulation (DES) to fulfil the aim of the research and carry the in-depth case study.

Chapter 6: This chapter introduces a comprehensive description of the Hadeed case study, the supply chain of a steel manufacturer (Hadeed), make-to-stock (MTS), whose products are sold worldwide, but has most of its customers in Saudi Arabia. The objective of this chapter is to prepare and introduce a simulation study to understand the different aspects of the Hadeed supply chain and to analyse a number of factors that have an influence on supply chain responsiveness and performance in terms of the decoupling points' positions by tracing the material and information flows.

Chapter 7: This chapter formulates the simulation protocols for the Hadeed case study, data requirements and data collection. It focuses on the modelling of the in-depth case study (Hadeed) using Arena. Then, it outlines the processing of the data.

Chapter 8: This chapter explains the experimentation design that involved the testing of the positioning of the information flow decoupling point upstream in the supply chain and the physical material decoupling point downstream. The chapter considers verification and validation. Also, it explains the range of scenarios investigated. Moreover, it explains the results of the experiments and scenarios. Lastly, it reports the results of experiments and shows how the zonal concept relates to the scenarios of the material and information decoupling points positioning of the Hadeed case study.

Chapter 9: This chapter concludes the thesis. It discusses the key findings and conclusions from each of the research stages and highlights the contribution to knowledge made by the research. Finally, the limitations, strengths, and weaknesses of the methodology are discussed and recommendations are made for future work in the research field.

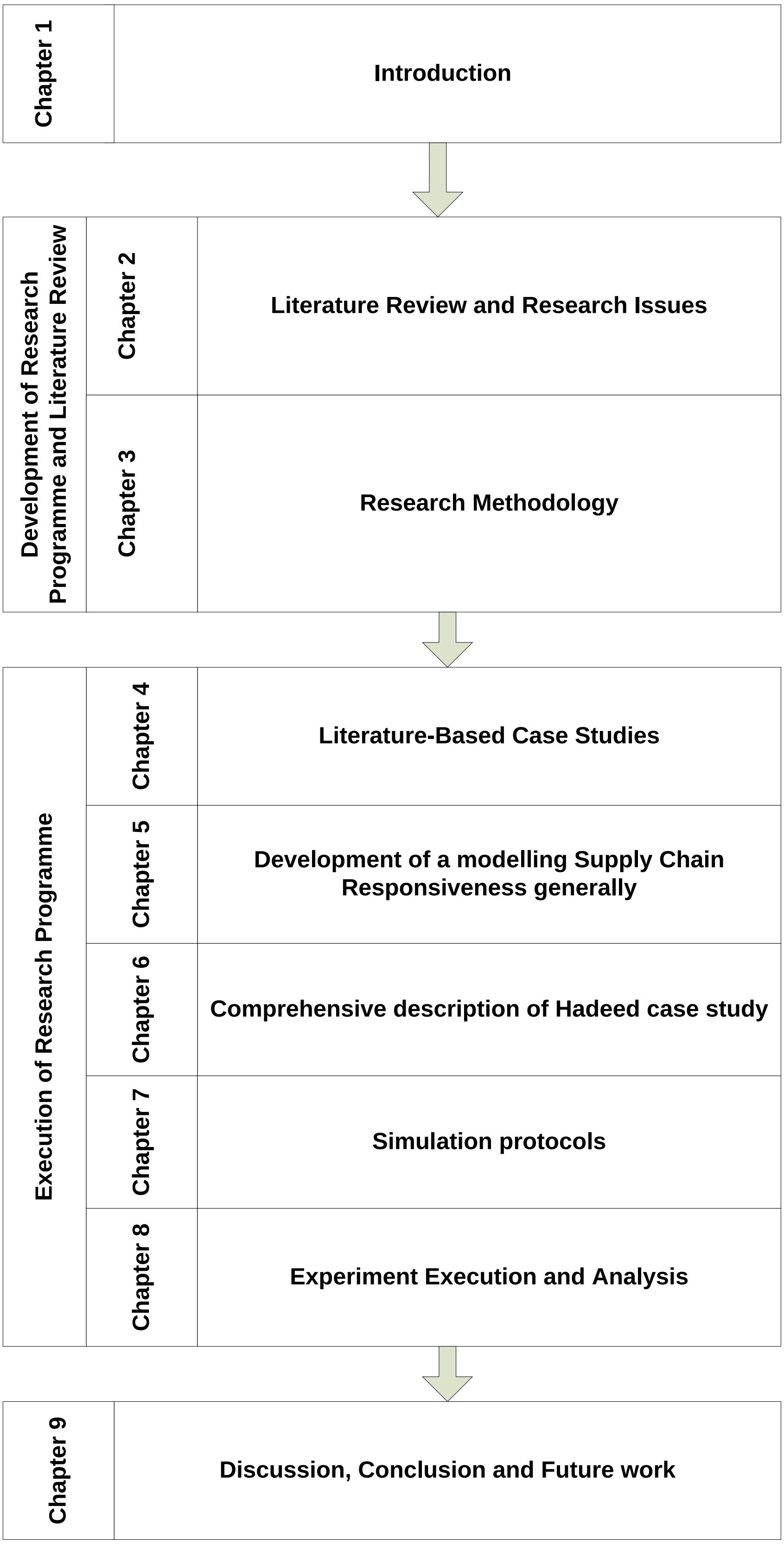

Figure 1.2: Thesis Structure

Chapter 2

Literature Review and Research Issues

2.1 Introduction

This chapter presents a critical and evaluative review of the existing literature defining key research issues. The goals of this chapter are to:

- Summarise and analyse the research from the literature in terms of agility thinking and how agility can be achieved from a supply chain perspective.
- Describe and analyse existing knowledge about the assessment of responsiveness and the aspects that relate to operational analysis.
- Evaluate the relationship of responsiveness, decoupling points, and efficiency.
- Reveal consistencies and inconsistencies in previous research for responsiveness, and for the customer order decoupling point.
- Identify the gaps in the existing literature.

2.2 Supply Chains

2.2.1 Supply chain definition

The term "supply chain management" arose in the late 1980s and came into widespread use in the 1990s. Prior to that time, businesses used terms such as "logistics" and "operations management". Some definitions of a supply chain (SC) and supply chain management (SCM) are offered below:

- The Council of Supply Chain Management Professionals (CSCMP) defines supply chain management: "Supply Chain Management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and customers. In essence, supply chain management integrates supply and demand management within and across companies. Supply chain management is an integrating function with primary responsibility for linking major business functions and business processes within and across companies into a cohesive and high-performing business model. It includes all of the logistics management activities noted above, as well as manufacturing operations, and it drives coordination of processes and activities with and across marketing, sales, product design, finance, and information technology" (Vitasek, 2010).

- "1) Starting with unprocessed raw materials and ending with the final customer using the finished goods, the supply chain links many companies together. 2) The material and informational interchanges in the logistical process stretching from acquisition of raw materials to delivery of finished products to the end user. All vendors, service providers and customers are links in the supply chain" (Vitasek, 2010).

- "The management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole" (Christopher, 2005).

- "Supply chain management is the coordination of production, inventory, location, and transportation among the participants in a supply chain to achieve the best mix of responsiveness and efficiency for the market being served" (Hugos, 2003).

2.2.2 Supply chain classification

There is a difference between the concept of supply chain management and the traditional concept of logistics. Logistics typically refers to activities that occur within the boundaries of a single organisation and supply chains refer to networks of companies that work together and coordinate their actions to deliver a product to market. Also, traditional logistics focuses its attention on activities such as procurement, distribution, maintenance, and inventory management. Supply chain management acknowledges all of traditional logistics and also includes activities such as marketing, new product development, finance, and customer service.

The value chain, also known as value chain analysis, is a concept from business management that was first described and popularised by Michael Porter (1985, see Figure 2.1; Power et al., 2001) and is defined as: "a chain of activities. Products pass through all activities of the chain in order and at each activity the product gains some value. The chain of activities gives the products more added value than the sum of added values of all activities. The concept of the value chain is not associated with the costs occurring throughout the activities. A diamond cutter can be used as an example of the difference. The cutting activity may have a low cost, but the activity adds to much of the value of the end product, since a rough diamond is significantly less valuable than a cut diamond" (Porter, 1985).

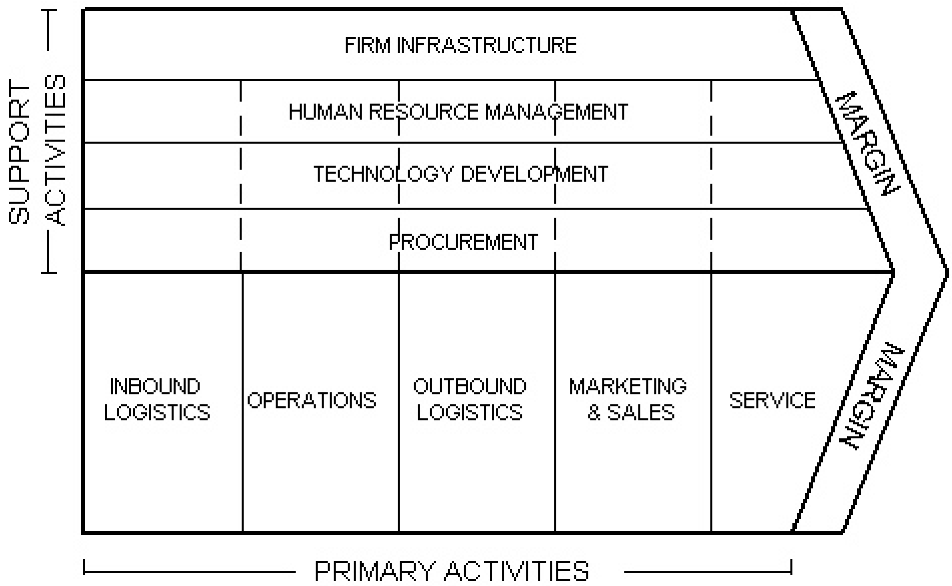

Figure 2.1: The value chain (Porter, 1985)

Logistics management, as defined by the CSCMP, is: "that part of supply chain management that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the point of consumption in order to meet customers' requirements. Logistics management activities typically include inbound and outbound transportation management, fleet management, warehousing, materials handling, order fulfilment, logistics network design, inventory management, supply/demand planning, and management of third party logistics services providers. To varying degrees, the logistics function also includes sourcing and procurement, production planning and scheduling, packaging and assembly, and customer service. It is involved in all levels of planning and execution – strategic, operational, and tactical. Logistics management is an integrating function which coordinates and optimises all logistics activities, as well as integrates logistics activities with other functions, including marketing, sales, manufacturing, finance, and information technology" (Vitasek, 2010). Figure 2.2 shows the logistics management process

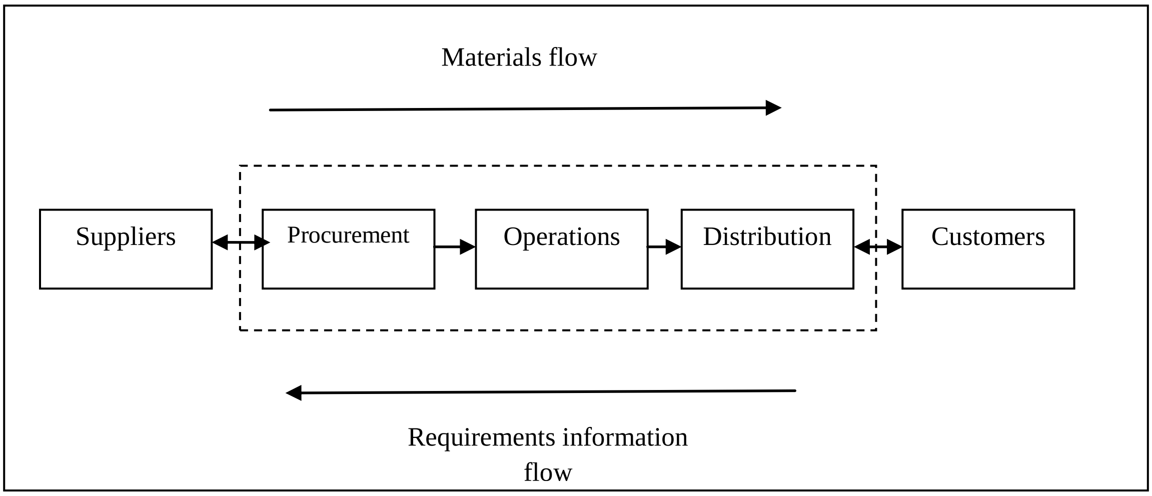

Figure 2.2: Logistics management process (Christopher, 2005)

2.2.3 Types of supply chain

Supply chains can be classified into several types based upon the manufacturing systems:

1. **Lean supply chain**

Lean supply chain (LSC) involves the Japanese concept "continuous improvement" process that adopts the elimination of waste along the chain provided by the reduction of setup times to allow for the economic production of small quantities, thereby achieving cost reduction, flexibility, and being able to respond to customer requirements. It can allow for higher profits, internal manufacturing efficiency, and flexibility, but lacks in external responsiveness to customer requirements. For internal responsiveness, organisations adopted the time-based competition paradigm, whereby development and production time is compressed, thereby achieving justifiably higher prices for enhanced customer service and leading to rapid innovation and lower cost of quality (Huang et al., 2002).

"Lean manufacturing is the production of goods using less of everything compared to mass production: less human effort, less manufacturing space, less investment in tools, and less engineering time to develop a new product. Lean manufacturing is a generic process management philosophy derived mostly from the Toyota Production System (TPS) but also from other sources. It is renowned for its focus on reduction of the original Toyota 'seven wastes' in order to improve overall customer value. Lean is often linked with Six Sigma because of that methodology's emphasis on reduction of process variation (or its converse smoothness) and Toyota's combined usage. Toyota's steady growth from a small player to the most valuable and the biggest car company in the world has focused attention upon how it has achieved this, making 'Lean' a hot topic in management science in the first decade of the 21st century" (Womack et al., 1990).

2. Agile supply chain

An agile supply chain (ASC) outlines the connection point between a supply chain and the market. It gains by responding rapidly to changing and constantly fragmenting worldwide markets by being dynamic, context-specific, forcefully changing, and expansion oriented, driven by customer-designed products and services. An ASC essentially places emphasis on responding to unpredictable changes and takes the chance to gain advantage from them. Its objective is to minimise delivery time and be flexible in terms of lead time. It brings new technologies and methods, exploits information systems/technologies and data exchange potentials, places more concern on organisation resolutions, integrates the whole supply chain process, intensifies innovations throughout the supply chain and relies on virtual companies and production based on customer-driven orders (Huang et al., 2002).

3. Hybrid/"Leagile" supply chain

There is still debate in the literature about the hybrid or leagile supply chain which involves assemble-to-order (ATO). It relates to postponement and mass customisation strategies. However, although lean and agile paradigms are different, they have been combined into total supply chains, and that led to the positioning of decoupling point research and consideration of market knowledge. They utilise the agile manufacturing paradigm downstream for satisfying a fluctuating demand (in terms of volume and variety) which will enable high productivity and low-cost processes to start with, followed by responsive processes to allow high levels of customisation thereafter and lean manufacturing paradigms upstream for a level schedule (Naylor et al., 1999).

Table 2.1 illustrates a comparison of various supply chain types (adapted from Harrison & Van Hoek, 2005; Huang et al., 2002; Mason-Jones et al., 2000b).

Table 2.1: Comparison of lean supply with agile supply

	Supply chain type		
Attributes	**Lean**	**Agile**	**Hybrid**
Typical products	Commodities	Fashion goods	Innovative
Marketplace demand	Predictable	Volatile	Predictable/volatile
Choosing suppliers	Low cost and high quality	Speed, flexibility, and quality	Low cost, high speed and quality, and flexible
Product variety	Low	High	Various
Inventory strategy	Generate high turnover and minimise inventory throughout the chain	Deploy significant stocks of parts to tide over unpredictable market requirements	Postpone product differentiation until as late as possible. Minimise functional components inventory
Product life cycle	Long	Short	Various
Lead-time focus	Shorten lead time as long as it does not increase cost	Invest aggressively in ways to reduce lead time	Shorten lead time but not at the expense of cost; accommodate customer requirements
Manufacturing focus	Maintain high average utilisation rate	Deploy excess buffer capacity to ensure that raw material/components are available to manufacture the product according to market requirements	Combination of lean and agile
Product design strategy	Maximise performance and minimise cost	Use modular design in order to postpone product differentiation for as long as possible	Components follow the lean concept and agile at later stages
Customer drivers	Cost	Availability	Mix
Profit margin	Low	High	Mix
Dominant costs	Physical costs	Marketability costs	Mix
Stock-out penalties	Long-term contractual	Immediate and volatile	Mix
Purchasing policy	Buy goods	Assign capacity	Mix
Information enrichment	Highly desirable	Obligatory	Mix
Forecasting mechanism	Algorithmic	Consultative	Mix
Logistic focus	Eliminate waste	Custom and markets	Mix
Partnerships	Long-term, stable	Fluid clusters	Mix
Key measures	Output measures such as productivity and cost	Measure capability, and focus on customer satisfaction	Mix
Process focus	Work standardisation, conformance to standards	Focus on operator self-management to maximise autonomy	Mix
Logistics planning	Stable, fixed periods	Instantaneous response	Mix

Also, based on production planning, customer order decoupling point (CODP) and inventory policies, the supply chain can be classified into the following policies:

4. **Make-to-stock (MTS)/Ship-to-stock (STS) supply chain**

The make-to-stock supply chains represent cases where a standard product is provided from a defined range. The make-to-stock strategy means that the supply chain can cope with demands in changing locations but with a steady overall demand for a standard product. Ship-to-stock is a similar strategy but supplies a standard product in fixed locations. This kind of supply chain depends on the accuracy of forecast demand. Also, the members of the supply chain in this case must hold the correct level of stock to minimise the risk of stockouts and overstocks (Naylor et al., 1999).

5. **Engineer-to-order (ETO)/Buy-to-order (BTO) supply chain**

Buy-to-order or engineer-to-order supply chains are appropriate for special products that are unique and do not have the same raw materials, where the consequences are long lead-times and highly variable demand for products. Also, the risk with this kind of supply chain is the stock becoming obsolete. The advantage of this type of supply chain is the low exposure to the costs of overstocking if the products are unsuccessful in the marketplace. On the contrary, the supply chain would not benefit from new market opportunities as rapidly as the make-to-order (MTO) supply chain (Naylor et al., 1999).

6. **Make-to-order (MTO) supply chain**

A make-to-order supply chain differs from ETO or BTO in its ability to supply various products since they share the same raw materials. Its advantages are that it can manage changing locations, volumes and product mixes, and a reduction in lead time with a considerable wait by customers to get the product they desire. This kind of supply chain is related to customisation since the demand for the product can vary, especially when numbers of different combinations and the basic model are high. The risk in terms of stock is the holding of raw materials and components (Naylor et al., 1999).

7. **Assemble-to-order (ATO) supply chain**

In an assemble-to-order supply chain, customisation is postponed until as late as possible. The advantages of this strategy are the ability of the supply chain to respond to a changing product mix from within a range of products with varied locations, and the significant reduction in lead time based on the final assembly location. The main risk is overstock or understock, as the value of products would be less than the fully assembled product. However, there would be no full risk of obsolescence. In contrast, this supply chain would take advantage of producing new developing products. The decoupling point moves between the manufacturers and assemblers in the supply chain (Naylor et al., 1999).

2.2.4 Product type and supply strategy

Understanding the environment and finding the most important characteristics will help in designing a supply chain in accordance with the nature of demand. Functional products do not change over time and have long life cycles and stable, predictable demand. Innovative products with their high margins and volatile demand require a fundamentally different supply system from stable, low margin, functional products. Fisher's framework (Fisher, 1997), which is shown in Figure 2.3, links the nature of the demand with the function of the supply chain. The four cells of the matrix represent the four possibilities of product strategy versus supply strategy.

	Functional Products	Innovative Products
Efficient Supply Chain	Match	Mismatch
Responsive Supply Chain	Mismatch	Match

Figure 2.3: Fisher's framework (Fisher, 1997)

Depending on the nature of the product demand, it can be predictable for functional products and unpredictable for innovative ones; and depending on the priorities of the supply process, that can be efficient at the lowest possible cost or responsive at the fastest possible speed.

With innovative products, decisions about inventory and capacity are not about minimising cost, but about where in the channel strategic reserves and excess capacity should be positioned to best hedge against demand uncertainty. And suppliers should be chosen for their speed and flexibility, not for low cost. The risk of shortages or excess supplies is very high with innovative products for which market reaction is uncertain. The key in this environment is to read quickly the market signals and react quickly. Thus the crucial information flows from the marketplace to the channel and within it: information such as early consumer sales or results from customer focus groups. The view of lean and agile production is synonymous with the functional product and innovative product strategies developed by Fisher (1997). This view of Fisher's presented two generic cases for lean and agile and provided the right solution to be applied to the right problem. If the market requirements are such that purely functional products suffice, then an efficient, lean process has to be engineered. If the market calls for a high degree of customisation, an innovative product, then the process has to be responsive and hence agile. Also, this solution has not taken into account when a customised product is required.

Christopher et al. (2006) include lead times in the classification scheme where they suggest three-dimensional classifications. The dimensions are products (standard or special), demand (stable or volatile), and replenishment lead times (short or long). Figure 2.4 shows the different pipelines that emerge from the classifications.

Supply Characteristics	Long Lead Time	**LEAN** PLAN and EXECUTE	**LEAGILE** Decouple through POSTPONEMENT
	Short Lead Time	**LEAN** CONTINUOUS REPLENISHMENT	**AGILE** QUICK RESPONSE
		Predictable	Unpredictable
		Demand Characteristics	

Figure 2.4: How demand/supply characteristics determine pipeline selection strategy (Christopher et al., 2006)

2.3 Agile Supply Chain Principles: Concepts

2.3.1 Agility history

Agile manufacturing emerged after lean production, and was initiated by researchers at Lehigh University in the early 1990s. In 1991, the Iacocca Institute at Lehigh University led an industrial *21st Century Manufacturing Enterprise Strategy* study (Nagel et al., 1991) involving 113 US companies to find the characteristics that manufacturing companies will probably have in 2006. The "agile manufacturing" term was invented to draw a new manufacturing paradigm that was classified as an extension to mass production. Key findings of the study are (Goldman et al., 1995; Groover, 2001; Nagel et al., 1991):

- A new competitive environment is emerging that is forcing changes in manufacturing systems and organisations.
- Agile companies that can rapidly respond to demand for customised products will have competitive advantage in this environment.
- Agility requires integration of: (1) flexible production technologies, (2) knowledgeable workforce, and (3) management structures that encourage cooperative initiatives internally and between firms.
- The American standard of living is at risk unless the US industry can lead the transition to agile manufacturing.

This study was followed by the book *Agile Competitors and Virtual Organisations* (Goldman et al., 1995). Agility has been recognised as "a new system of doing business" and is usually associated with the lean paradigm (Anderson, 1997).

A key characteristic of an agile organisation is flexibility. The origin of agility as a business concept arose from flexible manufacturing systems (FMS). The idea of manufacturing flexibility was extended into the wider business context, and the agility concept as an organisational orientation was born (Christopher, 2000).

2.3.2 Agility definitions

Agile manufacturing can be defined as (1) an enterprise level manufacturing strategy of introducing new products into rapidly changing markets, and (2) an organisational ability to thrive in a competitive environment characterised by continuous and sometimes unforeseen change (Groover, 2001).

"...the ability to cope with unexpected challenges, to survive unprecedented threats of business environment, and to take advantage of changes as opportunities" (Sharifi & Zhang, 1999).

"An agile enterprise is a fast moving, adaptable and robust business. It is capable of rapid adaptation in response to unexpected and unpredicted changes and events, market opportunities, and customer requirements. Such a business is founded on processes and structures that facilitate speed, adaptation and robustness and that deliver a coordinated enterprise that is capable of achieving competitive performance in a highly dynamic and unpredictable business environment that is unsuited to current enterprise practices" (Kidd, 2000). This comprehensive definition reflects the organisational point of view.

Agility is a business-wide capability that embraces organisational structures, information systems, logistics processes and, in particular, mindsets (Katayama & Bennett, 1999; Power et al., 2001).

Agility is also defined as the ability of an organisation to respond rapidly to changes in demand, both in terms of volume and variety (Christopher, 2000).

Dyer and Ericksen (2009) define business agility as "the capability of rapidly and cost efficiently adapting to changes. Recently agility has been applied e.g. in the context of agile software development and agile enterprise".

Business agility is "the ability of a business to adapt rapidly and cost efficiently in response to changes in the business environment, and can be maintained by maintaining and adapting goods and services to meet customer demands, adjusting to the changes in a business environment and taking advantage of human resources" (Tsourveloudis & Valavanis, 2002).

Agility, for a company, is to be "capable of operating profitably in a competitive environment of continually, and unpredictably, changing customer opportunities", and "the ability to thrive in a competitive environment of continually and unpredictably changing market opportunities" (Goldman et al., 1995).

However, agility works in the unstable and unpredictable contexts where demand is volatile and variety in customers' demands is high.

2.3.3 Reasons for the different definitions of agility

A review of the definitions demonstrates that the term "agility" can refer to manufacturing, to supply chain, and involves the firm's organisational structure, human resources, partnership with other organisations, and relationships with customers.

There are two interdependent aspects of agility: strategic and operational. At the strategic level an external-looking perspective is required. Necessary activities are required that include scanning the environment and assessing the likely impact of industry trends, technology drivers, competitive forces, market changes and market segment dynamics.

The operational level relates to what is happening inside the organisation, such as production processes, and process innovation. Closely aligning operations with strategy is essential in an agile organisation. Adopting an agile strategy means working in new ways of transforming multiple internal operations (Meredith & Francis, 2000). To become an agile organisation, which is a difficult journey, perhaps endless, depends upon the integration of the circumstances shown in the reference model in Figure 2.5.

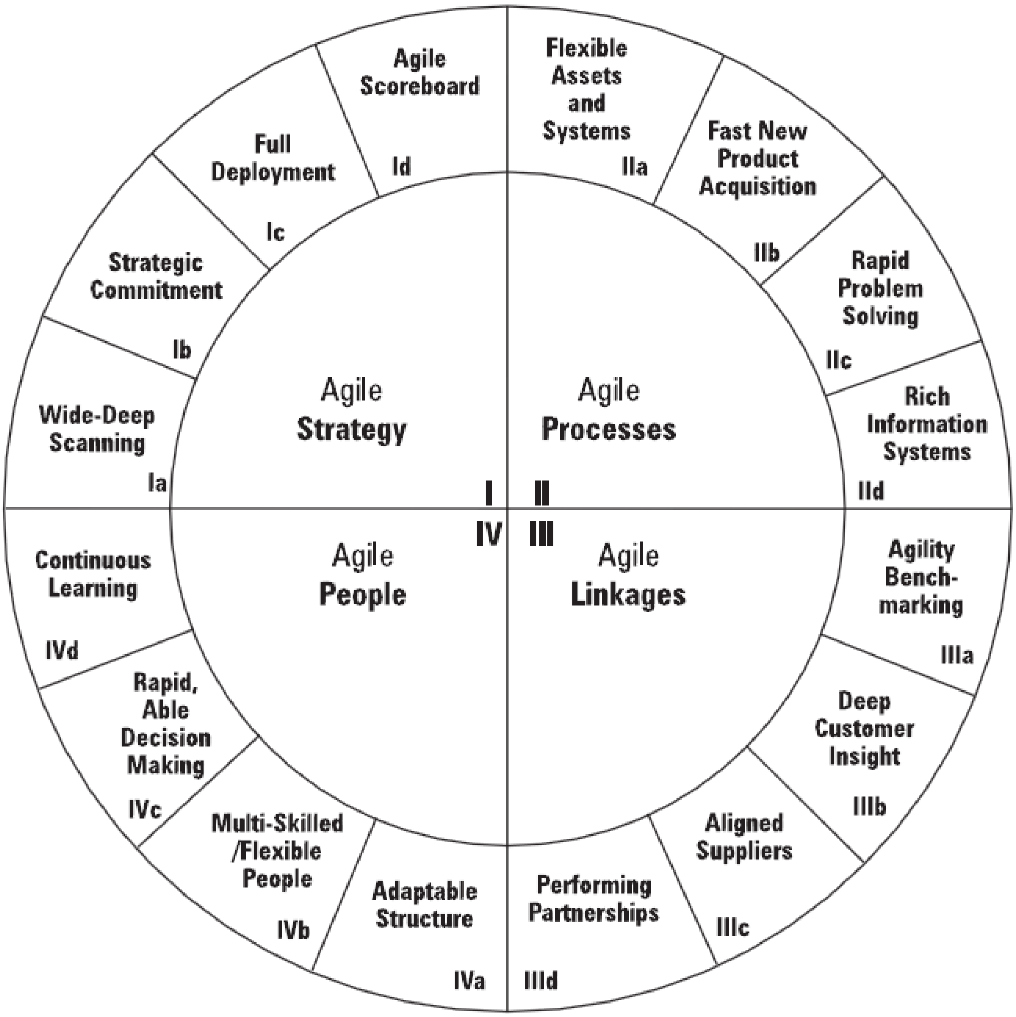

Figure 2.5: Agile manufacturing reference model (adapted from Meredith & Francis, 2000)

The focus in this project is on agility from the supply chain perspective through the operational scope.

2.4 Agility from Supply Chain Perspective

Agility is needed for a supply chain for the sake of adaptation to any change due to the business environment (Agarwal et al., 2006). Some factors have been suggested to contain such changes, which are as follows (Harrison et al., 1999):

- **Market sensitive**. Closely connected to end-user trends.
- **Virtual**. Relies on shared information across all supply chain partners.
- **Network-based**. Gains flexibility by using the strengths of specialist players.
- **Process-aligned**. Has a high degree of process interconnectivity between the network members.

Figure 2.6 sets the view of the agile supply chain (Harrison et al., 1999).

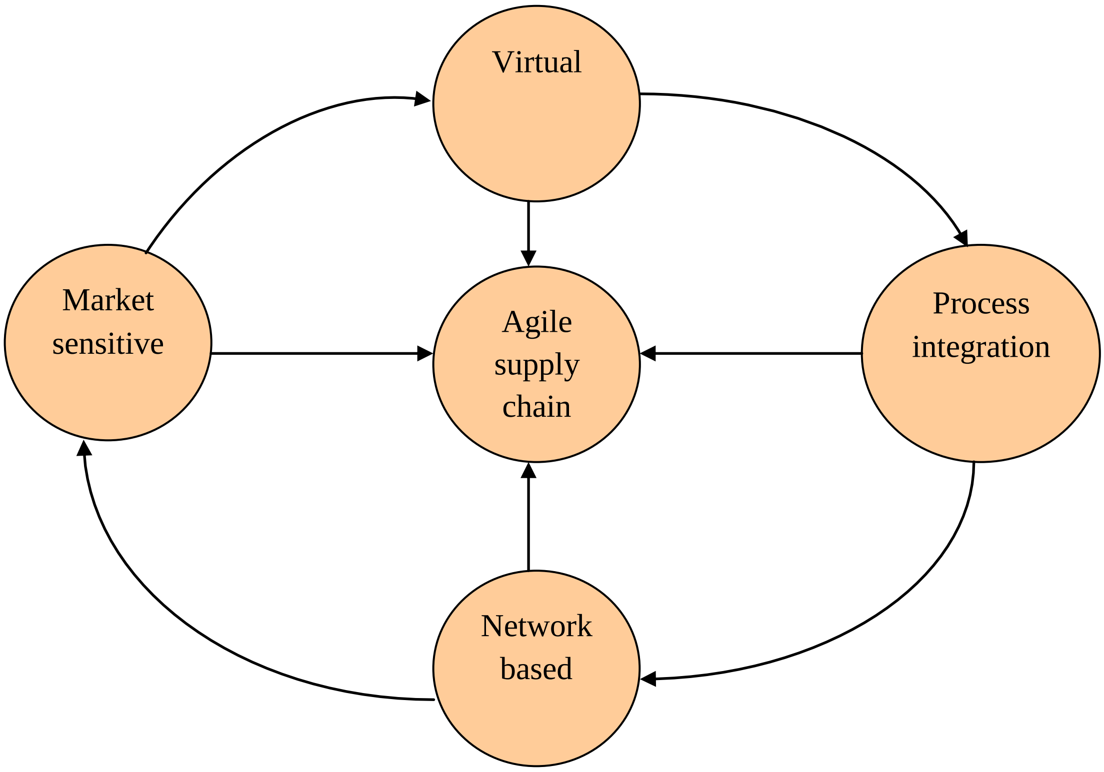

Figure 2.6: An integrated model for enabling the agile supply chain (1) (Harrison et al., 1999)

Christopher and Towill (2001) suggest a three-level framework summarising their view of the agile supply chain, which is shown in Figure 2.7. Level 1 represents the key principles that underpin the agile supply chain: rapid replenishment, and postponed fulfilment. Level 2 identifies the individual programmes such as lean production, organisational agility, and quick response, which must be implemented in order for the Level 1 principles to be achieved. Level 3 specifies individual actions to be taken to support Level 2 programmes, for example time compression, information enrichment, and waste elimination. This model is wide-ranging and provides a framework for understanding the concept and its link to the different perspectives and views.

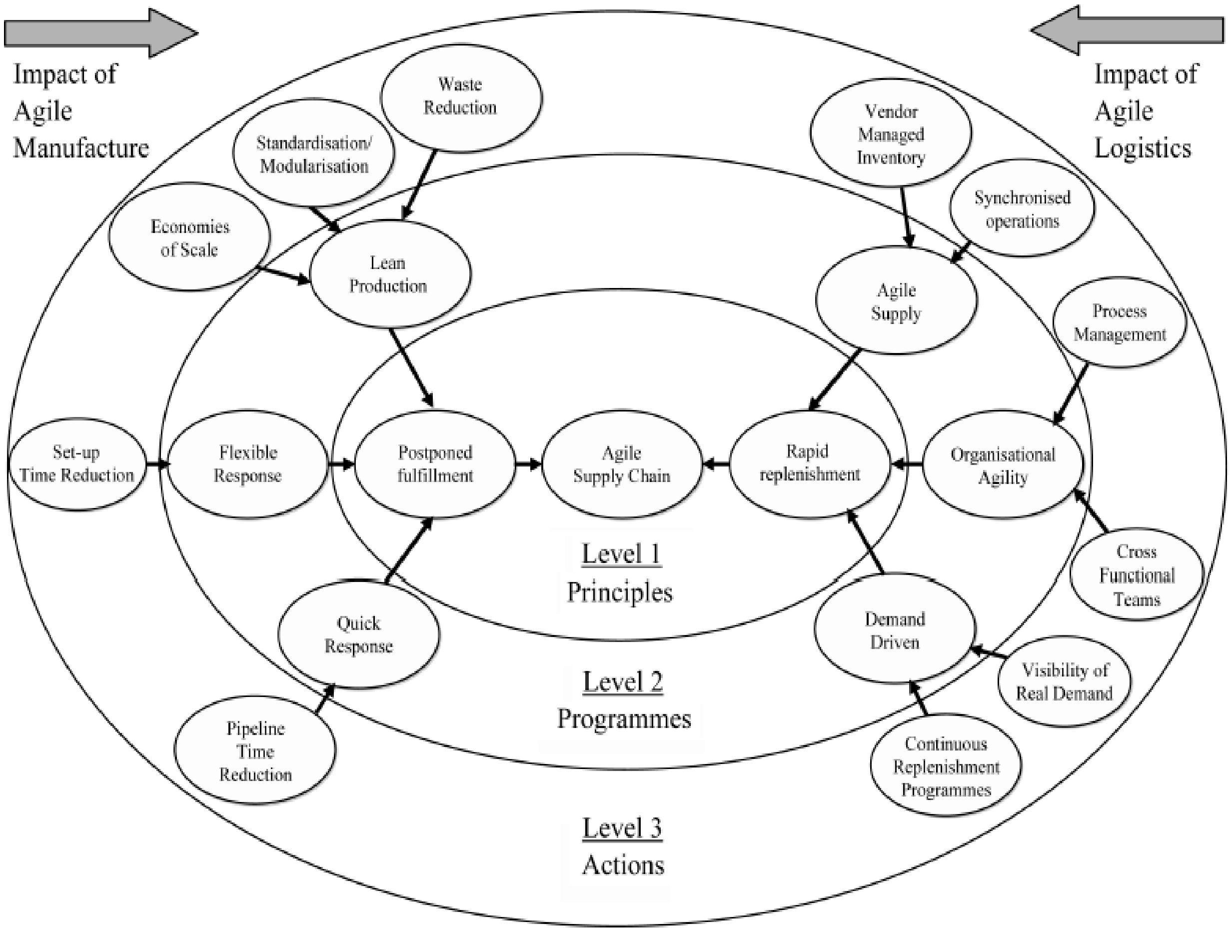

Figure 2.7: An integrated model for enabling the agile supply chain (2) (Christopher & Towill, 2001)

The main driving force behind agility is change. Manufacturing has tended toward gradual change and adjustment in response to the prevailing market circumstances (Yusuf et al., 1999).

Agility from the supply chain perspective is influenced by many factors. Agile organisations must be more demand driven than forecast driven to achieve agility (Christopher, 2005). In other words, the agile supply chain must be able to match supply with demand by responding within a short timeframe.

2.4.1 Agility drivers from supply chain perspective

The agility drivers in the supply chain are created because of the increasing rate of change and uncertainty in the business environment (Ismail & Sharifi, 2006). The four linked activities shown in Figure 2.6 contribute to the process of design, manufacture and delivery of products and services, and help in describing the measurement of supply chain agility and how the relationships between these links are managed in order to enhance achieving the objectives of agile manufacturing (Van Hoek et al., 2001; Yusuf et al., 2004). These objectives are: customer enrichment ahead of competitors, achieving mass customisation at the cost of mass production, mastering change and uncertainty through routinely adaptable structures, and leveraging the impact of people across enterprises through information technology.

2.5 Agility Measurement

2.5.1 Agility measures

Two main themes can be identified in the literature on measuring agility based on the supply chain in terms of strategy: (1) organisational theoretical measurement, and (2) operational measurement.

1. **First theme – organisational theoretical measurement**

Agility is a complex and multidimensional concept, and is context-specific. The impact of various attributes of agility on performance then needs to be studied (Vokurka & Fliedner, 1998).

Agility can be defined and measured in terms of improving the cycle time for managerial action which can be broken into three components across four time periods (Pal & Pantaleo, 2005):

- **Sense**: how long does it take to sense a need or change in conditions?
- **Decide**: how long does it take to make a decision?
- **Respond**: how long does it take to make a change and return to the beginning of the cycle?

- **Validate**: how long does it take to validate the outcome of the change?

There has been discussion on what agility is, while there is little research on how to measure agility or measure how a firm can be agile (Arteta & Giachetti, 2004). Since 1991, research has tried to answer the measurement questions, but because of the limited knowledge available it failed to capture all the on-hand measures. From an organisational point of view, Goldman et al. (1995) listed the four dimensions of agility which are: enriching the customer, cooperating to enhance competitiveness, mastering change and uncertainty, and leveraging people and information. Also, they designed a listed measurement table to assess the progress a company makes toward agility, which presents the traditional organisational model. The focus should be only on the key metrics as there is no need to measure every single thing that occurs in manufacturing enterprises (Kidd, 1995). The literature has suggested a range of metrics with different categorisations. Kidd assesses agile manufacturing according to a range of metrics: time, quality, and innovation metrics, which are explained in Table 2.2.

Table 2.2: Some key time, quality and innovation metrics (Kidd, 1995)

Time-related metrics	Quality-related metrics	Innovation metrics
Responsiveness to service request	Number of defects identified per employee	Number of exploratory activities
Manufacturing cycle efficiency	Number of field repairs	Number of patents applied for
Change-over times	Amount of scrap	Ratio of unsuccessful to successful product introduction
New product introduction time	Customer returns	Parts count trend
Distance travelled by parts within plant	Number and frequency of customer complaints	Fraction of workforce with degrees and advanced degrees
On-time delivery performance	Turnover of employees	Fraction of people participating in suggestion schemes, continuous improvement
Ratio of direct to indirect labour	Fraction of people trained in SPC, TQM	Number of suggestions per employee
Throughput times	Fraction of sales to repeat customers	Material types usage trend

Measuring agility is a difficult task since it is a new concept. Most of the measurement approaches are not dynamic.

A hypothesis is suggested by Arteta and Giachetti (2004) to test whether a less complex enterprise in terms of systems and processes is easier to change and is consequently more agile. They use Petri Nets to find the state space probabilities for the enterprise complexity measure. The main important relationships in an enterprise are the material and information flows between the system elements, the organisational relationships, and the communication network connecting people with other people or machines (Arteta & Giachetti, 2004).

Giachetti et al. (2003) argue that to deal with unanticipated change, agility must be a structural property of the system. The problem with this method is the difficulty of measuring complexity as well. Table 2.3 presents the various efforts in the literature regarding this theme.

Table 2.3: Summary of organisational agility measurement strategies

Strategy for agility measurement	Methodology	Proposed measurement
Measuring Agility: A Self-Assessment Approach (Goldman et al., 1995)	1. General questions for companies to determine which questions will favourably impact an agile business strategy.	1st: Enriching the customer (detailed questions) 2nd: Cooperating to enhance competitiveness (detailed questions) 3rd: Mastering change and uncertainty (detailed questions) 4th: Leveraging people and information (detailed questions)
	2. Listed measurements in a table for assessing the progress a company is making toward agility as shown in the next column that correspond to the four categories in the above column.	• The traditional organisational model • The emerging agile-virtual model • Metrics and measures to show the progress from the old to new system • Range of values in leading companies • Baldrige category
On the measurement of enterprise agility (Tsourveloudis & Valavanis, 2002)	A knowledge-based framework with the aid of fuzzy logic.	To calculate the overall agility of an enterprise, a set of quantitative agility parameters were grouped into production, market, people and information infrastructures.
Analysis of the structural measures of flexibility and agility using a measurement theoretical framework (Giachetti et al., 2003)	The measurement framework was based on relational measurement theory.	It defined and classified the extant measures according to whether they are structural or operational.

Weighing agile alternatives (Meade & Sarkis, 1999)	The analytical hierarchy process (AHP)	A framework represents a set of relationships between elements, determinants, dimensions, and characteristics of agility and business processes.
Framework measuring a supply chain's "agile capabilities" based on five dimensions of agility (Van Hoek et al., 2001)	Conceptual framework	• Customer sensitivity • Virtual integration • Process integration • Network integration • Measurement
Measuring the level of agility (Garbie et al., 2008)	Fuzzy mathematical approach	Measurement is based on existing technologies, level of qualifying people, manufacturing strategies, and management systems.
A balanced approach to building agile supply chains (Ismail & Sharifi, 2006)	Framework relies on research previously carried out by the authors in the areas of developing agile manufacturing and systems and models for demand network alignment.	Responding proactively to the market and business environment changes, agility can be facilitated by simultaneous development of supply chain and the output/product of the chain.

Metrics for agility were summarised as shown in Table 2.3 based on the definition that agility can be described as the potential to respond to change.

Unexpected change may be categorised into the following five groups, often associated with a state (systemic) diagram (Sarkis, 2001):

(1) Resources
(2) Technology
(3) Processes (internal conditions and mechanisms)
(4) Environment (external conditions and mechanisms)
(5) Demand (customer conditions and mechanisms).

Ramasesh et al. (2001) propose an exploratory framework for a structured analysis of the various elements of the manufacturing system in which agility at different levels is built in through different pathways and then linked to a set of aggregate performance measures.

This section summarises agility measurement in the literature from an organisational perspective that supports the supply chain.

2. Second theme – operational measurement

The main measure is the responsiveness of this theme as it is the most important capability for an agile supply chain. Supply chain agility has been discussed in terms of reach and range of activities covered by information networking among companies (Browne et al., 1995; Kehoe & Boughton, 2001; Yusuf et al., 2004). The responsiveness was seen as a main performance measure through the literature. There is a need to find a balance between responsiveness and efficiency by monitoring the lead time. Companies have been attempting to find ways to improve their flexibility and responsiveness and in turn competitiveness by changing their operations strategy, methods and technologies. This includes the implementation of the SCM paradigm and information technology (IT) (Gunasekaran & Yusuf, 2002). Responsiveness is a market winner with many markets becoming volatile and difficult to predict, as the focus of supply chain management has needed to “shift from the idea of cost as an order winner to as the market winner” (Towill, 2005b). The Supply-Chain Council (2011) support responsiveness as one of five core supply chain performance metrics. Theeranuphattana and Tang (2008) combines Chan and Qi’s conceptual model (Chan et al., 2003) and the supply chain operations reference (SCOR) model to demonstrate the applicability of the combined approach for measuring supply chain performance. Table 2.4 presents the various efforts described in the literature regarding this theme. Sharifi and Zhang (1999) list responsiveness as one of the capabilities of supply chain agility. Yusuf et al. (1999) argue that agility should not be considered equal with the speed of doing things, as it exceeds speed and compels massive structural and infrastructural changes. Gunasekaran (1999), and Gunasekaran and Yusuf (2002) agree with this argument and believe that agility covers such attributes as cost and quality coupled with responsiveness. Yusuf et al. (2004) emphasise that it is a major capability for an agile supply chain. Kritchanchai and MacCarthy (1999) mention that a major defect of the majority of the existing frameworks is a misunderstanding of the distinction between factors that *command* supply chains to be responsive and factors that *enable* them to be responsive (Ganguly et al., 2009). An important tool for the operational measurement is introduced by Kaplan & Norton (1992) to test the activities of a company if it meets its objectives in terms of vision and strategy. The balanced scorecard contains four perspectives: financial, customer internal business, innovation, and learning perspectives.

Table 2.4: Summary of operational responsiveness measurement strategies

Author	Framework characteristics	Factors considered
Three dimensions of responsiveness (Holweg, 2005)	Three dimensions of responsiveness (volume, product, process). The focus was on car manufacture based on BTO strategy.	• Customer lead-times • Volume stability • Demand specifications (Pareto) • Product variety (external, internal) • Point of customisation • Product life cycle • Total order-to-delivery (OTD) time • Distribution lead-time • Supply chain response lead-time • Decoupling points
The complexity of the enterprise system (Arteta & Giachetti, 2004)	Petri Nets was used to find the stated space probabilities needed for the complexity measure.	A hypothesis is that a less complex enterprise in terms of systems and processes is easier to change and consequently more agile (the quantification of complexity at the business process level).
Agility evaluation (Lin et al., 2006b)	Using fuzzy logic.	Identifies agility capabilities, selecting linguistic variables for assessing and interpreting the values of the linguistic variables, fuzzy rating and fuzzy weights integration, fuzzy index labelling, and defuzzifying FPII in order to identify the main adverse factors which can influence agility achievement.
Agility index in the supply chain (Lin et al., 2006a)	The application of linguistic approximation and fuzzy arithmetic (developed from the concept of multi-criteria decision analysis).	Developed a fuzzy agility index (FAI) based on agility providers using fuzzy logic. It comprises attribute ratings and corresponding weights, and is aggregated by a fuzzy weighted average.
Towards responsive vehicle supply: a simulation-based investigation into automotive scheduling systems (Holweg et al., 2005)	Using a simulation of a multi-tier supply chain system, investigated the impact of altering key aspects of the scheduling activities with the objective of determining the scope for potential improvements in responsiveness of the supply chain.	The simulation results show that current vehicle supply systems are not capable of supporting BTO due to insufficient feedback between supply and demand, as well as due to the strong reliance on forecasting in the scheduling process.
Evaluating agility in corporate enterprises (Ganguly et al., 2009)	Applying these three factors: market share, responsiveness, and cost effectiveness, to Apple's agile behaviour in the digital media sector.	• Market share • Responsiveness • Cost effectiveness

Fundamental behaviour of virtual build-to-order systems (Brabazon & MacCarthy, 2006)	A relationship has been identified between the ratios of customers fulfilled through each system and the ratio of product variety/pipeline length.	Simulation models have been used and showed a VBTO system is essential behaviour that changes the stock mix and levels; stock levels are higher than in a conventional system at certain variety/ pipeline ratios. It is applicable in such sectors as automotive.
Responsiveness of the order fulfilment process (Kritchanchai & MacCarthy, 1999)	They included a generic framework based on four components: stimuli, awareness, capabilities and goals.	They provided a basis from operational and strategic viewpoints to assess aspects of responsiveness in a company through these four components and questions included in the framework.

The section summarised agility measurement in the literature, from an operational perspective, that supports the supply chain. The focus in this research relates to measurement from an operational point of view. This enables clear evaluation of the resulting agility through some key performance indicators.

The literature that covers the agile supply chain from an operational point of view is limited and relies on the responsiveness measure mainly. There are extensive literature reviews regarding responsiveness and certain areas of the manufacturing assembly: a production line, manufacturing cells, reconfigurable machines, etc., but not relating to the particular focus of this research.

2.5.2 Efficiency measurement

Efficiency is a measure of how economically the firm’s resources are utilised when providing a given level of customer satisfaction. Lean production techniques have contributed to a magnificent improvement in efficiency. In this study, efficiency is not the major area of research but this measure will be covered in the simulation study.

2.5.3 Development of the responsiveness assessment

Throughout the literature there is still confusion and inconsistency associated with “agility”. A clear semantic definition is needed that removes the confusion and holds agility to be a beneficial measure, by analysing existing knowledge and focusing on the operational perspective, since the concept has been researched extensively from an organisational point of view but not from an operational and quantitative perspective.

A new responsiveness assessment is needed which can present a clear picture of agility, and responsiveness measures, considering the measures from an operational perspective for all processes and main activities. The evaluation will propose the main processes that affect supply chain functions as integrated processes: Inventory, Delivery, Distribution, Channels, Order Management, etc. For each process, according to its scope and the activities associated with that process, a number of criteria will be defined to assess the responsiveness of the process from different aspects.

Some of the challenges in agility measurement are:

- The diversity of organisations' strategies, activities, and professionals opinions
- The intangible and non-financial measurements that are difficult to perceive
- The change of management practices and its links to the different concepts
- Its newness and the fact that it is still in the development stage.

2.6 The Customer Order Decoupling Point (CODP) Concept

2.6.1 Introduction

The concept of the customer order decoupling point has been mentioned as an integration concept from the total supply chain perspective between the lean and agile paradigms. The decoupling point is an important element in designing the supply chain. It separates the part of the supply chain oriented towards customer orders from the part of the supply chain based on planning (Hoekstra & Romme, 1992). It represents the strategic stock that separates the demand side of the supply chain focused on delivery to the end user, from the supply side, based on logistics planning. It is also often held as a buffer between fluctuating customer orders and/or product variety and smooth production output.

Traditional methodology has suggested four typical cases as classified in Section 2.2.3 earlier in this chapter: Engineer-to-order (ETO), make-to-order (MTO), assemble-to-order (ATO), and make-to-stock (MTS).

The decoupling point has been critical when considering when to adopt agile or lean manufacturing techniques. Associated with the positioning of the decoupling point is the issue of postponement. Section 2.6.9 focuses on the relationship between postponement and

CODP. The aim of postponement is to increase the efficiency of the supply chain by moving the product differentiation point (at the decoupling point) closer to the end user.

Postponing the decoupling point is believed to reduce the risk of being out of stock for long periods and of holding too much stock of products that are not required. Once the need for agility and the position of the decoupling point have been identified there are further decisions to be made (Naylor et al., 1999).

2.6.2 Definitions of the customer order decoupling point (CODP)

1. **The material decoupling point**

The customer order decoupling point (material pipeline): "The point that separates the part of the organisation oriented toward customer orders from the part of the organisation based on planning." (Hoekstra & Romme, 1992)

"The point in the value-adding material flow that separates decisions made under uncertainty from decisions made under certainty concerning customer demand" (Rudberg & Wikner, 2004; Wikner & Rudberg, 2001) Figure 2.8 shows the material decoupling point.

2. **The information decoupling point**

The customer order decoupling point (information pipeline): "The point in the information pipeline to which the marketplace order penetrates without modification. It is where market-driven information flow meets." (Mason-Jones & Towill, 1999) Figure 2.8 summarises the two positions of the decoupling point within the supply chain.

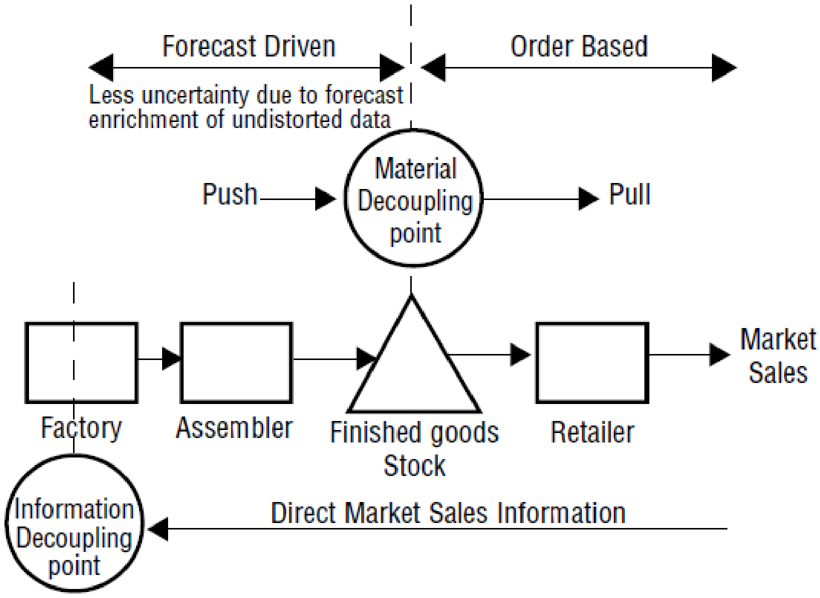

Figure 2.8: Comparison of material and information decoupling point positions within a supply chain (adapted from Mason-Jones & Towill, 1999)

2.6.3 Nature of the customer order decoupling point (CODP)

The birth of the decoupling point concept was based on the integral control of the total goods flow which required a customer-oriented approach to determine the nature of the relationships between organisations, product design and goods flow control (Hoekstra & Romme, 1992). An integral flow control that combines the material and information flow, which should define how to manage the two flows within the timeframe, is the main goal. Unfortunately, in too many instances there are still many problems in information and material flows: the distortion and magnification of order information remain, and the two pipelines are frequently changing (Feng-na & Shi-hua, 2005).

The positioning and the magnitude of the strategic stock, CODP, need careful engineering, considering product value, product complexity and product demand at each stage of the supply chain (Jones & Riley, 1985). The strategic stock should be kept at a minimum reasonable level to minimise stock and obsolescence costs while maximising service levels (Grunwald & Fortuin, 1992; Towill et al., 1997).

Figure 2.9 presents the family of simplified supply chain structures with the decoupling point marked as a stock holding point (Hoekstra & Romme, 1992). The manufacturers/assemblers represent one or more businesses in the supply chain. Varying the position of the decoupling point in Figure 2.9 highlights four common supply chain structures. These strategies range from providing unique products to an end user that is prepared to accept long lead-times (engineer-to-order (ETO)/buy-to-order (BTO)) through to providing a standard product at a fixed location (make-to-stock (MTS)/ship-to-stock (STS)). In addition to showing some basic supply chain structures, Figure 2.9 summarises the effect of the decoupling point on supply chain demand experienced by individual businesses within the chain. It is a highly variable demand with a large variety of products on the downstream side of the decoupling point, whereas demand is smoothed with the variety reduced upstream from the decoupling point (Hoekstra & Romme, 1992).

Repeated viewpoints make two clear-cut cases that the lean paradigm can therefore be applied to the supply chain upstream of the decoupling point as the demand is smooth and standard products flow through a number of value streams. Thereafter the agile paradigm should be applied downstream from the decoupling point as demand is variable and the product variety per value stream has increased (Mason-Jones et al., 2000a).

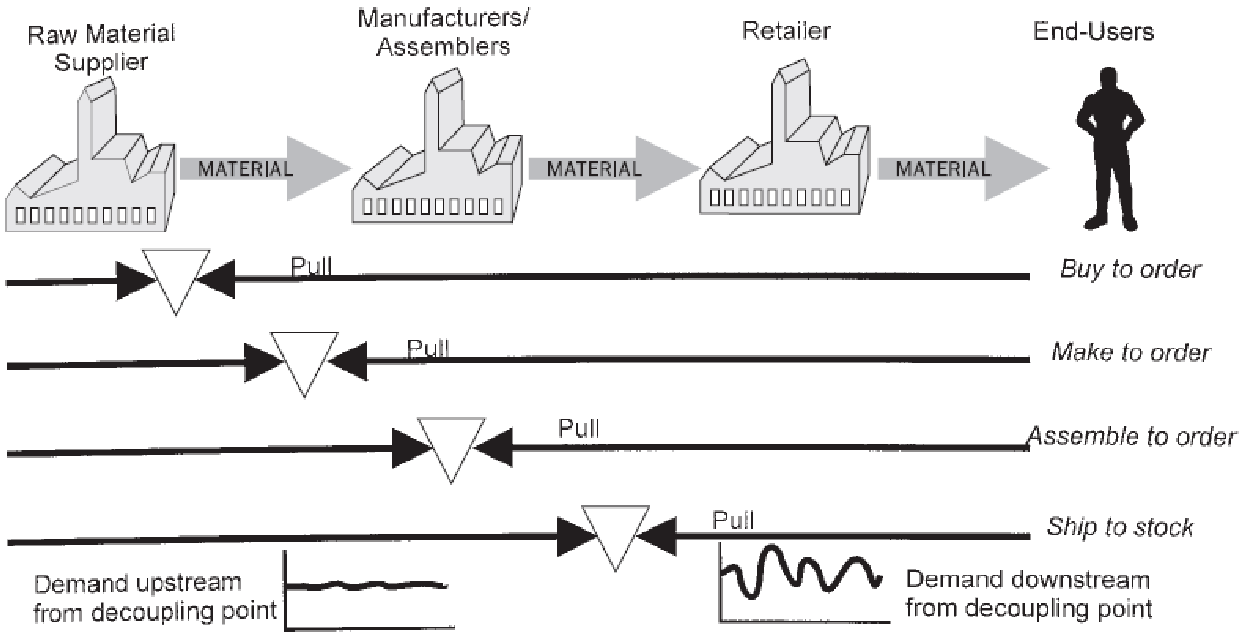

Figure 2.9: Supply chain structures and the decoupling point (Hoekstra & Romme, 1992)

2.6.4 CODP characteristics

The customer order decoupling point concept has been studied from different perspectives as shown in Table 2.5 later in this section, and is defined in several ways.

In production logistics the CODP separates production (long) lead-time and order lead-time in the market if there is a significant change in market risk. The different process, management, and control tools can be chosen on either side of the buffer. Also, the CODP is the natural boundary within an organisation between departments.

In mass customisation, CODP can be the means for a complete analysis of the various levels of mass customisation, and also for establishing operational processes of planning and control (Rudberg & Wikner, 2004).

The CODP separates the order-driven activities from the forecast-driven activities (Towill, 2005a). This is important not only for the distinction of different types of activities, but also for the related information flows and the way the goods flow is planned and controlled (Van Donk, 2001).

The material decoupling point is the main stock point from which deliveries to customers are made, and the amount of stock should be sufficient to satisfy demand in a certain period. The upstream activities can be optimised, as they are based on forecasts and are more or less independent of irregular demands in the market.

The original basis of the customer order decoupling point (CODP) is around the planning and control concept where within management it is the penetration point of the orders or the main stock point. From an operational strategy, it decouples operations in two parts: upstream of the CODP the activities are performed to forecast (on speculation), and downstream they are performed to customer order (Hoekstra & Romme, 1992).

Some parts of the logistics activities are performed as the customer is waiting, but also some preceding activities may have to be performed on speculation due to the fact that the production lead-time is longer than the required delivery lead-time (Rudberg & Wikner, 2004).

The CODP can be used as a business level concept with strategic, tactical as well as operational implications in the sense that the positioning of the CODP impacts many aspects of a company (Mason-Jones & Towill, 1999; Van Donk, 2001). Securing efficient operations could be very difficult if CODP positioning is unsuccessful between the operation of the manufacturing planning and control system, or between the design and operation of the production process. Also, it is too difficult to change from, for example, a make-to-stock approach to customer order driven manufacturing, which requires not only an updated approach to planning and control, as lead-times become a key issue, but also the introduction of the tools and techniques that fulfil the orders in a reliable time. These techniques and tools concentrate on matching production/manufacturing tasks and marketing requirements from a process choice perspective (Hill, 2000). Also, it can be considered for CODP-based analysis. It has been argued that the choice of manufacturing process is closely related to the positioning of the CODP (Olhager, 2003), However, most of these techniques concentrate on production alone. Rudberg and Wikner (2004) combine engineering activities with production activities as they try to merge these two functions. The CODP has been linked with logistics-related functions and production but they thought about the impact of the engineering activities involvement with CODP. The engineering activities are treated as something happening before any production activity takes place.

The CODP has been used as a tool for the analysis of activities associated with production and related material flows. It is sometimes referred to as the order penetration point (OPP). In some way the CODP is based on the concept of the P:D ratio introduced by Shingo (1981). In the P:D ratio, both P and D are lengths of the lead time, in which P represents the production lead-time and D represents the delivery lead-time starting from the order time. The P:D ratio can determine the amount of planning and production dependent upon speculation, and upon the basis of customer orders, by dividing P by D. Hence, the P:D ratio points out different positions of the CODP, as envisaged in Figure 2.10 (Hoekstra & Romme, 1992).

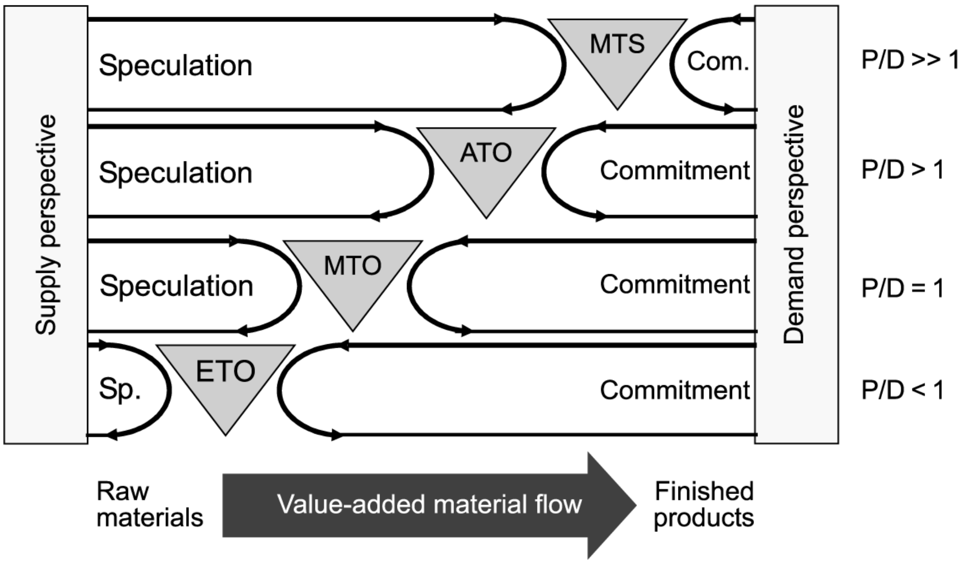

Figure 2.10: Typical CODP positions (Hoekstra & Romme, 1992)

In Figure 2.10, CODP positions divide the flow into parts based on speculation and customer order commitments, respectively. Typically, the main four CODPs (as described in Section 2.2.3) are engineer-to-order (ETO), make-to-order (MTO), assemble-to-order (ATO), and make-to-stock (MTS).

Throughout the literature review, most scholars have adopted the linear approach to the CODP concept. The further downstream the CODP is positioned the more of the value-adding activities must be carried out under uncertainty, and the further upstream the CODP is positioned the more activities can be based on actual customer orders.

Also, the point of product differentiation is at or downstream from CODP, and the stock held at the CODP is acting as a buffer between variable demand and a level production schedule. On the downstream side of the CODP is a highly variable demand with a large variety of products, and upstream from the decoupling point the demand is smoothed with the variety reduced.

Table 2.5 presents some of the literature compositions and classifications relating to customer order decoupling points.

Table 2.5: CODP literature review

Work	Contribution	Used toward which perspective
The rediscovery of logistics (Sharman, 1984)	Related the CODP to delivery strategies. Introduced order entry points for logistics control.	Manufacturing operations
Assemble-to-order manufacturing: Implications for materials management (Wemmerlo, 1984)	Pointed to the existence of different modes of operation for make-to-stock, make-to-order, and assemble-to-order.	Operation management
Integral Logistics Structures: Developing customer oriented goods flow (Hoekstra & Romme, 1992)	Introduced order entry points to improve logistics management in industrial companies, decoupled the activities into two parts upstream and downstream of CODP based on speculation and order processes.	Logistics management
Mason-Jones & Towill (1999); Mason-Jones et al. (2000a, 2000b)	Referred to the CODP information decoupling point.	Production, logistics and agile supply chain
Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain migration from lean and functional to agile and customised (Christopher, 2000; Christopher & Towill, 2000; Naylor et al., 1999)	Connected the lean paradigm with the agility of the supply chain.	Lean and agile
Production planning in Japan (Haan et al., 2001)	Identified two patterns: push production to stock and levelling versus pull production to order and chasing.	Production planning
Make to stock or Make to order: The decoupling point in the food processing industries (Van Donk, 2001)	Developed a framework to locate the CODP for a food industry based on balancing the factors and characteristics of the market and production process.	Production economics
Quantitative analysis on postpone-ment strategies of decoupling points in mass customisation (Rong et al., 2003)	Quantitative analysis on centralised and decen-tralised of controlling supply and replenishment network of mass customisation. It focused on customer demand with minimum inventory.	Mass customisation
The customer order decoupling point: Application in manufacturing and logistics (Rudberg & Wikner, 2003)	Background, definition of CODP.	Mass customisation
Leagile supply chain strategy in housing industry facing customer satisfaction (Zhong-fu et al., 2004)	A matrix designed to match the four alternatives with different customer requirements using an example of the house-building industry.	Leagile supply chain analysis
Mass customisation in terms of the customer order decoupling point (Rudberg & Wikner, 2004)	They adjusted the CODP typology by adding engineering with the production process into the mass customisation.	Mass customisation
Integrating production and engineering perspectives on the customer order decoupling point (Wikner & Rudberg, 2005a)	Introduced a new two-dimensional approach, defined CODP typology, and provided a classification of customer order influence based on a combined engineering and production perspective.	Operations and production management
Engineering management and the order entry point (Dekkers, 2006)	Developed a framework covering standard working methods for the conversion of customer requirements into components of modular product architecture, the management	Production research

	of customer-order activities and the separate development of new product architectures for future demands. He examined five case studies and implemented an Order Entry Matrix in engineering management.	
Decoupling the value chain (Olhager et al., 2006)	Combined the CODP with the Fisher model and distinguished between a product supply decoupling point and a demand mediation decoupling point with different characteristics upstream and downstream in value chain operations.	Value chain management
Implications of form postponement to manufacturing a customised product (Skipworth & Harrison, 2006)	Suggested CODP would be better located further upstream in the manufacturing process. Two alternative CODP locations were evaluated that prevent the removal of components, provide the same level of responsiveness and potentially improve delivery reliability.	Mass customis-ation and form postponement
Interference solving strategy in customer order decoupling point position based on Multi-Agent System (MAS) (Xu et al., 2007)	It focused on MAS theory and interference solving in CODP positioning process. It consisted of customer demands clustering and all participant negotiation process.	Mass customisation
Two-dimension model of customer order decoupling point position in mass customisation (Xuan-Guo et al., 2007)	Analysed CODP shift considering product design adaptation period. CODP was studied from production process into design and manufacture perspectives, and a two-dimension position model integrating design and manufacture was provided.	Mass customisation
Exploiting the order book for mass customised manufacturing control systems with capacity limitations (Wikner et al., 2007)	Lead time is a key factor in providing reliable delivery promises; order book control logic is introduced. The new MTO model of the customer facing part of a mass customisation system is an extension to the well-established APIOBPCS framework.	Mass customisation
Study on the customer order decoupling point position base on profit (Wu et al., 2008)	The relationship between the position of CODP and sales, then use M1M/N system of tandem queues to predigest the model. Numerical analysis was used to validate the model and give three deductions.	Mass customisation
Virtual build-to-order as a mass customisation order fulfilment model (Brabazon & MacCarthy, 2004)	They introduced virtual build-to-order (VBTO) related to mass customisation, ability to reconfigure flexibly, in which the producer has the ability to search across the entire pipeline of finished stock and change the product specification along the order fulfilment pipeline. They introduced floating decoupling point.	Mass customisation

2.6.5 Positioning and sizing the CODP

The factors that affect the positioning of the CODP can basically be divided into three categories, as suggested by Olhager (2003):

(1) Market,
(2) Product, and
(3) Manufacturing characteristics.

Also, the positioning of the CODP depends on the supply chain product type, consumer demand, degree of customisation, delivery due, and supply chain approach adopted (Feng-na & Shi-hua, 2005). These issues are outlined in Table 2.6. Even though all of them can influence the positioning of the CODP for a particular product, there are typically two main issues concerning the CODP positioning decision:

- The first main issue is the P:D ratio discussed earlier, i.e. the ratio between the production lead-time and the delivery lead-time, which indicates whether market requirements make MTO possible or whether some prefabrication is necessary.

- The second main issue is demand volatility, which indicates to what extent it is possible or reasonable to make products to order or to stock. Low volatility means that the item can be forecast-driven. However, high volatility makes forecasting difficult; therefore such items typically need to be produced to order.

Olhager (2003) discusses how these two issues can be combined in an approach for selecting the appropriate position of a CODP for products. Olhager and Wikner (1998) focus on profiles V, A, and X for material and capacity-dominated master scheduling. V is the profile for a process firm with a divergent material flow from raw materials to finished products. An A firm has a successive assembly of parts at many product structure levels, but firm T can assemble a large variety of end products from a narrow set of pre-defined modules, compared with the concept of postponement. An X profile is the result of a modular product design, where upstream operations are made to stock and downstream operations create the customer-specific product, based upon the choice of modules at the OPP, which is positioned at the material profile section. Thus, an X profile is built up by a V profile on top of an A profile.

Table 2.6 Factors that affect the position of the customer order decoupling point (adapted from Olhager, 2003)

Category	Factor	Characteristics
Market	Delivery lead-time requirements	Restricts how far backwards the CODP can be positioned. A benchmark for winning manufacturing lead-time improvements to make delivery speed an order.
	Demand volatility	Indicates to what extent it is possible or reasonable to make products to order or to stock.
	Demand volume	Related to the position in the product life cycle.
	Product range	A broad product range makes it impossible to provide products on a make-to-stock basis.
	Product customisation requirements	A wide set of customisation requirements by the customer makes it impossible to provide on a make-to-stock basis.
	Customer order size and frequency	Indicators of volume and the repetitive nature of demand. Large customer order sizes are typically associated with high demand volumes. High frequency leads to repetitive demand, making forecasting easier.
	Seasonality of demand	Typically uneconomical for the manufacturing firm to respond to all demand when it occurs.
Product	Modular product design	Typically related to assemble-to-order operations. Often responses by the producer to create a variety of choices for the customer, a relatively short delivery lead-time, and manufacturing efficiency for upstream operations.
	Customisation opportunities offered	If the customisation offered is wide and affects the product at early production stages, a make-to-order policy is necessary, whereas if customisation enters at a very late production stage, assemble-to-order may be more appropriate.
	Material profile (V, A, X, etc.)	The CODP is typically positioned at the material profile level, where independent demand occurs.
	Product structure complexity	A deep product structure typically corresponds to long cumulative manufacturing lead-times. The various paths of the product structure need to be analysed in terms of lead times to determine where in-process inventories need to be kept relative to delivery lead-time requirements.
Manufacturing	Manufacturing lead-time	Poses a major constraint on the CODP position, relative to market delivery lead requirements.
	Number of planning points (work centres)	Restricts the number of potential CODP positions. In a job shop where individual resources are planned, the variety for positioning the CODP is large. A dedicated line or continuous process can be treated as a single production unit and therefore offers only two possibilities: before or after the process.
	Flexibility	A prerequisite for producing to order. A wider range of products and customisation can be accommodated in the production system.
	Bottleneck position	It is advantageous to have the bottleneck upstream of the CODP, so the bottleneck does not have to deal with volatile demand and a variety of different products.
	Sequence-dependent setup times (or dominant setup times)	Best positioned upstream of the CODP. Such resources can easily turn into bottlenecks without proper sequencing and are not desirable for downstream operations.

Van Dijk et al. (2001) state that the point of product differentiation (PDP) in practice is not the same point as the CODP. When the CODP is located downstream of the PDP, this indicates that products are made customer/market-specific and then stored in this way at a central strategic inventory point which is the CODP.

Positioning the customer order decoupling point is a group decision process, which includes customer, supplier and manufacturer. The CODP position is affected by a number of factors such as cost, quantity, quality, and delivery time (Xu et al., 2007).

Many factors can potentially affect the position of the order penetration point. They are interrelated to some extent, as illustrated in Figure 2.11 (Olhager, 2003). The market can affect product characteristics and result in a delivery lead-time that customers want. The product structure with the levelled operations can be seen in terms of the production lead-time. The relationship between production and delivery lead-times is a major factor of the OPP position.

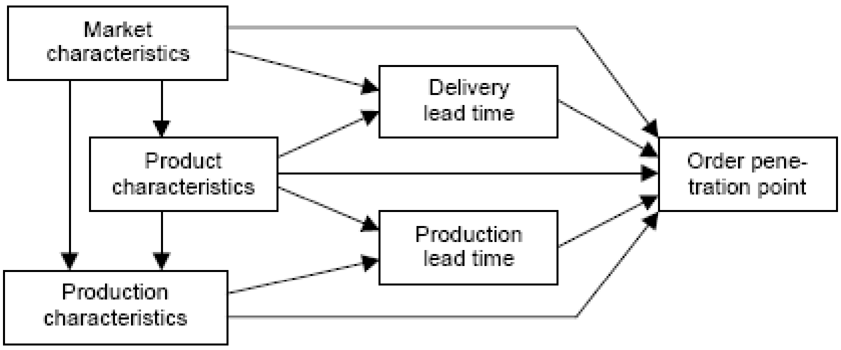

Figure 2.11: Conceptual impact model for factors affecting the positioning of the OPP (Olhager, 2003)

The position of the decoupling point has a vital impact on the assignment, leveraging and operation planning of the logistics system capacity in the whole supply chain. Capacity planning should be fixed before the material decoupling point, and scheduled capacity should be set to deal with uncertainty and improve the response speed (Feng-na & Shi-hua, 2005).

2.6.6 Boundaries for positioning of the decoupling point

The positioning is based on integrating the main functions, tasks, and areas of the supply chain. The integration of these foundations is influenced by a number of internal and external key factors which surround the case study and help to formulate the key factors that can affect supply chain responsiveness. The key factors are numerous but generally can be grouped as follows (Hoekstra & Romme, 1992):

- The basic structure of the supply chain: relates to the factors that map out the goods flow and the main functions structure of the material flow. The measurement of these factors will contribute to the responsiveness assessment from an operational point of view:
    - Physical stock points: represent input stock at the beginning of the supply chain or output stock at the end of the supply chain;
    - Physical resources: can be classified into three categories:
        - Material: the items consumed or converted by the system
        - Machines: the physical items utilised by the system
        - Labour: the people who operate the system;
    - Types of facilities and layout: can be classified into three categories:
        - Fixed position layout: job shop which is a low quantity and high product variety (0-100 products)
        - Process/cellular manufacturing layout: it could be job shop, batch production, mass production, depending on the product variety (100–10,000 products)
        - Product layout: this is mass production which is high volume and low variety (>10,000 items).
- The control structure of the supply chain: its relationship to the measures that control the systems that help in finding the boundaries of the decoupling points:
    - Material decoupling point: the locations in the product structure or distribution network where the main inventory/stock point is placed to create independence between processes or entities. Selection of decoupling points is a strategic decision that determines customer lead times and inventory investment;
    - Information decoupling point: the point in the information pipeline at which the marketplace orders data penetrates without modification. It is here where market-driven and forecast-driven information flows meet. This will help in finding the transparency of the information flow and information related to the orders, shipments, and the availability of goods.
- Logistics of the supply chain: relates to the measures that organise the logistics structure:
    - Mode of distribution

  - Distribution channels
  - Documentation-communication channels.
- Product structure of the supply chain:
  - New product development
  - The degree of modularity
  - The degree of producibility
  - The degree of standardisation
  - Product life cycle.

All these measures and their criteria are presented in Figure 2.12.

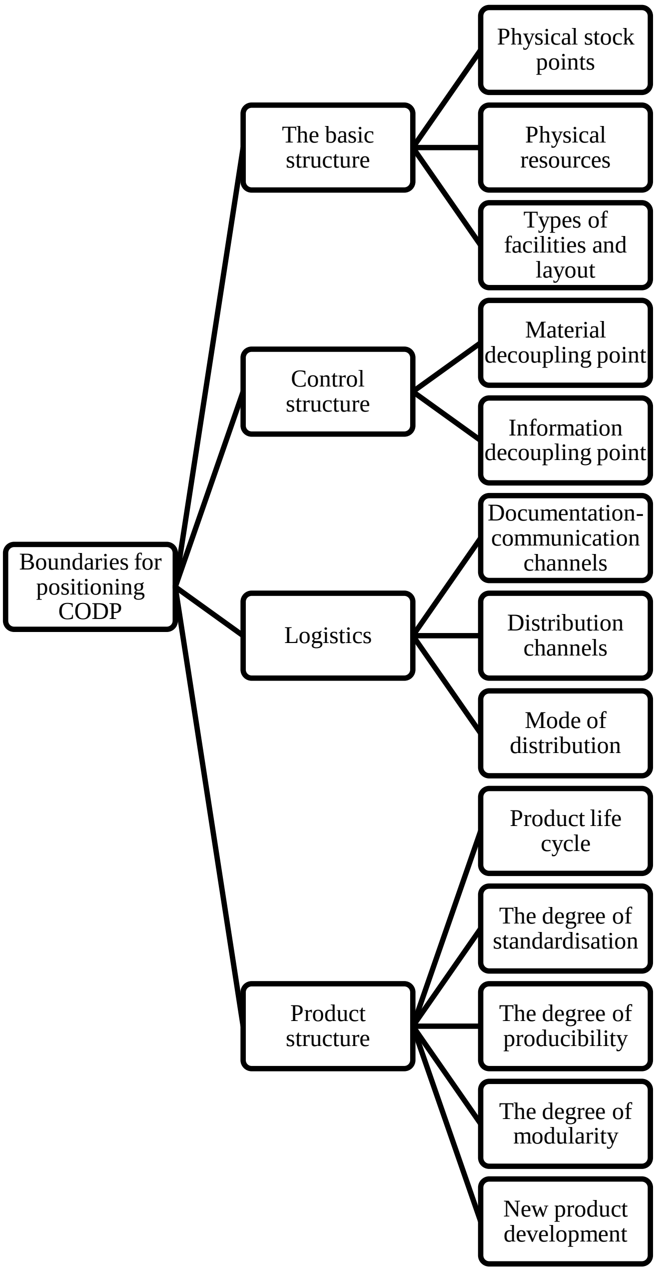

Figure 2.12: The hierarchy for developing the best position for the decoupling point for the responsiveness of the firm

2.6.7 The information decoupling point

The information decoupling point is referred to as the CODP by Mason-Jones and Towill (1999) who extend the traditional material flow and establish the role and importance of the information decoupling point. Their approach advises to place the information decoupling point as far upstream as possible and enable all the players in the supply chain to access the actual marketplace data. Information technology should not be mixed with the information decoupling point as IT is just a tool that is required for an organisation, not the unique solution for the transference strategy. Information decoupling enables the information pipeline to maintain the value of demand information, undistorted, without delay, and enables all players in the supply chain a timely share of actual, undistorted, rich demand information to improve the efficiency of the whole supply chain decision-making, reducing the capacity and cost waste (Feng-na & Shi-hua, 2005).

The information decoupling point is crucial in realising a timely, efficient response to the final users, diminishing the bullwhip effect (where orders sent create a larger variance than sales made), and achieving the whole supply chain competitive advantage. This should shorten the information pipeline's lead-time, reduce all kinds of uncertainty, and improve the speed of response to the final users through the integrated planning of the scheduled capacity (Feng-na & Shi-hua, 2005).

Mason-Jones and Towill (1999) raised the importance of the information decoupling point to the material decoupling point methodology and its help in maximising improvement in supply chain dynamics, as the distortion of marketplace sales information causes many of the material flow pipeline issues. Mason-Jones and Towill state that "therefore to maximise the strategic potential of undistorted information within the supply chain, in direct contrast to the material decoupling point, the information decoupling point should be moved as far upstream as possible". This seems logical and straightforward but how it can be done and whether this move will affect the dynamic response and therefore increase agility, need to be considered.

Sharing information in-depth sounds easy, but unfortunately does not normally take place in most companies (Towill et al., 1997). The information decoupling point strategy highlights the sturdy competitive advantages available only if information is shared through the whole supply chain. Systems controlled and analysed by computers have been providing instantaneous information for ordering, stock control and space allocation, that are connected through a communication network to head office, which enables them to be exploited directly by central business systems (Christopher, 1999).

A higher amplification of order and inventory fluctuation upstream of the supply chain is caused by the lack of timely sharing of production information, including delays and feedback, in the decision rules between players in the supply chain (Lee et al., 1997). A suitable location of the information decoupling point must be supported by intense use of modern information technology, such as websites, database systems, expert systems, decision support systems, EDI, and the Internet. (Kisperska-Moron & Swierczek, 2006). Modern technology, such as continuous-replenishment programs (CPRs) and vendor-managed inventory (VMI), has improved the efficiency of obtaining, coordinating and distributing the information in the supply chain (Sethi et al., 2005).

Sharing information, distortion, and updating have been the issues for the supply chain in terms of information effects. To overcome these issues, an investigation is needed to distinguish between the known, unknown, and the partially known to better understand the information that gives quick response. Information that can be transmitted upstream is, for example, that collected as sales data at the point of sales, and electronic data interchange (EDI).

Information can be classified into three types:

1. Planning and controlling information
2. Feedback information on logistics activities
3. Information from other sources, such as actual demand information, trade data, production planning, material or capacity programming, and so on.

Exploring the literature provides a clear understanding of information flow and an insight into the advancement and penetration of information feedback. This leads to a classification of information flow inside the plant, distinguishes which information can be tracked, and makes a difference in responding to demand and maximising responsiveness.

The physical material flow can be seen so it can be tracked, but information flow is intangible and difficult to track. Figure 2.13 shows a generic production information system (Sipper & Robert, 1998). The different functions and activities of the production system have either a partial or complete source to the outcome of the information flow, each with its own position in the supply chain. The information primarily relates to operating points that make decisions in the company. However, the focus in the research presented in this thesis is that the CODPs related to the information flow are on information related to the order not the IT.

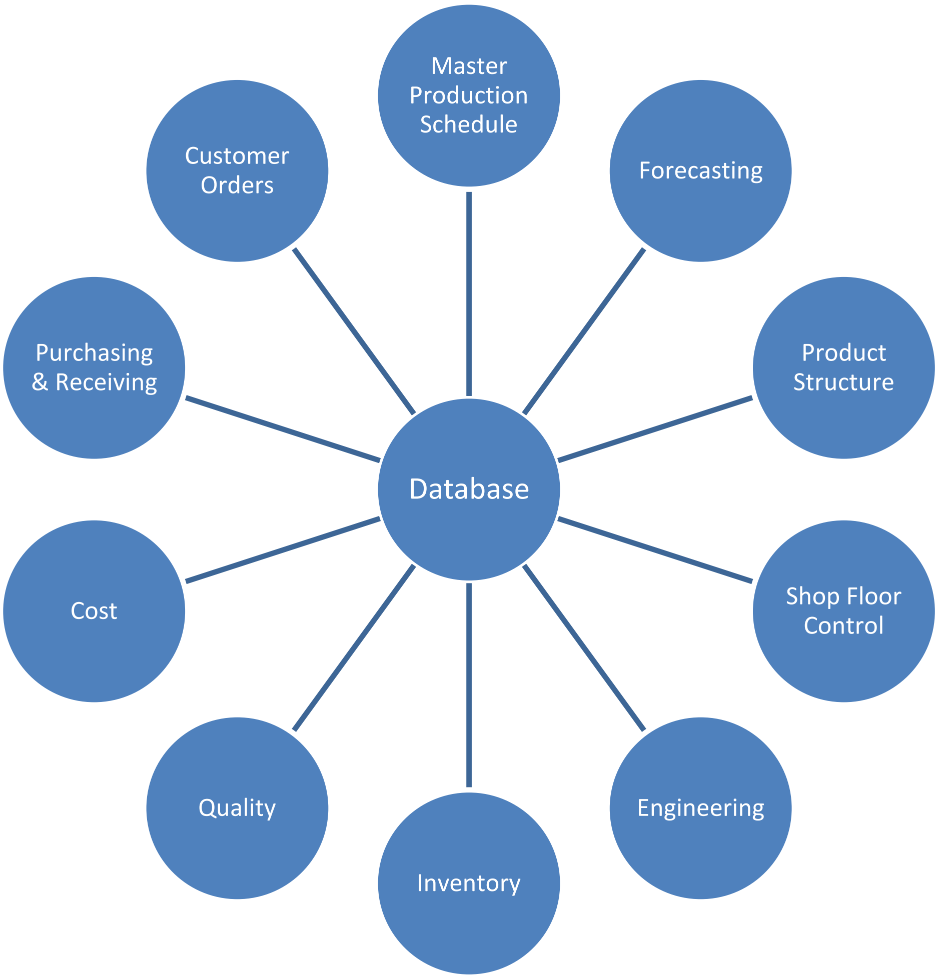

Figure 2.13: Generic production information system

2.6.8 Customer order decoupling zone (CODZ)

The first exploration of the CODP as a zonal concept is carried out by Rudberg & Wikner (2004), and Wikner & Rudberg (2005a, 2005b), who examine the engineering adaptation with the CODP by defining new typology (eight key decisions related to the decoupling zone) that enhance the knowledge of the properties of the CODP and the understanding of its possible use in operations and logistics.

The CODP identifies this distinction but the concept is limited in that it assumes either total uncertainty or total certainty concerning customer demand. Acknowledging a gradual increase in certainty across multiple independent dimensions provides a point of departure for extending the decoupling point to a decoupling zone.

The second supposition is investigated whereby they divide the CODP into two separate decoupling points: the product supply decoupling point (PSDP) and the demand mediation decoupling point (DMDP). They proposed separating the decoupling points such that they can be positioned away from each other, creating a middle zone upstream of the PSDP and downstream of the DMDP. The PSDP is placed on demand lead-time from the customer, and this is where products are assigned to a specific customer. This resulted in three zones as shown in Figure 2.14.

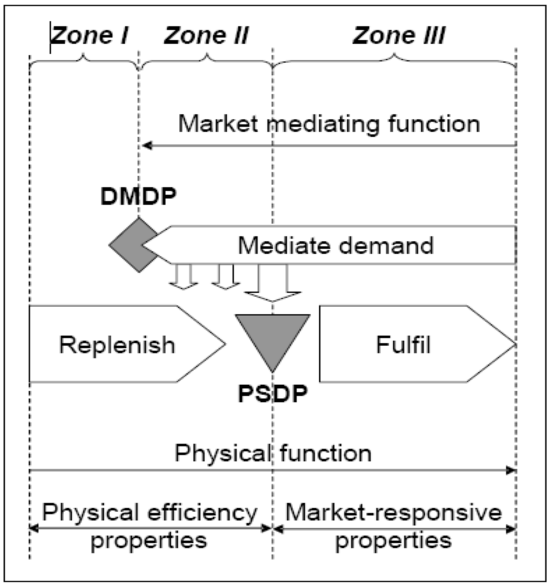

Figure 2.14: Three zones relative to the demand mediation decoupling point (DMDP) and the product supply decoupling point (PSDP) with supply chain design focus (Olhager et al. 2006)

Their idea, combined with the Fisher model, made the following findings regarding the zones:

1. Market mediation function manages demand information from the marketplace to the DMDP.
2. Physical function manages the supply of products to the market and acts along the entire value chain.
3. Physical efficiency properties are prioritised upstream of the PSDP.
4. Market-responsive properties dominate downstream of the PSDP.

2.6.9 Postponement and the CODP

Postponement is to move the point of differentiation further downstream, which is where the number of stock-keeping units (SKUs) increases, because the items are split into separate items (Lee & Tang, 1997, 1998). The concept of postponement has existed since 1920 and can be defined as "the delaying of operational activities in a system until customer orders are received rather than completing activities in advance and then waiting for orders" (Krishnamurthy & Yauch, 2007). Also, it refers to "a concept whereby activities in the supply chain are delayed until a demand is realized" (Van Hoek, 2001).

The main idea is to hold inventory in some generic or modular form and complete the final assembly or configuration just when the precise customer order is received (Christopher, 2005). Bucklin (1965) establishes the concept, focuses on the role of postponement in positioning inventory in the marketing channel, and is concerned with where in the channel inventory should be positioned (upstream waiting for customer orders, or downstream in anticipation of future customer orders) and which player (supplier or customer) should carry the inventory. However, the concept can be divided into three types: time postponement, place postponement and form postponement (Bucklin, 1965). Time postponement is delaying the manufacturing or logistics activity until a customer order is received; place postponement is keeping the product at the central warehouse until the customer's order is received, and form postponement is delaying product customisation until the customer order is received (Bowersox & Closs, 1996). Shapiro (1984) also treats the concept from a logistics perspective in positioning postponement in relation to inventory positioning broadly in the supply chain.

Later, Zinn and Bowersox (1988) describe postponement as consisting of five distinct types: labelling, packaging, assembly, manufacturing, and time; that is, four types of postponement constitute five types when combined with time. These types provide flexibility in deciding product content, package size, product version, material and amount to manufacture.

Dapiran (1992) gives an example of the delayed dyeing process in the Benetton case to show the principle of postponement. He mentions that added value should be as late in the supply chain as is compatible with satisfying customer needs.

Garg and Tang (1997) cover postponement from an operations research perspective and use a modelling study to compare the application of postponement upstream and downstream in the supply chain for two types of products/operating environment.

Lee and Tang (1997) formalise three basic paths to postponement: (1) standardisation, (2) modularity in design, and (3) process reorganising. Standardisation and modular design allows a firm to arrange a large number of different end products in a particular configuration from a limited set of standard components, by uniting a limited number of core modules with a range of modules that give different levels and different types of functionality (Lee & Tang, 1997; Ulrich, 1995). Process restructuring directs to move production activities that create the most variety to a later stage in the supply chain (postponement of operation) or re-sequence operations (Lee & Tang, 1998).

Van Hoek (1997) list seven generic CODPs that can be composed:

(1) Engineering-to-Order, as in construction.
(2) Purchasing-to-Order, as in high-end electronics.
(3) Make-to-Order, as in restaurants.
(4) Final manufacture/Assemble-to-Order, as in some PC products.
(5) Packaging/labelling-to-Order, as in some packaged foods.
(6) Shipment-to-Order, as in retailing.
(7) Adjust-to-Order in the retail channel, final adaptations can be made on the basis of customer orders, for example the making of fresh salads.

Van Hoek relates these generic CODPs' positions to the types of postponement in the supply chain as shown in Figure 2.15. Moreover, he includes the food industry case and develops a set of operating characteristics to determine the viability of postponed manufacturing in a decision model.

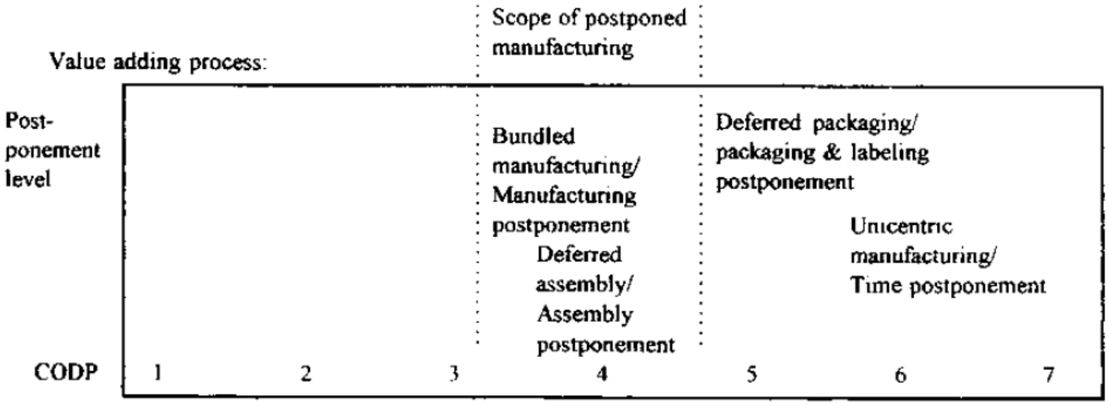

Figure 2.15: Postponement types and the CODP (Van Hoek, 1997)

Also, he reviews the literature on postponement (Van Hoek, 2001) and shows directions for extensive postponement research.

Pagh and Cooper (1998) identify four different supply chain postponement master plans for a general supply chain starting from the full speculation strategy, to the logistics postponement strategy, the manufacturing postponement strategy, until the full postponement strategy.

Van Hoek et al. (1999) explains that postponed manufacturing combines the three basic forms of postponement within one operating system; product finalisation (form) and shipment of products are delayed until customer orders are received (time) and operated from a central location in the channel (place).

Aviv (2001) analyses the advantages caused by the postponement strategy with unknown distribution of demand, and constructs quantitative analysis on the benefits carried with the postponement strategy versus different order costs. However, the analysis ignored the production capacity and lead-time constraints.

In Section 2.6.5 the classification based on profiles V, A, and X for material and capacity-controlled master scheduling represented that firm T can assemble a large variety of end products from a limited set of predefined modules, compared with the concept of postponement.

Aviv and Federgruen (2001) analyse the influence of the postponement strategy on a multi-product inventory system with production capacity constraints, but they do not suggest a positioning model of CODP. The major benefit given by them is that postponement in the supply chain relates to inventory reduction and service improvement, because holding inventory of a non-specific product requires less safety stocks compared to holding inventory of several specific products

Yang and Burns (2003) summarise seven postponement types focusing on the spatial/functional dimension of the supply chain from speculation until pure postponement in relation to standardisation and customisation activities, which resulted in seven CODP types (make-to-forecast, shipment-to-order, labelling-to-order, assembling-to-order, make-to-order, buy-to-order, and engineering-to-order) (Lampel & Mintzberg, 1996). This reflects how postponement is connected to CODP. Also, Yang and Burns (2003) mention that postponement application could be a logical starting point for making a decision on how to locate the DP by delaying the first product differentiation point in time close to customer and merging it with the DP. They add that postponement can alter the location of the DP directly (e.g. final configuration of products by customers) or indirectly (e.g. re-sequence activities) and therefore must regard the effects of its upstream and downstream exchange.

Diwakar and Benjaafar (2004) examine the costs and revenues brought about by the postponement strategy on the basis of the Queuing Theory, suggest the optimal position model of CODP, and raise an approximate solution.

Yang et al. (2004) review the postponement and propose a framework to give general ideas for further research toward postponement as they try to deduce the challenges that occur in implementing postponement strategies. Boone et al. (2007) reveal in their review a significant increase in the number of postponement research efforts, many of which at least partially address past challenges noted in previous research. Yang et al. (2007) investigate the postponement strategies from an inter-organisational structure and capacity planning with postponement applications.

Skipworth and Harrison (2006) use documentary, archival and database evidence to measure operational characteristics across a broad front and statistically explore postponement. They report results of implementing postponement at a manufacturer of industrial electric motors. The postponement includes making a standardised semi-finished product to stock instead of make-to-stock and postponing the production steps that follow, which lead to many different end-products until receipt of a customer order instead of make-to-order to overtake the long delivery times and inventory risks.

Davila and Wouters (2007) use regression analysis to examine whether higher levels of postponement are associated with better service, lower inventory, and lower cost. They indicate that higher levels of postponement, measured as the percentage of generic products shipped, are associated with better on-time delivery and lower variable costs. Moreover, they indicate that an increase in the percentage of generic products has a positive impact on on-time delivery as well as on operational costs but not on inventory turns. The paper lacks quantitative data for the whole supply chain and using longitudinal data from one company makes it hard to generalise the results beyond one company.

This section covered the postponement concept and its relationship with the decoupling point approach which shows that CODP employs the concept of postponement that is now increasingly widely used by organisations in a range of industries (Wikner & Rudberg, 2005a). Mason-Jones and Towill (1999) link the postponement with the DP and mention that it requires very careful thought about the location of the DP. In theory, the DP should not be the same point at which postponement is applied (Van Hoek, 2000; Yang & Burns, 2003). The postponement strategy implies the CODP in the way that it concerns the careful placement of the material decoupling point. The CODP can also be used to establish a postponement strategy. Through the stream of publications on postponement in various disciplines it basically moves product differentiation as close to the end consumer as possible via strategic stock at the material decoupling point. The literature reviews the strategy from providing highly customised products with high uncertainty (full postponement strategy) to the end of providing a standard product with low demand uncertainty (full speculation strategy). Regardless of the fact that the material decoupling points for each of the previously mentioned postponement strategies are at different points of the supply chain, the rule idea is always to move the material decoupling point as near to the end consumer as possible to ensure the shortest lead-time for the consumer (Mason-Jones & Towill, 1999).

2.6.10 Product variety and the CODP

Over the years, product variety has been revealed as a significant matter of market competition. Managing product variety is challenging with the difficulty of today’s supply chains (Ramdas, 2003). Ulrich and Eppinger (2003) indicate product variety as the various range of product models a company can manufacture within a certain time period in response to market demand.

The ability of a firm to economically deliver variety can be attributed to a number of factors, including but not limited to manufacturing and assembly flexibility, product structure, and raw materials and parts procurement flexibility. Manufacturing flexibility is frequently associated with flexibility of the process equipment and manufacturing costs, along with flexibility of assembly systems (Ulrich, 1995). Also, the lot size is an important factor in the manufacturing flexibility; the larger the lot size, the higher the inventory cost. However, inventory costs and setup costs can be balanced against each other, for example smaller lot sizes can drive down inventory costs but increase setup costs. Ulrich (1995) state that product variety can be attained with a thrifty modular product structure with or without flexible processing equipment. He insists that the policy for delivering variety in a product is extremely contingent upon the degree and type of modularity. He determines a number of different kinds of modularity, such as:

- component swapping,
- combinatorial,
- bus,
- sectional, and
- fabricate-to-fit modularity.

Aitken (2000) developed the product variety/volume predictability matrix as shown in Figure 2.16 with the focused factories of MRP, Kanban, a packing centre, and a design-and-build division to improve the agility of the organisation.

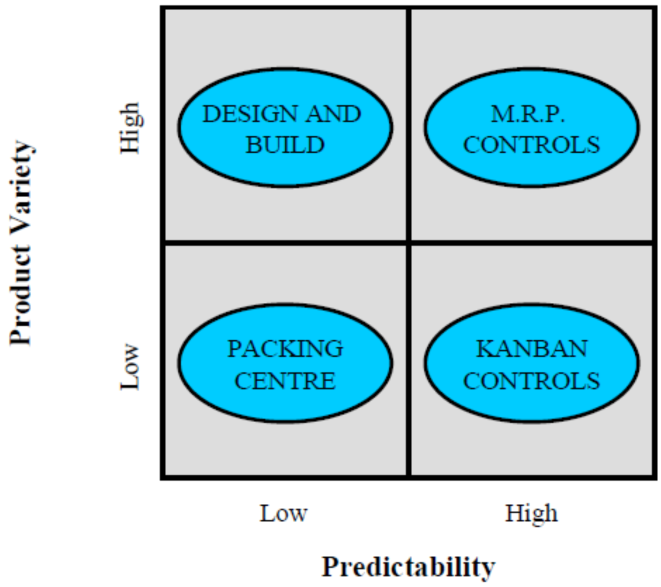

Figure 2.16: Lighting factory supply chain strategies (Aitken, 2000, Aitken et al., 2002)

Randall and Ulrich (2001) suggest using empirical evidence of firms that match their supply chain to the type of product variety they offer, and perform better than firms that do not make use of such opportunities. Also, they describe that demand uncertainty is amplified by product variety, although the same aggregated demand is divided over more SKUs, causing an increase in the aggregated errors related to each forecast.

Holweg and Pil (2001) distinguish between three dimensions of product variety. First, external variety (product proliferation) applies to the number of SKUs making their variations accessible by a firm's customers at any time. Second, internal variety describes the complexity within the manufacturing processes and is similar to the number and variety of components required for manufacturing a given product. Third, dynamic variety typically refers to the speed with which consumers will gain access to new products.

Holweg (2005) groups three categories of responsiveness: product, process, and volume; and includes three case studies from the automotive and electronics industries. The assemble-to-order approach adopted by the electronics manufacturer was so effective and included low internal and high external product variety. The two automotive cases, with their enormous product variety and fairly patient customer base, showed a misalignment between the product, process, and volume dimensions that led to a strategic conflict in the supply chain.

Brabazon and MacCarthy (2004) develop a form of order fulfilment system, Virtual-build-to-order (VBTO), in which the manufacturer possesses the capability to search transversely the whole pipeline of finished stock, products in production, and those in the production plan, so that they can set the product demanded by a customer. It is a system design that is related to Mass Customisers (e.g. automotive sector) whose manufacturing lead time exceeds their customers' acceptable waiting times, and for whom keeping semi-finished stocks at a fixed decoupling point is not practical. They introduce the concepts of reconfiguration flexibility and floating decoupling point, and discuss the process of changing a product's specification at any point along the order fulfilment pipeline. They describe the operational features of the generic VBTO system and use simulation to study its behaviour and performance.

Brabazon and MacCarthy (2006) used simulation on a VBTO and identify a predictable relationship between the ratio of customers fulfilled and the ratio of product variety/pipeline length. The VBTO system show essential behaviour that changes the stock mix and levels, resulting in stock levels being higher than in an identical conventional system at specific variety/pipeline ratios. The results suggest beneficial impacts for the design and management of order fulfilment systems in sectors such as the automotive industry where VBTO has a reasonable chance of a successful operational model, but it is also of interest to other sectors with resembling characteristics, such as with high levels of variety and vital large-scale planned product pipelines.

Er and MacCarthy (2006) indicate that the levels of variety in products continue to elevate in almost all sectors and demand better understanding of the management of product variety in international operations. They use a simulation model representing a multinational corporation supply chain to examine the impact on supply chain performance of the increased product variety associated with supply lead-time and demand uncertainty in a global set. The model focuses on the upstream activities of production planning, inbound supply and manufacturing. It shows a damaging impact when the level of product variety is increased on supply chain performance.

Davila and Wouters (2007) and Villarreal et al. (2000) emphasise the link between postponement and managing product variety as an effective strategy. It can be achievable by postponing the configuration of a product to customers' specifications and customisation is made as late as possible in the supply chain close to the point when demand is known. Under this strategy, products inside a family share common parts and processes until their point of differentiation.

Martínez-Olvera and Shunk (2006) determined the manufacturing structural elements: the product variety is inversely proportional to (1) the level of standardisation, and (2) the volume level. The level of standardisation is inversely proportional to the processing time.

MacCarthy and Brabazon (2008) illustrate the range of approaches in schematic form for manufacturing companies in responding to the growth in product variety and demand for product customisation, as shown in Figure 2.17. The categories are as follows:

- Category 1 shows the standard MTS strategy with fixed variety.
- Category 2 comprises the standard BTO strategy; a BTO manufacturer typically has a set of product offerings in catalogue form with pre-engineered product variety.
- Category 3 includes those companies that allow product attributes to be specified to some degree.

- Category 4 covers mass customisation, postponement and ATO approaches. These approaches are accompanied by high levels of customer-led variety in products.
- Category 5 reviews the basic approaches: locate-to-order (LTO), available-to-promise (ATP), global-available-to-promise (GATP), and open pipeline planning, which are developed for fulfilling customer orders quickly and efficiently with the specific variants the customers seek.
- Category 6 considers the rapid and reactive approaches to the marketplace, which introduce new product variants from a fixed range or by customisation.

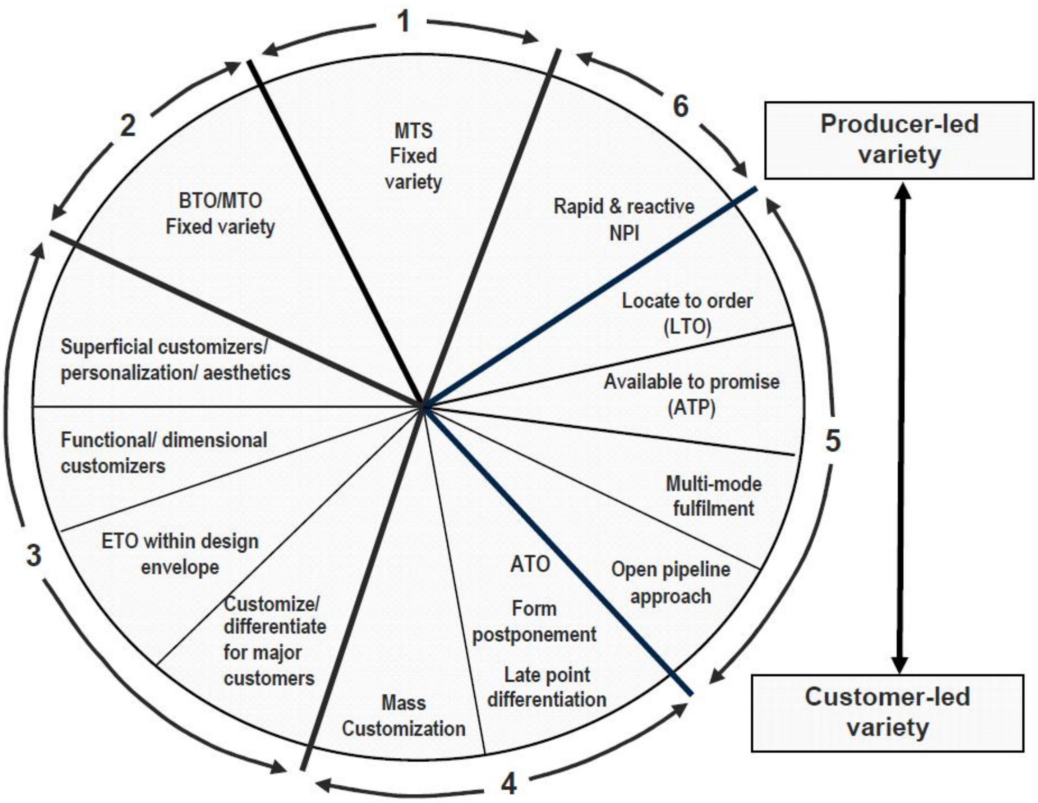

Figure 2.17: A range of approaches for providing variety and customisation (MacCarthy & Brabazon, 2008)

The relationship between product variety and the decoupling point is apparent especially in the products that show high degrees of modularity in their structures, which impacts the selection of decoupling points. Which product variety is delivered has an intense influence on where, how, and when in the value chain the product is customised (Kundu et al., 2008). However, it becomes reasonable to implement lean methods upstream of the DP and use an adjusted demand of products with a low degree of variety. Likewise, the practice of an agile strategy will be appropriate for the operations downstream of the DP subject to the variability of demand and a high degree of product varieties.

The products change dynamically in a life cycle starting from the emergence, through advanced growth, maturation, and decline sequentially. There is a relationship between the supply chain and the life cycle of the product where the decoupling point is associated with it. Figure 2.18 and Table 2.7 show the life cycle along the different stages.

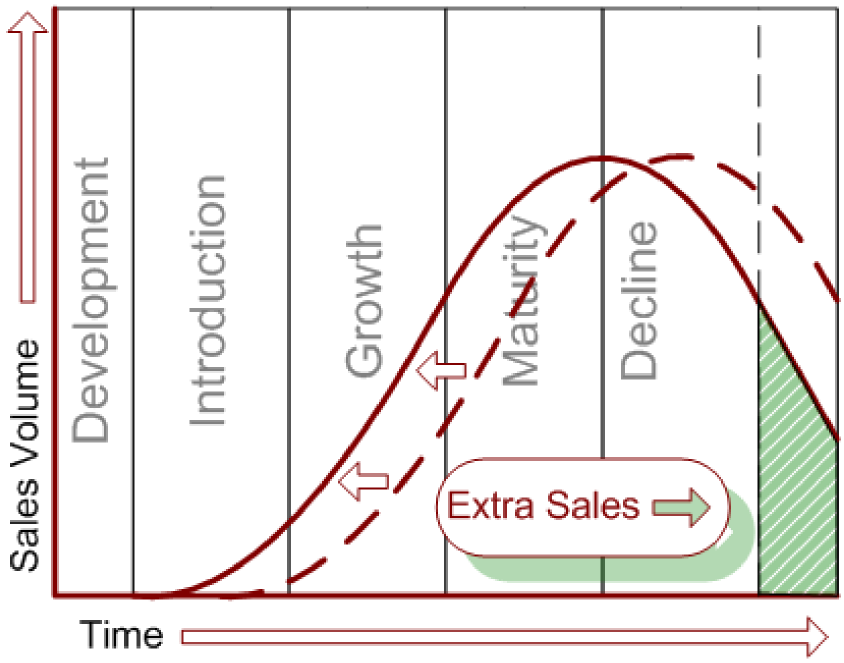

Figure 2.18: Relationship between product life cycle and decoupling point positions (Sehlhorst, 2007)

Table 2.7: Relationship between product life stages among different aspects

Aspects	Emergence	Advanced Growth	Maturation	Decline
Supply chain strategy	BTO	MTO	ATO	MTS
Variety	Innovative	Standardisation	Consolidation	Characterisation
MW	Service level (fashion)	Availability, quality, cost	Quality, price, reliability	Cost, lead time
MQ	Quality, cost, availability	Availability, cost, lead time	Lead time, quality, cost	Quality, lead time, service level
Automation	Low	Medium	Medium to high	High

In Figure 2.18 the horizontal axis is time, usually in years. The beginning of a new product starts with low volume. The advanced growth happens when the standardisation occurs and volume increases. The maturation develops when the process design emerges. The decline happens when the product is changed or removed. Real world supply chains are cyclical in character. This means that this year's market winner is next year's market qualifier (Christopher, 2000). An order winner makes the product win orders in the marketplace, whereas qualifiers are criteria that must be supplied by the firm to enter and stay in the market (Hill, 2000). Table 2.8 shows the contrast between product and market characteristics and their CODP type, depending on the products and customers.

Table 2.8: Product and market characteristics and their CODP type (adapted from Silver et al., 1998)

Characteristics	Types of Process/Industry			
	Job Shop	Batch Flow	Assembly	Process
CODP	MTO	MTS/MTO	MTS/ATO	MTS
Number of customers	Many	Many, but fewer	Less	Few
Number of products	Many	Fewer	Fewer still	Few
Product differentiation	Customised	Less customised	More standardised	Standardised (commodities)
Marketing characteristics	Features of the product	Quality and features	Quality and features or availability/price	Availability/price
Families of items	Little concern	Some concern	Some concern	Primary concern
Aggregation of data	Difficult	Less difficult	Less difficult	Easier
By-products	Few	Few	Few	More
Need for traceability	Little	Intermediate	Little	High
Material requirements	Difficult to predict	More predictable	Predictable	Very predictable
Control over suppliers	Low	Moderate	High	Very high
Vertical integration	None	Very little	Some backward, often forward	Backward, often forward
Inventories - Raw materials - WIP - Finished goods	 Small Large None	 Moderate Moderate Varies	Varies, frequent deliveries Small High	Large, continuous deliveries Very small Very high
QC responsibility	Direct labour	Varies	QC specialists	Process control
Production information requirements	High	Varies	Moderate	Low
Scheduling	Uncertain, frequent changes	Frequent expediting	Often established in advance	Inflexible, sequence dictated by technology
Operations challenges	Increasing labour and machine utilisation, fast response, breaking bottleneck	Balancing stages, designing procedures, responding to diverse needs	Rebalancing line, productivity improvement, adjusting staffing levels, morale	Avoiding downtime, timing expansions, cost minimisation
End-of-period push for output	Very much	Frequent	Infrequent	None (can't do anything)
Capital versus labour/ material intensive	Labour	Labour and material	Material and labour	Capital
Typical factory size	Usually small	Moderate	Often large	Large
Level of automation	Low	Intermediate	Low or high	High
Number of raw	Often low	Low	High	Low

materials				
Bottlenecks	Shifting frequently	Shifting often, but predictable	Generally known and stationary	Known and stationary
Speed (units/day)	Slow	Moderate	Fast	Very fast
Process flow	No pattern	A few dominant	Rigid flow pattern	Clear and inflexible
Type of equipment	General purpose	Combination of specialised and general purpose	Specialised, low or high tech	Specialised, high tech
Flexibility of output	Very	Intermediate	Relatively low (except some assemble to order)	Low
Run length	Very short	Moderate	Long	Very long
Definition of capacity	Fuzzy, often expressed in cash units	Varies	Clear, in terms of output rates	Clear, expressed in physical terms
Capacity addition	Incremental	Varies	Chunks, requires rebalancing	Mostly in chunks, requires synchronisation
Nature of maintenance	As needed	As needed, or preventive when idle	As needed	Shutdown
Energy usage	Low	Low, but can be higher	Low	High
Process changes required by new products	Incremental	Often incremental	Incremental or radical	Always radical

The production planning and scheduling systems relating to the product-process matrix can be located at various positions based on the primary focus of each system, as shown in Table 2.9.

Table 2.9: Systems with relevant industries and primary focus of system (Silver et al., 1998)

System	Nature of relevant industries	Primary focus of system
Sequencing rules Factory physics	Low volume fabrication	Flexibility to cope with many different orders Meeting due dates Increasing throughput Predicting lead times
Optimised production technology (OPT)	Batch; low volume assembly	Bottleneck management
Material resources planning (MRP)	Medium volume assembly	Effective coordination of material and labour
Just-in-time (JIT)	High volume, repetitive fabrication and assembly	Minimising setup times and inventories High quality
Periodic review/Cyclic scheduling	Continuous process	Minimising sequence- dependent setups High capacity utilisation

2.7 Analysis of Supply Chains

2.7.1 Concepts of modelling and simulation

Simulation deals with system models. A system is "a facility or process, either actual or planned" such as a distribution of plants, warehouses, and transportation links (Kelton et al., 2010). Table 2.10 overviews the simulation definitions from the main textbooks on simulation.

Table 2.10: Overview of simulation definitions

Author	Definition
Law (2007)	"Numerically exercising the model for the inputs in question to see how they affect the output measures of performance."
Seila et al. (2003)	"A set of numerical and programming techniques for representing stochastic models and conducting sampling experiments on those models using a digital computer...a set of techniques-analysis methodology."
Kelton et al. (2010)	"A broad collection of methods and applications to mimic the behaviour of real systems."
Kelton et al. (2010) Computer simulation	"Methods of studying a wide variety of models of real world systems by numerical evaluation using software designed to imitate the system's operations or characteristics, often over time."
Kelton et al. (2010) Practical point of view	"The process of designing and creating a computerised model of a real or proposed system for the purpose of conducting numerical experiments to give us better understanding of the behaviour of that system for a given set of conditions."

Generally, modelling approaches in SCM can be categorised into five broad classes. Simulation refers to "a broad collection of methods and applications to mimic the behaviour of real systems, usually on a computer with appropriate software" (Kelton et al., 2010).

The logical or mathematical system models use just a set of approximations and assumptions, both structural and quantitative, about the way the system does or will work. If the model is simple enough, a traditional mathematical model, such as queuing theory, differential-equation methods, or something like linear programming to get answers, can be used (Kelton et al., 2010). Table 2.11 shows the different classifications of the simulation perspectives (Baines, 1994; Mihram, 1972; Siebers, 2004), and Appendix A covers the simulation in more detail.

Table 2.11: Classification of model types and techniques (adapted from Baines, 1994; Mihram, 1972; Siebers, 2004)

Class	Subclass	Definition	Generic modelling technique
Physical	Replication	A spatial transformation of an original physical object in which the dimensionality of the modelling is retained in the replica.	Model construction using an identical mechanism to that used in real system under study.
			Model construction using any mechanism that provides a spatially identical model to the real system under study.
	Quasi replica	A physical model in which one or more of the dimensions of the physical object are missing or modified.	Model construction using any mechanism that provides a fully functional scale model.
			Model construction using any mechanism that provides a scaled model that lacks functionality.
			Model construction using any mechanism that provides a two-dimensional scaled model that lacks functionality.
	Analog	A model which bears no direct resemblance to the modelled phenomena.	Modelling using an analog computer.
Symbolic	Schematic	A graphical representation of a system using symbols.	Rich picture
			Integrated enterprise modelling
			$IDEF_0$
	Simulation	A model of the behaviour of a system as a whole by defining in detail how various components interact with each other.	Discrete event simulation (DES)
			System "dynamics" (SD)
	Mathematical	An explicit analytical formula describing known relationships.	Queuing theory
			Active-based costing
			Business planning

The simulation is used in the research and reported in this thesis as a tool. This section has clarified and provided an overview of the different simulation modelling types, classes, and perspectives.

2.7.2 Simulation in supply chain management

Supply chain performance can be improved by reducing the uncertainties. It is clear that there is a need for some level of coordination of activities and processes within and between organisations in the supply chain to reduce uncertainties and add more value for customers. This requires interdependent relationships between decision variables of different processes, stages and organisations to be established. These relationships may change with time and are very difficult to analytically model, if not impossible. However, simulation provides a much more flexible means to model the dynamic and complex networks. Simulation is considered the most reliable method to date in studying the dynamic performance of supply chain networks. Simulation also provides an effective tool to evaluate supply chain reengineering efforts in terms of performance and risk. Towill (1996a) uses simulation techniques to evaluate the effects of various supply chain strategies on demand amplification.

Kleijnen and Smits (2003) differentiate four simulation types for SCM:

- Spreadsheet simulation
- System dynamics (SD)
- Discrete-event dynamic systems (DES) simulation
- Business games.

System dynamics simulation was used mainly for explaining the bullwhip effect. The use of simulation as a systems engineering tool to research and understand the impact of supply chain dynamics on business performance was established 40 years ago by Jay Forrester (Forrester, 1961). It was named industrial dynamics and then called systems dynamics. Cardiff Logistics Systems Dynamics Group (LSDG) proposed the Automatic Pipeline Inventory Order Based Production Control System (APIOBPCS) to develop material flow principles to guide supply chain members wishing to reduce the bullwhip effect, and thus to improve supply chain competitiveness (Towill, 1996a). The simulation model order decision rule for each echelon of the supply chain is represented in causal loop format. Prior to analysis the influence diagram has to be translated into a simulation model, which may be described in block diagram form and which is used to model the behaviour of the essential elements (Naim & Towill, 1993). Wikner et al. (2007) and others use systems dynamics to model supply chains. Verma (2006) dealt with the application of the stochastic inventory model to the three-tier supply chain and verified the values obtained using a mathematical model in physical simulation. Chan et al.

(2001) designed a simulation approach to measure supply chain performance which incorporates order release theory. A simulation model of a typical, single channel logistics network was developed.

A DES simulation is more detailed than system dynamics and has the following two features:

- it represents individual events
- it incorporates uncertainties.

The majority of advanced computer simulation tools implement a discrete-event simulation (DES). This paradigm provides an implementation framework for most simulation languages for the different worldview supported by these languages (Altiok & Melamed, 2007). DES is the most spreading paradigm and is still dominant as per Banks et al.'s (2005) survey in supply chain analysis and modelling. A detailed description of supply chain simulation and comparison between them are provided in Appendix A.

2.7.3 Purpose and benefits of a simulation study

System modelling ought to study system behaviour, measure its performance, enhance its operation, or deign it from scratch if it does not exist. If a modeller experiments directly with the system and nothing else about it will change significantly, then it is unquestionably the right thing needed for the purpose sought (Kelton et al., 2010). Also, a model can be built to serve as a stand-in for studying the system and asking questions about what would happen in the system if something changes, or if a situation beyond control were to develop. A model can provide the opportunity to try a wide range of ideas that would test different alternatives, which it might be impossible to try with a real system.

However, most systems that are modelled and studied are quite complicated so that valid models of them are quite complicated too and there may not be an exact mathematical solution worked out, which is where simulation comes in.

2.7.4 Stages of a simulation study

Figure 2.19 shows the simulation study stages usually studied. The built model should carefully reflect the real system in enough detail that suits the modeller's purposes as to what is needed from the model, is valid, and doesn't differ from the real system.

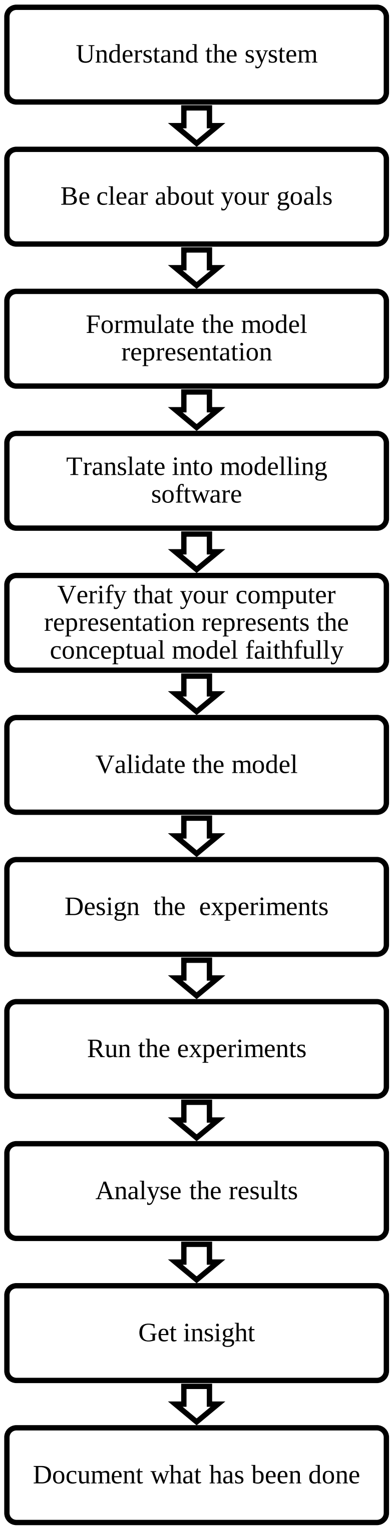

Figure 2.19: The stages of the simulation study (adapted from Kelton et al., 2010)

2.8 Literature Review Findings

This literature review is conducted in the domain of lean, agility, CODP, mass customisation, and postponement from a supply chain perspective, together with simulation modelling as a tool. CODP has proved to be a useful concept for the analysis of the agile supply chain. This chapter identified some of the theoretical viewpoints and gaps in the present literature about positioning CODP and agility. The topic focuses on two main parts in the literature, which are agility and CODP, with focus on the high level of the supply chain. The main tool selected is simulation as it is the most used tool in complex manufacturing systems and supply chain design and analysis, and is usually the most effective in the analysis.

Most literature indicates that from an information point of view CODP has received little attention from analysts, who merely focus on the material flow type of analysis. The literature suggests it is important for information to be moved upstream as far as possible to achieve competitive advantage and organisational success through sharing this information with all the players.

There appears to be no clear measurement for agility, so it has been decided to utilise the responsiveness measure after reviewing the literature related to agility. Responsiveness has been adapted as it is the main aspect of agility from an operation and quantitative perspective, which can lead to an effective assessment when coupled with CODP and simulation.

The two main gaps are identified in Section 1.2. Having identified these gaps in the knowledge, derived from the literature findings, a set of research questions was formulated and presented in Section 1.2.

This research work will add to the knowledge through:

- The identification of alternative positioning of the customer order decoupling point (CODP) and analysis of the production systems which can encompass decisions involving product and service design, capacity planning, process design and layout planning, design of work systems, and location planning.
- The assessment of responsiveness in the supply chain analysis and through the use of the case studies and simulation modelling in a manufacturing company.
- By implementing a customer order decoupling point methodology, through a simulation modelling approach and investigating well-known case studies.

2.9 Chapter Summary

This chapter presented a review and comprehensive analysis of the literature related to agility, the customer order decoupling point, their importance within the supply chain as a source of gaining competitive advantage, and the simulation modelling of the supply chain. It has introduced the concept of agility associated with the supply chain and the CODP. Within this methodology a vital step is the evaluation of design alternatives, which involves a combination of analysis, judgement and bargaining. In addition, the positioning of the CODP is required to guide the analysis process of the supply chain performance and agility. This chapter has also reviewed simulation modelling and the processes involved in a simulation study. Gaps in the knowledge were concluded and uncovered an opportunity to develop an assessment methodology for diagnosing the supply chain around a combination of CODPs in terms of information and material flow, and agility, with the aim of increasing responsiveness and improving supply chain performance. The next chapter, Chapter 3, focuses on research methodology for this research inquiry.

Chapter 3

Research Methodology

From the literature reviewed in Chapter 2 it is apparent that the customer's order decoupling point positions can have a real effect on supply chain performance and the resulting agility. The effect of the decoupling point's positions on responsiveness is not yet reflected in the simulation modelling of supply chains. The intention of this research is to investigate the importance of considering this performance variation when changing the CODP positions within simulation modelling and case studies analysis.

This chapter explores in depth a study of the research method orientation, approach, and methodology (qualitative and/or quantitative). A literature review of case studies, a detailed analysis of a specific subsequent case study, and preparation of the simulation will be the next steps, as well as the data collection process. Then, an experimentation of the simulation study with its analysis is carried out. The literature review has shed light on the gaps in knowledge and helped in the formulation of research questions and the process of defining research objectives.

3.1 Research Problem

Most supply chains are highly complex constructs and their behaviour is of a dynamic and stochastic nature. A major advantage of simulation modelling compared to analytic modelling is its ability to model random events based on standard and non-standard distributions and to predict the complex interactions between these events. It is generally agreed that simulation is a useful aid for the analysis of complex systems within manufacturing systems. Due to the complexity of real systems, a model can only be a restricted copy of the real system; the process of simplification and abstraction is used when simulation modelling. This leads to a gap between the performance predictions of a system model and the performance of the real system.

Marczyk et al. (2005) emphasises that to draw a cause-and-effect conclusion, researchers must use experimental research, which involves comparing two groups on one outcome measure to test some hypotheses regarding causation. Hence, the problem definition is presented in two parts:

Cause: The way in which the customer order decoupling points (CODPs) are represented within the supply chain is oversimplified as a consequence of ignoring the material and information order decoupling points and their zones on responsiveness.

Effect: This affects the supply chain and the resulting agility. The behaviour of the CODP's positioning and its effects on supply chain responsiveness will be represented through DES simulation modelling and analysis of the case studies to achieve a reflection of the performance of a real system in an appropriate way.

3.2 Research Aim and Objectives and Deliverables

Taking into account the reasoning given above, a research aim is submitted for this thesis that will, if satisfied, make a worthy contribution to knowledge about assessing responsiveness through decoupling point positioning and agile supply chain design using the simulation. The research aim is stated in Section 1.2.

Objectives should be considered, if possible, in terms of achievements, measures and constraints. "Measurement is important in research design in two critical areas. First, measurement allows researchers to quantify abstract constructs and variables. Second, the level of statistical sophistication used to analyse data derived from a study is directly dependent on the scale of measurement used to quantify the variables of interest" (Marczyk et al., 2005).

In order to answer the research questions raised in Section 1.2 a number of research objectives have been identified:

Objective 1: Identify the characteristics of CODP methodology, and the zonal concept, from the material and information decoupling points, their positions, and the extent to which that can be used to analyse the agile supply chain.

Objective 2: Assess responsiveness from an operational perspective that can be used to analyse and measure the performance of the agile supply chain.

Objective 3: Investigate whether or not positioning the material decoupling point downstream of the supply chain and the information decoupling point upstream of the supply chain is maximising responsiveness. Relate the decoupling zone as a valid concept.

Objective 4: Critically evaluate the effect of the positioning of the decoupling point upon supply chain agility in a real case study within a simulation modelling analysis.

Objective 5: Critically evaluate a new modelling representation that is suitable for the analysis of an agile supply chain.

Objective 6: Test the effect of the positioning of the decoupling point upon supply chain responsiveness.

Two deliverables are expected from this research. The first is the responsiveness assessment that supports the decision-makers when considering the different decoupling points required within the supply chain, and how to implement these points most efficiently. The second deliverable is the results of experiments that demonstrate the various effects on supply chain responsiveness. This allows business managers to become familiar with this new form of assessment working of the modelling and to gain experience by experimenting with the modelling methodology provided.

3.3 Development of Research Programme

To realise the above aim and objectives, a strategic research programme is necessary to direct the activities of this research through a number of stages. The following sections review different research methodologies and concepts available. The development of the research programme is based on the research methodologies and concepts reviewed by identifying the activities and methods that are required to realise the objectives in a structured manner.

3.3.1 Research orientation: Introduction

"Facts do not simply lie around waiting to be picked up. Facts must be carved out of the continuous web of ongoing reality, must be observed within a specified frame of reference, must be measured with precision, must be observed where they can be related to other relevant facts; all of this involves methods" (Ghauri & Gronhaug, 2005; Rose & Peterson, 1965). Much inconsistency has been applied by different authors in the use of terminology such as 'method', 'technique' and so on, which is due to the different multidisciplinary natures of the research approaches that have been used for the variant disciplines (Budd, 2001). "Research is not about changing the world; it is about making your own discovery that can inform others in some way". The prominence here is on the 'doing' rather than on the 'debating' (Pickard, 2007). The hierarchy for conducting a research study is shown in Figure 3.1, which outlines the relationships between the various levels of the research hierarchy as built by Guba and Lincoln (1998) that include all the significant parts of a research study.

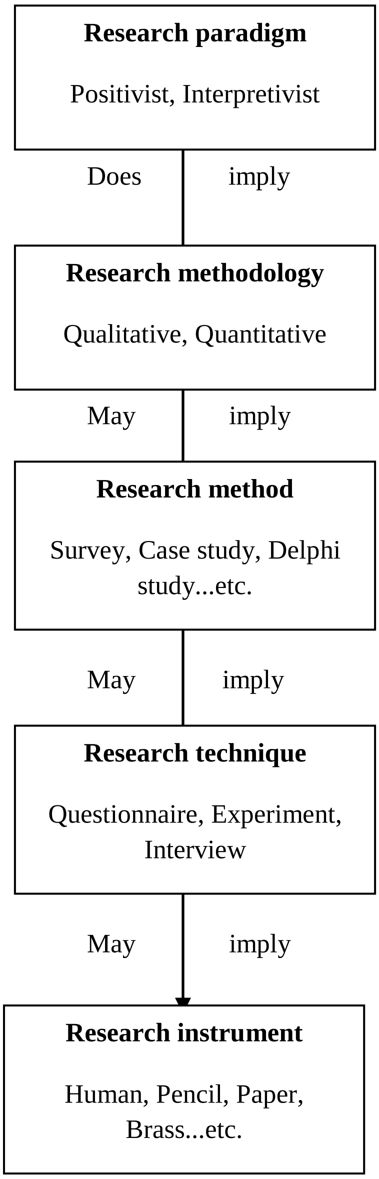

Figure 3.1: The research hierarchy (Guba & Lincoln, 1998; Pickard, 2007)

Adams and Schvaneveldt (1985) define research methodology as the tools for obtaining useful information, or the techniques used to gather this information, so that understanding will make the information more meaningful to us. "Methodology" should be thought of as encompassing the entire process of conducting research (i.e. planning and conducting the research study, drawing conclusions, and disseminating the findings) (Marczyk et al., 2005).

3.3.2 Research paradigm

According to Lincoln and Guba (1985), asking three essential questions will help to describe a research paradigm: the ontological question, the epistemological question, and the methodological question. Different research paradigms have been taken through the research, which helps in creating the different models of inquiry.

The first type is positivism, which is concerned with stating a philosophy as authentic knowledge or scientific knowledge; such knowledge can only occur from positive affirmation of theories through strict scientific methods (LeGouis, 1997). It was originated by Auguste Comte in the mid-nineteenth century (Mill, 2005). In the early twentieth century, logical positivism was developed in Vienna and grew to become one of the dominant movements in American and British philosophy (Outhwaite, 1987). Hence, physical evidence is essential to logical positivists and premises that the social world coexists externally and is viewed objectively, and the researcher is independent and an objective analyst (Blumberg et al., 2005).

Epistemology (or objectivism/dualism) is known as observing the development of such an observation based on the reality where dualism introduces the researcher and the subject as entities that are independent of each other, so objectivity can be demonstrated through replication (Pickard, 2007). Table 3.1 provides a detailed examination of the different paradigms.

Interpretivism principles reside on the basis that the social world is being constructed and given meaning subjectively by people; the researcher is incorporated into the observation, and the research is oriented toward their interests (Blumberg et al., 2005).

Realism is a combination of both the world’s positivism and interpretivism. It accepts that a reality exists that is independent of human thought and beliefs.

Table 3.1: Characteristics of major research paradigms (Lincoln & Guba, 1985)

	Positivism	Post-positivism	Interpretivism
Ontological stance	**Realism**	**Critical realism**	**Relativist**
	Belief in a tangible social reality. This reality exists independently of those 'creating' the reality. A social reality can exist just as natural reality exists (water remains water whether someone is swimming in it or not).	Belief in a social reality but acceptance that knowing this reality will always be inhabited by imperfections in detecting its nature. The imperfections are the result of human fallibility.	Belief in multiple, constructed realities that cannot exist outside the social contexts that create them. Realities vary in nature and are time and context bound.
Epistemological stance	**Objectivist/dualist**	**Modified dualist/objectivist**	**Transactional/subjectivist**
	Investigator and investigated are independent of each other	Acceptance that independence is not possible but objectivity is seen as the goal and demonstrated by external verification	The results of the investigations are a product of interaction between the subject and the investigator. What can be known as a result of the interaction?
Methodological stance	**Experimental/manipulative**	**Modified experimental/manipulative**	**Empathetic interaction**
	Hypothesis testing variables identified before the investigation. Empirical order to establish the 'truth' of the proposition.	Hypothesis testing but more emphasis placed on context.	Investigator interacts with the object of the investigation. Each construction of reality is investigated in its own right and is interpreted by the investigator.
	Predominantly quantitative	Quantitative and qualitative	Qualitative, including hermeneutics and interchanges. Analysis by case.
Purpose	**Prediction/control/explanation**	**Prediction/control/explanation**	**Understanding/ reconstruction**
	Framing of general laws	Generalisations	Transfer of findings

Adams and Schvaneveldt (1985) defined research methodology as the tools for obtaining useful information, or the techniques used to gather this information, so that understanding will make the information more meaningful to us. "Methodology" should be thought of as encompassing the entire process of conducting research (i.e. planning and conducting the research study, drawing conclusions, and disseminating the findings) (Marczyk et al., 2005). Figure 3.2 shows the levels of the research process which represent the research as five layers of an 'onion' (Saunders et al., 2003).

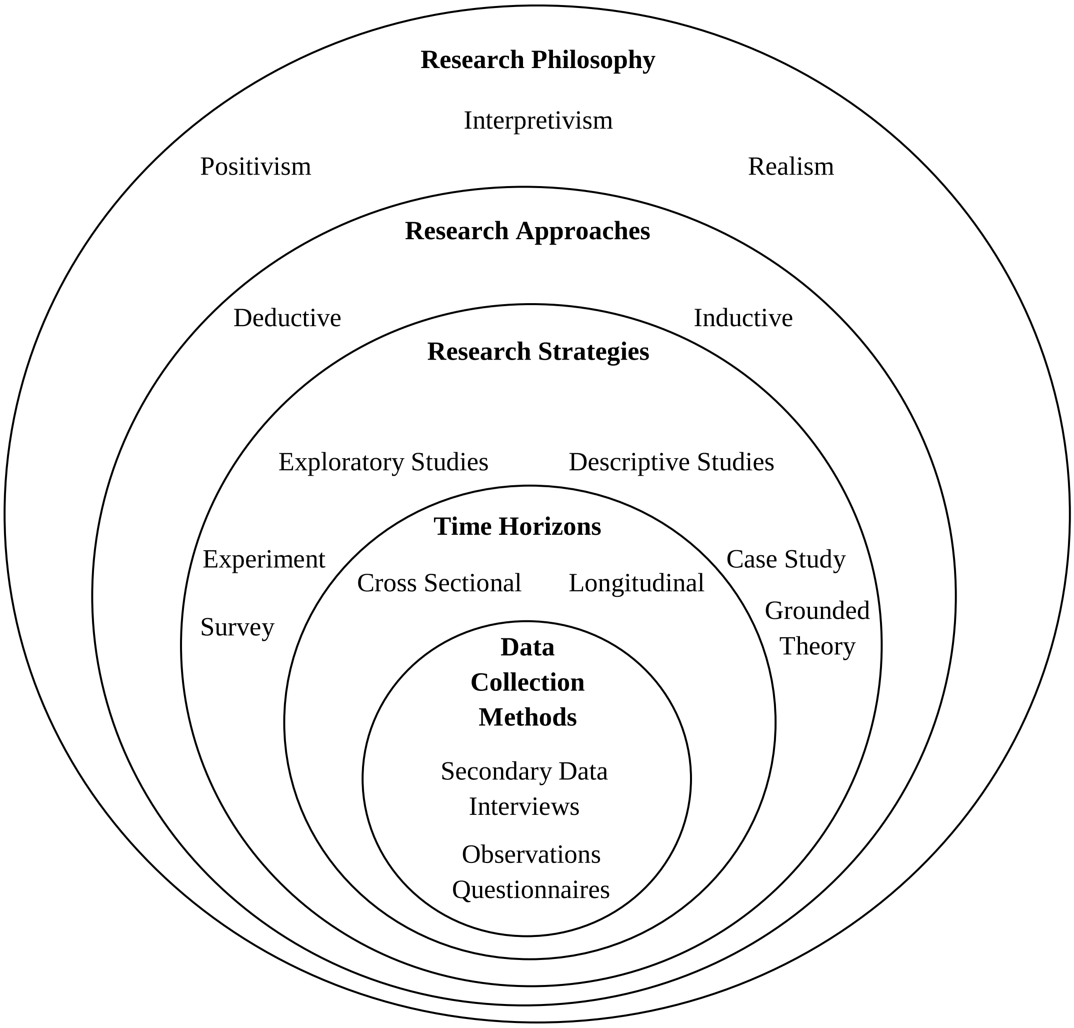

Figure 3.2: The research process 'onion' (inferred from Saunders et al., 2003)

Post-positivism and interpretivism are the main research philosophies considered in this thesis, as it is rare for a research project to be approached from one perspective alone. The research methodology doesn't necessarily use a particular research method. In other words, it is the perspective from which a researcher chooses to handle the research questions. In this research, the angle was to examine the positioning at which the decoupling points maximise responsiveness and thereby agility, and this could be expressed in quantitative and qualitative ways by following a variety of approaches rather than focusing on one specific research method.

It is obvious that a research paradigm implies a research methodology. Positivists represent theoretical ideas which lie in observable phenomena that could be transformed into variables to be manipulated through experimentation and that would produce the results to which the laws of a hypothesis are assigned. The verification of the hypothesis begins with an empirical mechanism for determining the relationships among the variables that result in general study observation (Pickard, 2007).

3.3.3 Research approach

The research approach can be classified into two different aspects: Deductive and Inductive. The deductive approach is used when theory already exists and needs to be tested. The inductive approach is used when theory does not yet exist and needs to be built. Deduction promises conclusion through logical reasoning where it should not be true in reality, but it is logical. The hypothesis is deduced from existing knowledge which could be subject to empirical examination and that could be accepted or rejected (Ghauri & Gronhaug, 2005). The research’s task is not only to build hypotheses from the existing literature but also to present them in operational terms, to show the way the information can be collected and the concept being used to test these hypotheses (Bryman & Bell, 2003). The influence of the research shall be built on the hypotheses first and continue in this way throughout the research process. Based on the above considerations, the research approach in this thesis is deductive since the theory that positioning the material decoupling point downstream and information decoupling point upstream maximises the agility of the supply chain already exists and needs to be tested. Moreover, it was decided based on the research questions (Section 1.2) in the early stage of research design that the research approaches include quantitative and qualitative approaches that involves the collection of quantitative data, which is put through rigorous quantitative analysis in a formal and rigid manner. This includes experimental, inferential, and simulation approaches to research. In contrast, the qualitative approach uses the method of subjective assessment of opinions, behaviour and attitudes. Research in such a situation is a function of the research’s impressions and insights. (Marczyk et al., 2005). Table 3.2 is a summary of the major differences between deductive and inductive approaches (Saunders et al., 2003).

Table 3.2: Summary of the major differences between deductive and inductive approaches (adapted from Saunders et al., 2003)

Deduction emphasises:	Induction emphasises:
Scientific principles	Gaining an understanding of the meanings humans attach to events
Moving from theory to data	A close understanding of the research context
The need to explain causal relationship between variables	
The collection of quantitative data	The collection of qualitative data
The application of controls to ensure clarity of definition	
A highly structured approach	A more flexible structure to permit changes of research emphasis as the research progresses
Researcher independence from what is being researched	A realisation that the researcher is part of the research process
The necessity to select samples of sufficient size in order to generalise conclusions	Less concern with the need to generalise

3.3.4 Research design

Research design refers to the plan used to examine the question being asked for which research can be conducted to answer it (Marczyk et al., 2005). It constitutes the blueprint for the collection, measurement, and analysis of data. It aids the scientist in the allocation of his limited resources by posing crucial choices: is the blueprint to include experiments, interviews, observation, and the analysis of records, simulation, or some combination of these? Are the methods of data collection and the research situation to be highly structured? Is an intensive study of a small sample more effective than a less-intensive study of a large sample? Should the analysis be primarily quantitative or qualitative? (Blumberg et al., 2005).

Although there are endless ways of classifying research designs, they usually fall into one of three general categories: experimental, quasi-experimental, and non-experimental (the most widely used approaches: case studies, naturalistic observation, surveys, and focus groups). This classification system is based primarily on the strength of the design’s experimental control (Marczyk et al., 2005; Trochim, 2001). Additional considerations have to be made during the research design stage when conducting real world studies. Robson (2002) stresses the importance that “any real world study must obviously take serious note of real world constraints”; access and cooperation are similarly important. Table 3.3 is a classification of research design using eight different descriptors.

Table 3.3 Descriptors of research design (Blumberg et al., 2005)

Category	Options
The degree to which the research question has been crystallised	Exploratory study
	Formal study
The methods of data collection	Monitoring
	Interrogation/communication
	Archival sources
The power of the researcher to influence the variables under study	Experimental
	Ex post facto
The purpose of the study	Descriptive
	Causal
	Predictive
The time dimension	Cross-sectional
	Longitudinal
The topic scope, breadth, and depth of the study	Case
	Statistical study (sample or census)
The research environment	Field setting
	Laboratory research
	Simulation
The participant's perceptions of research activity	Actual routine
	Modified routine

"Typically books about research treat techniques and methods together, thereby implicitly limiting the use of a particular technique to a certain method" (Harvey, 2002). The technique is the approach taken to data collection in such a way that the empirical evidence would be harvested from the source (Pickard, 2007). No method is entirely qualitative or quantitative but techniques can be either quantitative or qualitative. Figure 3.3 illustrates this point (Jankowicz, 1991).

The research strategy describes the plan of answering the research questions. Two different strategies are used: Exploratory and Descriptive studies. A cross-sectional approach means that it is a study of a situation at a particular time. Another option would be longitudinal studies, which study change and development. A cross-sectional approach is used in this thesis due to the limited time during the in-depth case study, and therefore logically for the literature-based cases study, since they were studied at a particular time. The research process is a sequential process that describes several steps of the research task.

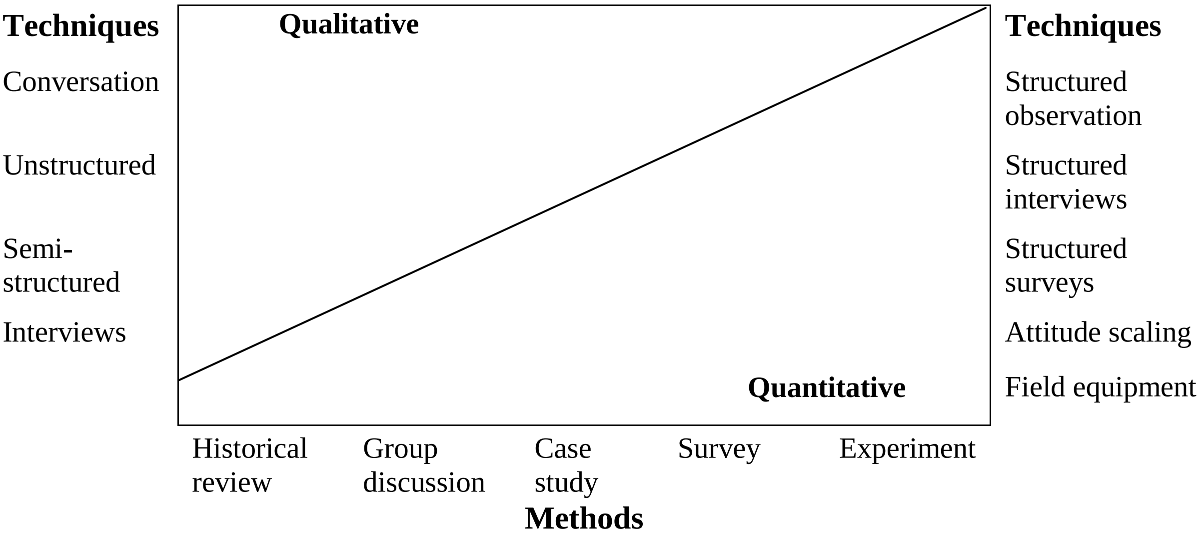

Figure 3.3: Quantitative and qualitative methods and techniques (Jankowicz, 1991)

3.3.5 Experimental research

The study is more about positivism and post-positivism orientation as they are more focused on using quantitative methods (Neuman, 2007). Study participants are randomly assigned to experimental and control groups in a true experimental design. This provides the highest degree of control over a research study, by allowing the researcher to draw causal inferences with the highest degree of confidence (Marczyk et al., 2005). The researcher manipulates the independent variable whilst eliminating the effects of other factors involved, in order to evaluate the effects on the dependant variable (Neuman, 2007). When the natural environment is an organisation, it is better known as “experimental organisational research” (Bryman, 1989) in the case of field experiments where the setting is a realistic environment. Experimental research is often used where:

1. There is time priority in a causal relationship (cause precedes effect).
2. There is consistency in a causal relationship (a cause will always lead to the same effect).
3. The magnitude of the correlation is great.

3.3.6 Case study research

A case study requires an in-depth examination of a single person or a few people, and its goal is to produce an accurate and complete description of the case studied (Marczyk et al., 2005). However, the case study is common in social sciences and life sciences, and may be descriptive or explanatory. There is an increase in using case studies for conducting scientific research in organisational and management studies (Bryman & Bell, 2003). The focus of the case-study approach is on individuality and describing the individual as comprehensively as possible, and that requires a considerable amount of information (Marczyk et al., 2005). In organisational studies, the unit of analysis is the organisation as a whole, a department, a section or a network of organisations working in a specific field (Bryman, 1989). Yin (2009) defines the case study research method as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used". Its advantages are being able to answer questions such as what, how and why; it does not provide answers for such questions as "who" and "how many", and it is more focused on contemporary events in a natural sitting (Yin, 2009).

The following sections focus on the methodology used in this thesis based on the above research methodology background.

3.4 Assessment of different positions of CODP considerations on supply chain's responsiveness

Based on the research design considerations above, assessment of responsiveness suggests a deductive approach, testing the hypothesis that having the material decoupling point to the latest point downstream and the furthest information decoupling point upstream will have different effects on a supply chain's agility, performance and responsiveness, which will be proved in the simulation modelling output. Deduction promises conclusion through logical reasoning where it should not be true in reality, but it is logical. The hypothesis is deduced from the existing knowledge, which could be subject to empirical examination, and that can be accepted or rejected (Ghauri & Gronhaug, 2005). The research's task is not only building hypotheses from the existing literature but also presenting them in operational terms, to show the way the information can be collected and the concept being used to test these hypotheses (Bryman & Bell, 2003). The influence of the research shall be built on the hypotheses first and the research process shall continue in this direction. This type of research is a quantitative type of research in the in-depth case study and qualitative in the literature-based cases study.

Figure 3.4 summarises the research methodology for conducting the research.

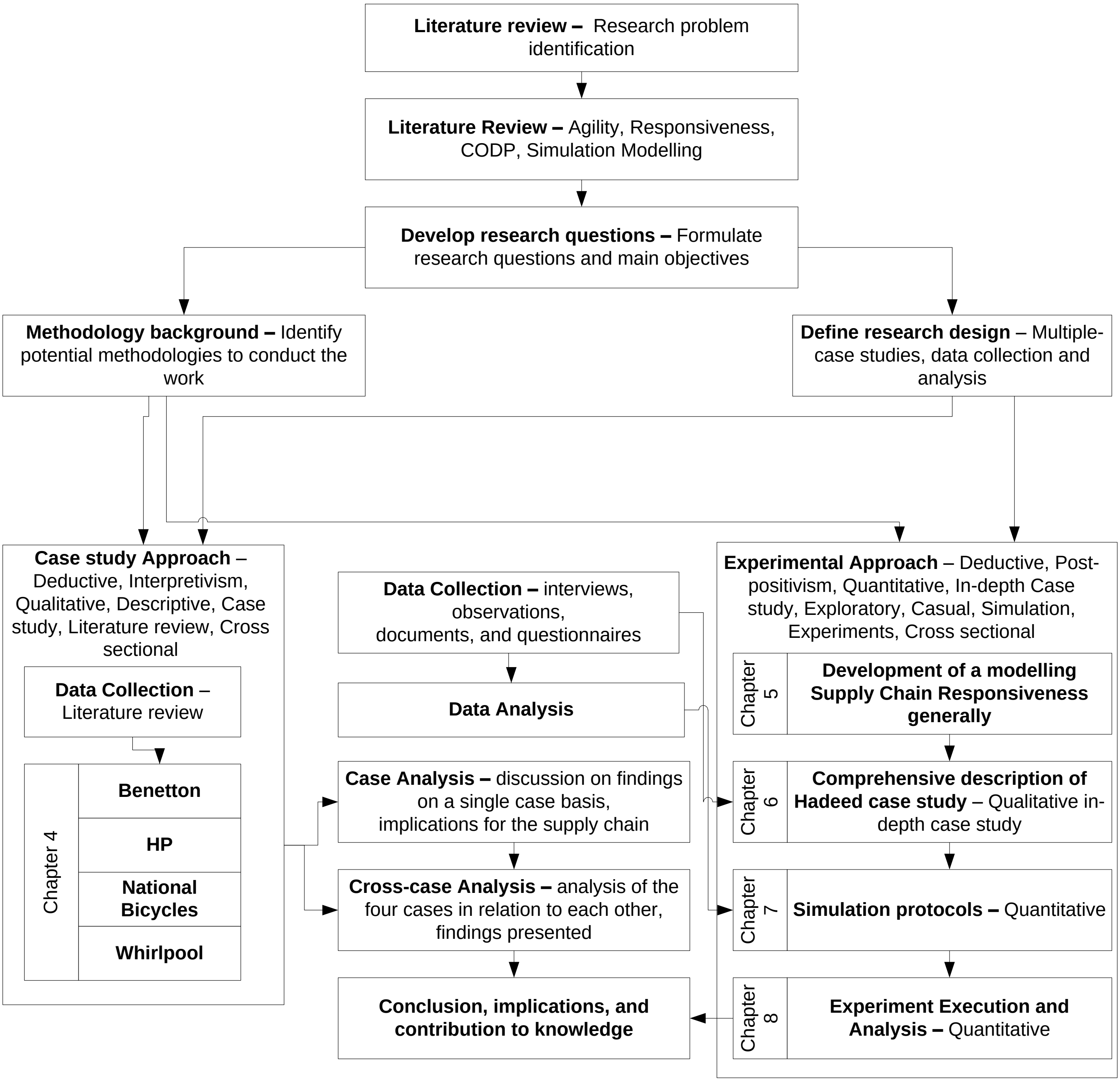

Figure 3.4: A flow diagram for conducting the research

In the literature-based cases studies (Chapter 4), the research is descriptive and uses case study type research as it determines what is actually happening and needs to be able to measure the operational responsiveness to achieve agility. The descriptive study attempts to find answers to the research questions from the literature review related to the cases study, and involves an assessment of the studying interaction of two or more variables (Blumberg et al., 2005) , but the disadvantage of such a study is that it cannot explain the rationale of an event occurrence or the way the variables interact.

In the in-depth case study, it is exploratory and poses 'What if?' questions. Hence, it is experimental though based in part on the results of the case study. Based on the above theory and practice, in this research simulated experiments have been used. The simulated in-depth case study is covered in Chapters 6, 7, and 8. Chapter 5 introduces modelling the supply chain's responsiveness in general. The experiment that is carried out to fulfil this stream requires a demonstration of the effect that different representations of CODPs can have on the responsiveness of the supply chain system using the simulation model. This can be demonstrated through analysis of simulation output, which can be used to determine whether the simulation output changes significantly when the value of an input parameter is changed, when an input probability distribution is changed, or when the level of detail for a subsystem is changed (Law & Kelton, 1991).

In this experiment a further aspect of interest is to find a suitable way in which CODP can be represented within the supply chain using simulation modelling. During the planning of data collection, the focus was on the main tasks as they would appear in the supply chain or the production system. Once the decisions have been made, a statistically significant amount of data has to be collected, processed and the model designed. The model has then to be integrated into the most advanced simulation model produced.

The experiment itself consists of two parts. The first part investigates whether simulation model performance changes significantly during the current position of CODPs. The second part investigates the impact of different representations of CODPs on the performance of a manufacturing system simulation model. The impact is then compared with the results from considering the responsiveness assessment produced as a benchmark. In this way the impact of the different positions of CODPs can be compared in the supply chain.

As a result, recommendations can be made on the best positions for CODPs to be located within the manufacturing system. Furthermore it is possible to state in which position the CODP has the biggest impact on agility in terms of the output and performance of the manufacturing system using the simulation model.

The simulation experiment follows the basic stages of an industrial simulation project. The following requirements for the choice of suitable simulation modelling tool have been identified:

- It needs to be a typical simulation modelling tool that can reflect what is happening during the operation of the manufacturing system.
- It needs to be designed by simulation software that is capable of modelling a supply chain (see Appendix A for more details).
- There is a possible need to access each case study modelled in order to collect data, validate the models and ensure that enough details are represented in the original simulation models.

Once the case study is modelled using the simulation tool, and data on the actual lines have been collected, the simulation models must be validated. An experiment has to be executed using simulation modelling to quantify the difference between the performance from simulation modelling and the performance data collected from the real manufacturing system. This demonstrates the responsiveness assessment using simulation modelling. The number of experiments to be conducted depends on the various positions of the decoupling points available.

3.4.1 Integrated study design

(Yin, 2003) stated that the research questions and the evidence required should not be isolated. Based on the above considerations, it was preferred to use the case study type of research. The focus in this research is on the leading questions when designing the case studies, and collecting, presenting, and analysing the data needed to fulfil the main research questions.

Figure 3.5 shows the theoretical framework that was deduced from the literature review. The framework introduces the research questions by illustrating how the material decoupling points (MTS, ATO, MTO, ETO) can be pushed as far downstream as possible and the information decoupling points can be pushed as far upstream as possible in terms of the four dimensions (the information dimension related to the information decoupling point: Mix, Demand, Specification, Timing).

“The case study is the method of choice when the phenomenon under study is not distinguishable from its context” (Yin, 2003). The complex interaction between the decoupling points, responsiveness and the context, support the use of case studies. The theoretical base for discussing decoupling points and responsiveness is derived from the areas of leanness, agility, leagility, and operations management literature in general. The decoupling point's strategy touches different industries and other strategies so the interest was in multiple case studies to explore the decoupling point's combination and determine the optimum strategy for each case.

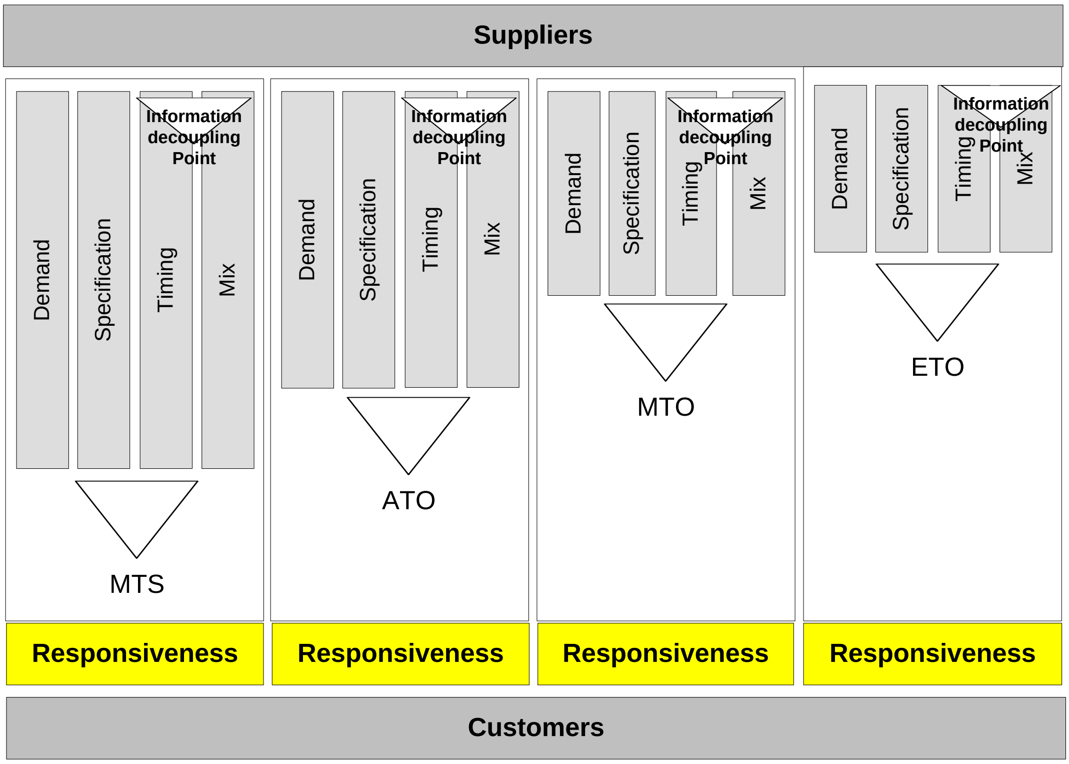

Figure 3.5: The theoretical framework

The analysis of the case studies combined the description and analysis of the material (physical flow), information processes (orders information: demand, mix, specification, timing) and their link to responsiveness, and thereby strengthened the idea of merging the two disciplines.

According to Yin (2003), the five components of substantial importance in a research design are the questions, propositions, unit of analysis, the logic linking the data to the propositions, and the criteria for interpreting the findings.

The study includes the collection of qualitative and quantitative data through the literature. The main attributes considered are those related to the information and material decoupling points. The same analysis was used to indicate the measures of responsiveness and variables related to the decoupling points.

Each of the four cases is analysed in the same way in terms of determining the material and information decoupling points using the same method of material analysis

and information boundaries. The cases represent different product types, markets, and processes to help in the comparison between the responsiveness measures in terms of the different positioning of the decoupling points.

The following chapters apply the methodology used here in this chapter. The results of these case studies assisted in completing the objectives and determining decoupling point positioning through the supply chain.

Chapter 4 uses the literature-based case studies to determine the effect of the positioning of material and information flow through the case study supply chain. The model followed methodology presented in Chapter 5, based on a generalised methodology for simulation experimentation. Chapter 6 describes comprehensively the in-depth case study. Chapter 7 outlines the simulation protocol including data collection processes for the in-depth case study using DES simulation analysis. The discrete event simulation was developed using ARENA software for the Hadeed supply chain through simulation modelling of the production line that produces long products. Chapter 8 utilises this evaluation to test the effect of positioning over responsiveness in an experimental design.

The data was analysed utilising DES simulation tools (see Appendix A for a detailed description of the comparison between DES and SD simulation tools) to identify what role supply chain material and information flow had in responsiveness at a high level, and how that information was penetrating to the upstream echelons. Chapter 9 discusses the completion of all the objectives and the adapted methodology for each objective.

The performance of the case study supply chain was evaluated, potential decoupling points improvements were identified, and DES simulations were run to evaluate potential improvements. The case study supply chain was evaluated utilising supply chain responsiveness and performance measures identified in the literature (Chapter 4). The potential improvements were based on increased information sharing upstream and delaying the material decoupling point downstream utilising performance measures presented in Chapter 5.

3.4.2 Case selection, companies, number of case studies

In this section the rationale for the focus on the literature case studies, selection of the business firms and the number of companies in the study, is explained and documented.

The companies reviewed in the multiple case studies are well-known companies to provide sufficient data from the literature and lead to beneficial analysis of the decoupling point's concept. There are several reasons for this, as discussed below.

These are companies that create and deliver products based on the assemble-to-order and make-to-order strategies. The choices made were typical examples from the literature including companies manufacturing computers, bicycles, and textiles. There is an expectation that these companies use unique and leading-edge technology, and invest heavily in supply chain management. Furthermore, the companies selected have leadership positions in the industry. Hence, it will be beneficial to understand how such companies manage their supply chain. Therefore a number of cases can be deemed sufficient and appropriate to compare and contrast findings and establish replication (Yin, 2003). An overview of these four case studies is provided in Table 3.4.

Table 3.4: Overview of the four cases and their sources

Company	Business type	Number of employees	Sources
Benetton	Textile	Exceeding 90,000 people	(Camuffo et al., 2001; Dapiran, 1992)
Hewlett-Packard	Computer	Exceeding 96,200 people	(Feitzinger & Lee, 1997; Lee & Billington, 1993, 1995; Lee et al., 1993)
National Cycles	Bicycle	Over 470 people	(Kotha, 1996; Kotha & Fried, 1993; Towill & Christopher, 2010)
Whirlpool	Appliance provider	71,000 employees	(Slone, 2004; Waller et al., 2000)

The number of cases recommended by various authorities varies. Ideally, fewer than four cases are considered to be difficult to generate theory from (Eisenhardt, 1989; Yin, 2009). Since all the cases for this research are well-known companies, they are subjected to and faced with similar external issues. Hence, for this thesis, four companies, four cases, are studied for the literature-based case study, and one in-depth case study that follows an experimental research method.

The case studies rely on the theoretical concepts of the assessment of responsiveness implying the responsiveness forces under the influence of decoupling point positioning, taking into account the dynamic and complex structure of the supply chain. Such theoretical concepts can be used in conducting different methods of case study as exploratory case studies (Yin, 2003). The findings from these case studies provide process-related elements essential for the development of responsive supply chain formulation based on the decoupling point's strategy.

The case studies' particular methodology was chosen as it is the most desirable methodology in those circumstances of exploratory research in operations management, as it provides depth and insight into a phenomenon. The researcher believes that positioning the material downstream and information upstream of decoupling points enhances the agility represented in the responsiveness measure of the supply chain, in order to examine the upstream and downstream positions of the decoupling points in terms of material and information forces that affect responsiveness.

Each case study will be explored individually. It is very important for the generation of insights that each case study, within case analysis, is written up and presented separately (Eisenhardt, 1989; Pettigrew, 1990). Therefore, cases' profiles, resources from the literature and results for each case study will be presented on an intra-case basis, exploring the effects of the decoupling point's related factors and its structures on the supply chains, and analysing each case within its own context. A discussion on the effects of the decoupling point's positioning and the resultant responsiveness is also presented.

A multiple-case study can provide robust insight and thus achieve a higher level of external validity and reliability. Cases can be viewed and studied alone and across cases (within-case analysis and cross-case analysis) to provide comparison, contrast, and richer details and insights regarding research issues (Eisenhardt, 1989; Stake, 1995; Yin, 2009).

Case studies can vary in number and size depending on factors such as time and resources (Robson, 2002). The main reasons for selecting a single in-depth case study in this thesis are the time needed, cooperation issues, coordination difficulties, available resources, and too many variables, although it is known that there is a single case study limit to which the conclusion could be generalised. It has been decided to use a single (in-depth) case study for the simulation modelling and experiments conducted during the research programme.

This chapter has not focused on the simulation tool nor simulation-based as a research methodology but as a tool to help identify the CODP effect on responsiveness. Chapters 5, 6, 7, and 8 concentrate on the in-depth case study methodology, description of the case study, data collection, experimentations and analysis. Appendix A covers simulation modelling in the supply chain, tool comparison, and tools used; Appendix B covers the SIMAN/Arena modules; and Appendix C describes the observation and rotations during data collection in the Hadeed supply chain to identify the information and material flow through the case study supply chain, and main processes, transfer times, processing times, and waiting period, which were identified and recorded.

3.4.3 Rigorous case studies

According to McCutcheon and Meredith (1993), the case studies can be used more widely inside more paradigms and with different forms of data, and the method's perspective depends on the researcher's rigour in carrying out the case studies and their analysis.

Triangulation is generally defined by Denzin (1978) as "the combination of methodologies in the study of the same phenomenon". Triangulation is used in the case studies with different techniques to study the same phenomenon, and provides validity within the case study method (Ellram, 1996). Triangulation is an accepted way of reducing bias by providing multiple instances of evidence from different sources (Miles & Huberman, 1994). Also within case research, among the analysis of data, triangulation through the use of multiple sources and methods can assist in obtaining the most accurate view of events (McCutcheon & Meredith, 1993). Stake (1995) focused on multiple triangulation methods that are used in case studies to increase validity. Patton and Appelbaum (2003) state that "Analyzing data in different spaces, at different times and in different contexts; having other researchers, perhaps from totally different backgrounds, review procedures and conclusions; and using different data sources to study the same object (interviews and archived records) all serve to attain triangulation and increase confidence in conclusions". The inclusion of quantitative analyses is mainly used when trying to generalise the results. In the qualitative content analysis in case study research, triangulation actually takes place on two different levels (Kohlbacher, 2006):

1. On the first and more obvious level, data is triangulated by integrating different material and evidence – often also collected by using various methods – as well as by integrating quantitative and qualitative steps of analysis.

2. On the second level, triangulation takes place by applying a method of analysis (qualitative content analysis) that has not been particularly developed for this purpose, to a different research design (case study research).

There are four main types of triangulation (Law et al., 1998):

- By source – data is collected from different sources, e.g. different people, resources;
- By method – different data collection strategies are used such as individual interviews, focus groups and participant observation;
- By researcher – which involves the use of more than one researcher to analyse the data, and develop and test the coding scheme; and
- By theories – multiple theories and perspectives are considered during data analysis and interpretation.

The qualitative evidence included the contextual data such as the companies' environments and factors affecting the decoupling point's positioning. It also incorporated data regarding how the information flow with the considered domain was analysed such as product mix changes and demand changes.

3.4.4 Analysis of the case studies

The approach for the analysis of these case studies is based on the literature discussed in Chapter 4, as outlined in Figure 3.6, and is the same analysis for each case. The analysis mainly answers research questions about identifying for each case exactly where the decoupling point is upstream or downstream from material and information flows. The main four strategies as suggested by Yin (2009) are followed:

1. Relying on theoretical propositions
2. Developing a case description
3. Using both qualitative and quantitative data
4. Examining rival explanation.

The simulated in-depth case study follows the methodology presented in Chapter 5 and analysed in the subsequent chapters through the experimentation.

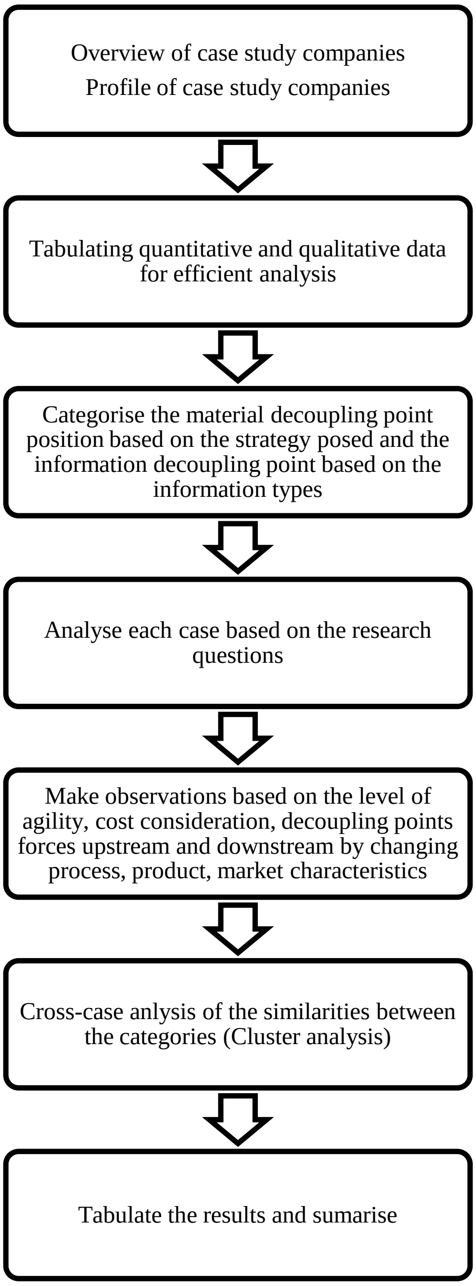

Figure 3.6: Case studies analysis flow

3.5 Data Collection Methods

The data collected could be quantitative and/or qualitative data in one study. Data can also be grouped into primary and secondary data. Primary data is collected by the researcher. The data collection method used for primary data is by interviewing industry experts. Secondary data is data that has already been collected but can be reused in the research. These data are also used and collected from books, websites, government publications and branch organisations.

Data can be quantitative or qualitative. Quantitative research attempts to quantify data and uses statistical analysis to test the hypothesis that the researcher begins with. On the other hand, qualitative research produces findings without the use of statistical procedures as in the literature-based case study.

Quantitative research can be divided into two types: exploratory and conclusive, as shown in Figure 3.7 (Singh, 2007). First, the research follows an exploratory design to explore in detail the concept related to responsiveness and CODP during the simulation protocol and the experimentations to test the research hypothesis. Also, it is conclusive during the description of the in-depth case study.

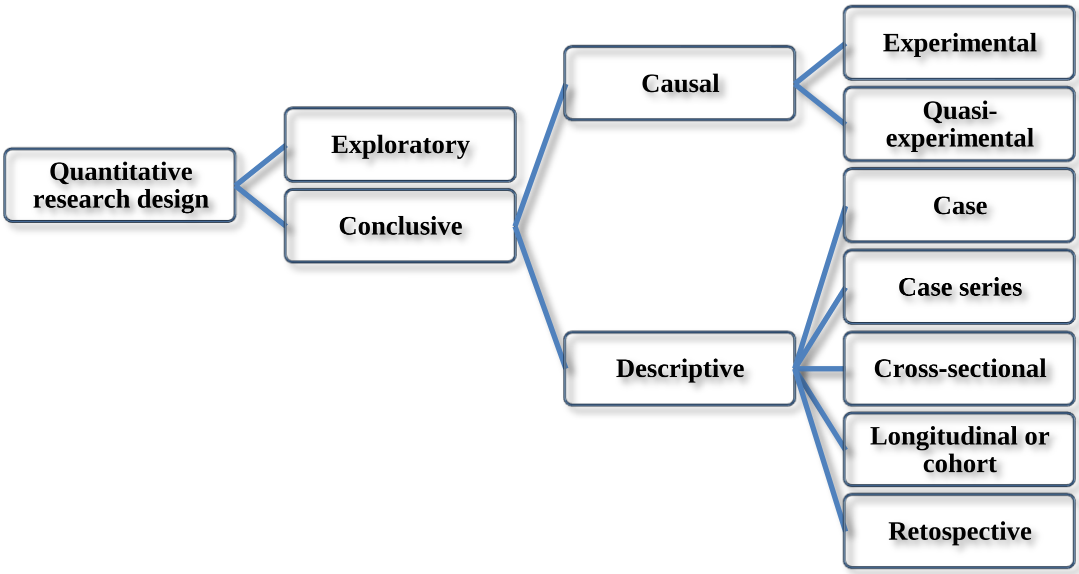

Figure 3.7: Quantitative methodology types

Second, the data collection process for the in-depth case study took place on the research site while the statistical analysis of the collected data usually takes place somewhere other than the collection site. Third, quantitative methods tend to give little attention to context by focusing on a set of parameters without understanding how these parameters fit with other aspects of the research context. They also give little attention to operational aspects of organisational reality by offering a static analysis of variables, whereas qualitative methods make possible rich understanding of context and linkages between variables (Bryman, 1989). Qualitative data collection methods have a different pattern; the separation between data collection and analysis is not clear as in the case of quantitative methods. Thus, data analysis can be initiated while the data collection process is still going on. Fourth, the sampling approaches used in both qualitative and quantitative methods have been considered as one of the main differences that distinguish the two methods. The qualitative inquiry is interested in in-depth understanding from a relatively small sample size that is selected purposefully to answer specific research questions. In contrast the quantitative inquiry is interested in measuring specific variables or factors from a large sample size that can be selected randomly from a population (Patton & Appelbaum, 2003).

3.6 Chapter Summary

This chapter presented the research methodology used in the research. It focused mainly on introducing the literature-based case studies. The simulation study is to be investigated through a preparation chapter (Chapter 5). This chapter also focused on introducing a rigorous presentation of the flow of activities followed in the research inquiry. It started by reviewing the research orientation, and the available schools of thought and philosophical stances in research paradigms such as positivism, post-positivism, and interpretivism that underlie scientific research. This provided the researcher with insights on available theories that suit the present research. Second, a review of the research questions and objectives were presented to justify the selection of the most appropriate research design. Third, the research approaches were presented, from experimental research to the use of case studies as the research strategy, and were explained. Fourth, case selection for the literature-based case studies with an in-depth case study were illustrated by presenting the triangulation concept of collecting qualitative and quantitative data and the data collection methods used. Finally, the data analysis methods were discussed and the rigours in the case study were presented. The chapter was designed to match the research methodology with criteria for judging the quality of the research design.

Chapter 4 explores the literature-based case studies, which is deduced from the literature review, and the results gained will be presented.

Chapter 4

Literature-Based Case Studies

4.1 Introduction

The previous chapter presented the methodology for the current research. A discussion of the use of four literature-based case studies has been given, involving the triangulation designs and data collection methods used. The reasons for choosing these cases are also presented.

The purpose of this chapter is to examine some published industrial cases to fulfil the objectives of this research and answer the research questions (see research questions in Table 2.12).

Each case study will be examined separately, for the benefit of perception within each case analysis, and described and demonstrated individually (Eisenhardt, 1989). Therefore, the sources for these case studies' descriptions, the data collected, the literature reviews and results will be presented in tabulated form, examining each case based on the research questions' structure. The analysis is within its own context and the available literature. A discussion on the effects of the decoupling points and responsiveness levels is also presented.

The proposition is that by positioning the material decoupling point downstream and information decoupling point upstream, this will enhance supply chain agility.

4.2 Analysis of the Case Studies

The analysis of the case studies merges the description and analysis of the material (physical flow), information processes (customer order information related to the product mix, product specification, lead time, and demand volume) and their link to agility (responsiveness), and thereby strengthens the idea of merging the two disciplines.

Section 2.5.1 identified two themes of assessing responsiveness starting from agility during the literature review, and the focus was mainly on the responsiveness measure. The operational measurement theme identified the main measures of responsiveness as shown in Table 2.4. Specific metrics of agility were determined within these measures based on the characteristics of the responsiveness and the dimensions classified in Table 4.1, which were revealed in Chapter 2. Any noticeable adaptation of these metrics in the cases studied are presented in Table 4.1 for each case and discussed in this chapter.

Table 4.1: Responsiveness measures and metrics

Level of responsiveness assessment	Definitions
Mixing flexibility	• This is related to volume flexibility, and represents the number of frameworks for products that can be produced (Gupta & Somers, 1992). • The ability to alter the product mix (within the existing product range) the system delivers within a given time period (Holweg, 2005; Holweg & Pil, 2001). • The ability to change products in production in terms of response and range (Helo, 2004). • The number of different products that can be produced within a given time period (product mix flexibility range); or the time required to produce a new product mix (product mix flexibility response) (Beamon, 1999; Slack, 1987). • The ratio of the number of components processed by the equipment to the total number processed by the factory (Guba & Lincoln, 1998; Neely et al., 2005).
Ability to rapidly reconfigure production facilities	• The ability to alter the product flow in order to affect throughput, quality, and other attributes (Chick et al., 2000). • The ability to swiftly reconfigure the production system (and the supply and distribution systems) to meet new product requirements (Court et al., 2006).
Coping with variable demand	• The ability of an organisation to manage a wider range of demand fluctuations (Swafford et al., 2006). • The ability to change the system's aggregated output (Reichhart & Holweg, 2006). • The ability to adjust volume of products during peak demand and slack periods (Sanders & Premus, 2002). • The ability to change throughput in terms of response and range (Helo, 2004). • To be able to consider, at the aggregate level as well as at the level of individual components, how high capacity limits are set and how rigid these limits are, which can be measured in terms of the average volume fluctuations that occur over a given time period divided by the capacity limit (Neely et al., 2005).
A much wider variety of products can be provided	• It is part of the agile manufacturing element to be able to produce efficiently a large variety of products (Gunasekaran, 1999). However, in lean production, keeping far less than half the inventory needed on site, resulting in fewer defects, enables the production of a greater and ever-growing variety of products (Womack & Jones, 1996). The agile manufacturing concept was developed parallel to lean thinking (Gunasekaran, 1999).

	• Companies adopt new principles for late differentiation of goods, and products are built according to customer orders. Sometimes many selections need to be made before the product is fully specified. Mass customisation is a good example of this tendency (Pine, 1993). • Also, the ability to produce a variety of products of high quality at low cost for greater product customisation (Vernadat, 1999).

The positioning of the decoupling point was related to the strategies (make-to-stock, assemble-to-order, make-to-order and engineer-to-order) through the customer order information and inventory locations. The information decoupling points are assessed according to demand, specification, mix, timing of the customer order, stock, cycle time, and production information. The following working definitions help in finding the decoupling points' boundaries.

4.2.1 Customer order decoupling point (CODP)/material flow

This is the location in the product structure or distribution network where the main inventory/stock point is placed to create independence between processes or entities. The selection of decoupling points is a strategic decision that determines customer lead times and inventory investment (see Section 2.6 for more discussion).

4.2.2 Customer order decoupling point (CODP)/information flow

This is the point in the information pipeline at which the marketplace orders data penetrates without modification. This is also where market-driven and forecast-driven information flows meet. It helps in finding the transparency of the information flow and the information related to orders, shipments, and availability of goods (see Section 2.6 for more discussion).

The zonal concept is judged by the gradual increase in certainty concerning the above dimension of the decoupling points in terms of demand, specification, mix, and timing of the customer order. Separating the proposed type of decoupling points on a forecast and speculation basis is the considered method for positioning the decoupling points.

A multiple-case study can provide robust insight and thus achieve a higher level of external validity and reliability. Cases can be viewed and studied alone and across cases (within-case analysis and cross-case analysis) to provide comparison, contrast and richer detail and insight regarding research issues (Eisenhardt, 1989; Stake, 1995; Yin, 2009)

4.3 First Case Study: Benetton

4.3.1 Background

Benetton is a global fashion brand based in Treviso, Italy, and was founded by the Benetton family in 1965. It has a network of around 6,000 stores in 120 countries, 7,000 employees, and manufacturing facilities worldwide. The Group produces over 150 million garments every year. The stores are managed by independent partners and generate a total turnover of over 2 billion euro (Benetton, 2010). Table 4.2 provides a summary of Benetton's history.

Table 4.2: Benetton historical summary (summarised from Dapiran, 1992; Camuffo et al., 2001)

- Three brothers and a sister merged their talent for fashion and their profitable business decision.
- Luciano Benetton, with sister Giuliana and brothers Carlo and Gilberto, started with $2,000 and turned a global vision into a multinational corporation in less than 20 years.
- They started selling the brightly coloured garments to local stores in northern Italy.
- The head office, main plant and distribution centre are located in Treviso.
- The Benetton Company was formed in 1965, initially manufacturing for other retailers.
- In 1968 it opened its first three stores.
- A year later it took its first global step and opened its first retail shop outside Italy.
- The growth has been harsh with a five-year period in the 1980s during which one store a day was opening somewhere in the world.
- In 1987 Benetton stopped making progress when it sold a variety of products into the financial services business.
- Production or sale of a variety of products turned out unsuitable and, in 1989, the company sold its commercial banking interests and refocused on its knitting.
- It comprises over 6,000 retail stores in more than 83 countries on every continent. These outlets sell the 60 million garments manufactured each year.
- In 1977, 2 per cent of sales were to markets outside Italy. By 1986, this figure had increased to 61 per cent of which 40 per cent went to other European countries and 15 per cent to North America. Total sales in 1990 reached $1.7 billion.
- A recent analysis of the overall performance of the top European companies has ranked Benetton third after Glaxo and Reuters Holdings.
- Its global products have been called McFashion, known as fast fashion.
- Benetton's strategy is a truly global one.
- The models have been its youthful market and a multiracial and multinational philosophy showing its message of world peace and the United Colors of Benetton.
- In the 1980s and 1990s it achieved prominence as a network organisation that outsourced activities to subcontractors.
- Benetton sold its production to entrepreneurs with no more than $100,000 to invest in a Benetton-products outlet.
- It hit saturation in the 1990s and profits slide throughout the rest of the 1990s.

- Still based in Italy, Benetton has approximately 5,500 shops in 120 countries, 7,000 employees, and annual revenue over $1.8 billion.
- In 2000, it streamlined its brands, eliminated labels and divided ranges on the basis of age, for children, men, and women.
- The Benetton collection can be grouped into three areas: casual wear 74% of total revenue in 2000; sportswear 20% of total revenue; and complementary activities 6% of total revenue.
- In-house production in 32 production centres: 22 in Italy and 10 abroad.
- Strong upstream vertical integration.
- Outsourcing of production to a network of small to medium-sized enterprises (SMEs) directly controlled by the Italian and foreign production poles.

4.3.2 Positioning of CODPs in the Benetton case

Table 4.3 presents the methodology used in the analysis of the Benetton case. The main sources of information used are Dapiran (1992) and Camuffo et al. (2001).

Table 4.3: Positioning of decoupling points in Benetton case

Description	Questions used to draw meaning and verify conclusions
Research questions	***Does Benetton attempt to meet the agility requirement by positioning the decoupling point as far downstream as possible? Does Benetton create some disadvantages by moving the decoupling point downstream?***
Positioning of the material decoupling point	Manufacturing begins with the garment design using Computer-Aided Design (CAD) technology. The designers can retrieve the historical data of all the clothing styles and colours and produce designs using 250 sets of colours through modern software. Then, it feeds garment cutters and knitting machines by transferring the data of these designs. After that, manufacturing these garment designs takes a few hours. Afterwards, the garment assembly is executed by subcontractors. Any fabric and garment dyeing is performed by Benetton until subcontractors are again used for the finishing operations. Such a manufacture requires a mix of high technology and high labour so Benetton covered these requirements by taking advantage of the economies of scale inherent in volume manufacture and through subcontracting. Customarily, clothing manufacturing starts with dyeing the yarn followed by knitting the garment. The issue of this sequence is that the knitting process is slow so to meet the volatile customer demand, high levels of inventory of finished garments are needed. The logical result of this method will be that the colours wanted will be out of stock while there are extra inventories of the less popular colours. The poor matching between inventory and demand is not suitable for such a market characterised by very short product life cycles. Benetton devised a process to manufacture the garments from the bleached yarn and delay dyeing until information is available through EDI for the appointed colours. This act showed the following benefits: • cost savings by cutting the added expenses of the delayed dyestuffs; • improved customer service by matching supply and demand; • increased sales by providing the customers with favoured products from available stock; and • a reduction in the nominal value for the assets for the same reason.

	This delayed dyeing process is an example of the postponement. This position of the material decoupling point as far downstream as possible placed the added value in the supply chain as late as possible to be compatible with meeting customer needs (Dapiran, 1992). Also, the result of this delayed movement is focused on the different geographical areas with differentiation only 35–40% of the styles it offers. In addition, it reduced the number of articles offered in the two basic collections while it increased the number of flash collections. The garments were divided under the United Colors of Benetton and Sisley collections for children, men, women and expectant mothers (Dapiran, 1992).
Disadvantages of moving the decoupling point downstream	It needed to develop partnership-based commercial relations with the big specialised distribution chains, adapting new strategies to align with competitors. The variety reduced as Benetton customised around 20% of its ranges to satisfy national markets, and reduced this to around 5–10% in order to communicate one image of Benetton in global markets. It entailed complete downstream integration, focusing on large display areas with a high level of styling outlets. Also, it invested more than $5 million in systems for designing sports equipment, which was required to face the competition and variety of products (Camuffo et al., 2001).
Research questions	***Does Benetton go to some lengths to improve the quality and utility of information which is transmitted upstream? Does Benetton transmit this information as far upstream as possible? Does it show any evidence of the zonal concept in information penetration?***
Moved information upstream	Benetton has relied on the support of information systems technology. Information technology linked the marketplace directly with the factory. Electronic Data Interchange (EDI) enabled Benetton's retailers in each country to regularly transmit orders to Benetton's main office. This allows Benetton to cautiously track and respond to demand by manufacturing only the required garment styles, colours and sizes. Benetton succeeded in using the information technology to integrate the supply chain and maximise its revenue. It has integrated communications technology with CAD/CAM systems to provide Benetton with the necessary speed and flexibility to compete efficiently in the fashion market. This shows that Benetton shares its order information through the global EDI network which gives the agents access to information about what is in production, in the DC or in transit, licensee billing, and credit status. The speed and flexibility of the whole system resulted in filling an agent shop replenishment order in the middle of the season within two to four weeks, which includes the time from manufacturing the garments. Also, it allowed speedy dispatching by transmitting documentation ahead of consignment arrivals, clearance through customs, and forwarding to the outlets. The result of the utilisation of moving information upstream was a 55 per cent reduction in distribution costs and a reduction in lead times to seven days (Dapiran, 1992). Ten million garments can be sent worldwide each month (Camuffo et al., 2001). This provides a full decision-making zone and shows that Benetton can share the order information regarding specification in this dimension. The information (related to the specification) required from the customer regarding colour and a customer order does not have to be completely specified at a single point in time. This provides a full decision-making zone and shows that Benetton can share the order information regarding specification in this dimension.
Research question	***What sort of agility does Benetton achieve?***
Agility	Benetton has showed agility and learned how to rapidly respond and constantly

characteristics	adapt to changing customer tastes while gaining efficiency through economies of scale. It needed to develop flexibility and speed and to manage diversity in so competitive an environment in the fashion industry. It has increased responsiveness and reduced cycle times through time management as one of the key competitive strategies. Cycle time management includes redesigning operating processes. Benetton also made garment cutting and assembly faster and more flexible using CAD software along with computerised cutting and assembly. The fashion market is a highly competitive, fully developed industry and subjected to a changeable demand, and increasing variety of products. Also, product life cycles are arranged to be short to assert consumer attention. Benetton used appropriate technologies to measure customer demand, developed fast response times, and achieved flexibility and responsiveness to the market (Dapiran, 1992). Also, it has been a classical prototype of the network organisation that is based on outsourcing, subcontracting, and its relationships between a large company and small producers and distributors (Camuffo et al., 2001).

The answers presented in Table 4.3 have identified the solutions for the research questions by reviewing the available literature. The approach was to observe, analyse and evaluate the case, to address the research questions and provide results by describing and summarising the case study. The capabilities showed that Benetton has partially aligned or coordinated its operation along the supply chain, reflecting the requirements of the market and the business environment. The key player was information sharing, as the information systems technology linked the marketplace with the manufacturing process. Electronic data interchange (EDI) allowed Benetton's agents in each country to frequently transmit orders to Benetton's headquarters. It is updated every 24 hours, allowing Benetton to carefully track and react to demand by manufacturing only those garment styles, colours and sizes required. The customers are linked directly to the factory (Dapiran, 1992). This shows how far upstream the information decoupling point is positioned. Moreover, the material decoupling point is positioned downstream where manufacturing the garments from the bleached yarn and dyeing is delayed until information on the preferred colours becomes available through EDI. It was evident through Benetton's understanding of its CODP positioning strategy, its logistics and the information technology, that it had developed a flexible and responsive supply chain.

4.4 Second Case Study: Hewlett-Packard

4.4.1 Background

HP, the Hewlett-Packard Company, was founded in 1939 by William Hewlett and David Packard to create innovative products that increase knowledge and improve organisations' output (Lee & Billington, 1995). HP is a leader in supply chain management and logistics; in 1993 it employed over 96,000 people and has been involved in the development of analytical frameworks and models for managing the supply chain (Meade & Sarkis, 1998). A well-known example of postponement strategies is HP printers and its supply chain with shipping and transportation until the final packaging. Table 4.4 provides a historical glance of supply chain development at HP. The case study has focused on the DeskJet part of HP.

Table 4.4: HP supply chain historical development (adapted from Lee & Billington, 1995)

- The Hewlett-Packard Company (HP) was founded in 1939 by William Hewlett and David Packard.
- HP produces computation and measurement products which include manufacturing integrated circuits, board assembly, final assembly, and delivery to customers.
- The supply chain for HP's products contains manufacturing, research and development (R&D) sites in 16 countries, and sales and service offices in 110 countries.
- The total number of catalogue products exceeds 22,000.
- In the late 1980s, HP faced inventories growing into the billions of dollars and causing customer dissatisfaction with its order fulfilment process.
- In 1988, HP formed a group known as Strategic Planning and Modelling (SPaM) and staffed it with industrial and computer systems engineers. HP called on teams of industrial engineers, management scientists, and academics who were collaborating to reduce inventory and improve order fulfilment.
- In 1988, HP introduced printers based on inkjet technology, sold under the DeskJet label and manufactured at the Vancouver division.
- It won the 1988 Datek Printer of the Year Award, and sales grew to 600,000 units in 1990 ($400 million).
- The division also manufactures other printer products, but their main line is DeskJet printers. Since its introduction, the DeskJet has been one of the fastest growing product lines at HP.
- In 1990 the CEO, John Young, put a key objective to the company to solve the agility issue and one way of achieving the objective was through better supply chain management.
- In 1993, the company employed 96,200 people, 37,300 of them outside the US.
- President and CEO, Lew Platt, identified successful order fulfilment as one of his top goals for the 1993 budget and nominated a vice-president to work full time toward that goal.
- HP distributes through its own distribution network. This network consists of two major distribution centres (DCs) in the US, several in Europe, and one in the Asian-Pacific region.
- Manufacturing sites are located all over the world. Sales of HP's peripheral products: LaserJet printers, DeskJet printers, and inkjet components have been growing at a record pace.
- In 1990, the DeskJet printer volume grew from 600,000 units per year to over 400,000 units a month, an 800% increase.
- In early 1992, the executive vice-president realigned the distribution network. This realignment reduced the total distribution cost in Europe by $18 million a year. In particular, DeskJet printers experienced explosive growth.

4.4.2 Positioning of CODPs in the HP case

Table 4.5 presents the methodology used in the analysis of the HP case. The main sources of information used are Feitzinger and Lee (1997), Lee and Billington (1993, 1995), and Lee et al. (1993).

Table 4.5: Positioning of decoupling points in HP case

Description	Questions used to draw meaning and verify conclusions
Research questions	***Does HP attempt to meet the requirement of agility by positioning the decoupling point as far downstream as possible? Does HP create some disadvantages by moving the decoupling point downstream?***
Positioning of the material decoupling point	The manufacturing process of the DeskJet printers by HP's Vancouver division has two phases: (1) printed circuit board assembly and test (PCAT); and (2) final assembly and test (FAT). HP localised the DeskJet Plus for different countries and packaged the appropriate power supply module (with the correct voltage and plugs) and the appropriate manual with the printer; this step was done by the factory. Hence, the factory manufactured finished printers intended for all other countries but then grouped them into three groups for the distribution centres (DCs) in North America, Europe, and Asia and the Pacific (factory-localisation). The Vancouver factory ships to the three DCs by sea. HP decided to follow make-to-stock at the DCs to supply a very high amount of availability to the dealers, which act as inventory stocking points, to satisfy the planned mass-produced fill rate, where the manufacture triggers the replenishments rates just in time so that the function is in pull mode to maintain the target safety stock. Also, the HP factory placed safety stocks for incoming materials at the factory (Lee et al., 1993). It took a month to ship the different DeskJet versions to the two non-US DCs by sea. This complicated the responsiveness of the DC, with fluctuations in demand for the different versions of the product. Also, the European and Eastern Asia DCs had to maintain high levels of safety stocks. For the North American DC, most of the demand is for the US version, and there is little localisation product-mix fluctuation. HP delayed the material decoupling point where the factory would manufacture and ship a generic DeskJet Plus printer without the power supply module and manual up to this point and then the DCs would respond as needed to the different specific options of the generic products (Lee et al., 1993). Hence, HP decided for Vancouver to manufacture two types of DeskJet printers: (1) a fully localised US one; and (2) a generic one without the power supply module and manual, for localisation in Europe and Eastern Asia. The assembly takes place at the factory, it maintains all safety stocks of the power supply modules and manuals; and the DCs keep safety stocks of the finished products. When the dealers receive actual orders, the DCs quickly assign the generic version for the specified products. This shows the postponement of the material decoupling point by means of deferring the localisation process for the DeskJet printer at HP, while inventories are kept in finished goods form (Lee et al., 1993). The Vancouver division's printer variety thrived as it tried to satisfy many different customer segments, each requiring different functionalities. With product life cycles becoming shorter and shorter, the benefit of postponement with universal power supply outweighs the additional material cost. HP has collaborated with its dealers in postponing the decoupling points

	that encompass localisation operations, distribution activities, and customisation tasks (Lee & Billington, 1995).
Disadvantages of moving the decoupling point downstream	The movement of the decoupling point downstream can greatly affect the company's inventory and service trade-off. In order for HP to perform this move and localise the DC which encompassed the designs of the product and the production process, it needed to change the product design, which required costly engineering resources, a site at which localisation could be done, and the cost of localisation. Changing the engines to switch the power supply is not a minor task and incurred some significant labour and material costs. Also, it had to add final configuration and packaging capability to the Eastern Asia and European DCs at a cost which needed some investment. This affected subsequent Vancouver products and products from other divisions, to offset this one-time investment (Lee et al., 1993). There was also a need to build a local supply base of the localisation materials for the DCs. In addition, this move may have cultural and organisational barriers to overcome in order to succeed. The overall strategy required detailed analyses before making these DP decisions, which included visiting and negotiating with dealers, quantifying the costs and benefits, assessing the marketing implications, and considering government regulations and local content laws, environmental requirements, and organisational impacts (Lee et al., 1993). These disadvantages were for a one-time investment, but it succeeded in the long term of this delaying decision and redesigned the product so that the power supply module would be the last component added. This DC-localisation led to an 18 per cent reduction in total inventory investment.
Research questions	***Does HP go to some lengths to improve the quality and utility of information which is transmitted upstream? Does HP transmit this information as far upstream as possible? Does it show any evidence of the zonal concept in information penetration?***
Moved information upstream	The depth of the information flow in the HP case includes most of the dimension as dealers depend upon having timely and accurate information about (revised) delivery dates, order status, and product availability (Lee & Billington, 1995). Modularisation is an essential part of fulfilling mass customisation at HP where it is relevant to a wide range of products. HP was interested in finalising local specifications via add-ons, fitting the module to the marketplace (Feitzinger & Lee, 1997). HP considered a new innovative method of postponing the final packaging until a customer order was acknowledged. It identified a new shipping design that separates the printers into 15 layers of 16 printers. The position of the decoupling point is settled at the packaging point. HP reduced inventory requirements by 60% (Feitzinger & Lee, 1997). The HP case has been mentioned as a company case in the bullwhip effect and in information distortion literature as a proven example of the benefits of sharing information in demand requirements in a two-level supply chain, which showed high demand requirements when there is a correlation between demand and time (Ho, 2007; Lee et al., 1997). This proves that HP was moving the demand information upstream in a timely manner, forming an information decoupling zone that is proportional with the time. Regarding the specification, HP uses the information decoupling point by moving it further upstream and exploiting modularisation to the full, fitting the product to the individual customer (Feitzinger & Lee, 1997).
Research question	***What sort of agility does HP achieve?***

Agility characteristics	The environment facing the Vancouver division is both uncertain and dynamic. Uncertainties in supply, process, and demand coexist. At the same time, the division faces tremendous pressure from external competition as well as internal competition from the LaserJet and PaintJet printers (Lee & Billington, 1993). HP postponed final assembly of its DeskJet printers until the very late stages of the supply chain. This postponement of final assembly, combined with the shift of assembly locations closer to customers, resulted in a more cost-efficient production process while reducing transportation and logistics costs (Feitzinger & Lee, 1997). Delaying the decoupling points increased the company's flexibility to respond to changes in the mix of demands from different market segments, helped in reducing transportation cost to DCs, reduced inventory investment, and improved service. The investment in inventory has improved HP customer service (off-the-shelf fill rate) by changing from factory-localisation to DC-localisation (Lee et al., 1997).

Figure 4.1 shows the supply chain with the material flow including the decoupling point delayed at the distribution centres.

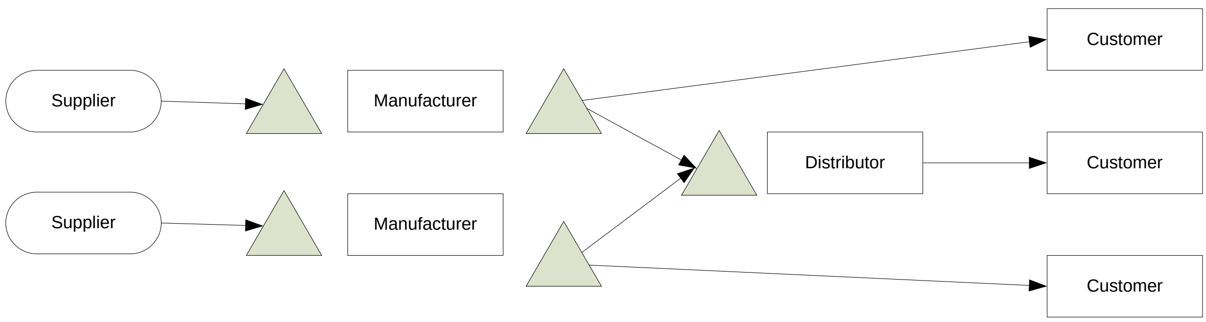

Figure 4.1: A supply chain comprising of suppliers, manufacturers, distributors, transportation links and customers (adapted from Lee & Billington, 1995)

The HP case showed that positioning the CODP until the last point at which HP delayed customisation after each unit was county-specific. Previously the power supply was specific for each of these markets and two different types of printers were produced at the factory in Japan (Feitzinger & Lee, 1997). The repositioning of final assembly activities into the distribution channel, downstream from manufacturing operations, was required to postpone to the latest point possible. This caused localisation of the supply chain and required postponement of manufacturing operations in multiple market areas (Lee et al., 1993). Some studies showed that sharing the demand and inventory levels information of HP cases reduced the bullwhip effect. The combined information from the literature shows how the positioning of the CODP has an impact on responsiveness and increases the flexibility to respond to changes in the mix of demands from different market segments.

4.5 Third Case Study: National Bicycles

4.5.1 Background

National Bicycles has two main channels: one channel focuses on local customers for repair services, and the other for large sales. National Bicycles is the main Japanese manufacturer of bicycles. In 1987 the firm initiated the Japanese innovative and advanced absolute production system called the Panasonic Order System (POS) which provided custom-made bicycles made by robots, computers and skilled workers (Kotha & Fried, 1993). Such a system enables more than 8 million variations based on different design choices, model types, frame sizes, and other options. Table 4.6 provides a historical glance at NBIC development.

Table 4.6: NBIC historical development (adapted from Kotha, 1996; Kotha & Fried, 1993)

- Matsushita Electric was founded in 1918.
- In 1952, commenced bicycles manufacturing and sales.
- In 1956, began manufacturing and selling racing bicycles.
- In 1960, established the National Bicycle Factory in Sakai city.
- In 1965, completed a new factory in Kashihara city.
- In 1967, adapted bicycles for world championships.
- In 1971, commenced export of Panasonic bicycles to the US.
- In 1973, automated the new assembly line.
- In 1979, began exporting to Europe, Canada, and Australia.
- In 1987, built the mass-custom factory, initiated the Panasonic Order System (POS), and produced 10 million bicycles.
- In 1988, started 3-weeks delivery order system to US customers.
- In 1992, NBIC was Japan’s second largest manufacturer of bicycles, with sales of about ¥20 billion.
- It manufactured three different brand names: Panasonic, National, and Hikari.
- National and Hikari brands form the main NBIC production and sales. Panasonic was the most expensive line with less than 20% of total production in 1992.
- Custom-made Panasonic bicycles are produced for individual customers.
- In 1992, produced 700,000 bicycles, 90% were produced by the mass-production factory to Matsushita’s (NBIC’s parent corporation) sales subsidiaries and only about 12,000 were produced at the mass-custom factory.
- In 1993, 470 workers worked in the mass-production factory (more than 66% are classified as direct workers and the rest as indirect workers).

4.5.2 Positioning of CODPs in the National Bicycle case

Table 4.7 presents the methodology used in the analysis of the National Bicycle case. The main sources of information used are Kotha (1996), Kotha and Fried (1993) and Towill and Christopher (2010).

Table 4.7: Positioning of decoupling points in National Bicycle case

Description	Questions used to draw meaning and verify conclusions
Research questions	***Does National Bicycle attempt to meet the requirement of agility by positioning the decoupling point as far downstream as possible? Does National Bicycle create some disadvantages by moving the decoupling point downstream?***
Material decoupling point	The manufacturing process starts with a CAD system, located in the control room, by scanning the bar label code, and the information is sent for a blueprint of the bicycle frame and other structural details, which is produced in 3 minutes. The next stage is the frame and front fork production which starts by cutting tubes that form the frame of the bicycle, using a rotary saw. Then the two tubes are welded together using an arch cut special machine. Small parts such as brake guides are brazed to the frame by a skilled worker. Then the joints of the frame are brazed by a brazing machine following the front triangle assembly machine that uses special jigs and other features. Next, a worker using a rear fork assembly machine adds the welded chain-stay hanger section, seat stay, and the seat lug section. After that, these are brazed to the frame. Slitting and reaming the seat lug and inside the seat tube is the next step using a slitting and reaming machine. Tubes forming the front fork are cut and assembled. A quality check takes place using a 3D automated machine. The second phase is the preliminary painting using a robot after cleaning the surfaces. Two skilled workers complete final and special painting. The final phase is the labelling and engineering process where a skilled worker or engraving machine does the printing or engraving on the frame or handle bar stem. Then, final assembly joins the completed frame and fork with selected wheels, chain, gears, brakes, tyres, and other parts that complete a bicycle. It is then sent boxed to a holding area to be shipped the same day. The total time to complete a single order is 150 minutes by 15 workers to finalise 60 custom-order bicycles per day (Kotha & Fried, 1993). NBIC faced a unique market segment for each of the three brands of bicycles. The firm has had two factories, one for mass production and the second for mass customisation. The project leader worked with a multi-functional team and invented the new system, the "Panasonic Ordering System" (POS) to face the competition and meet industry conditions in Japan. These custom-made Panasonic bicycles were delivered in two weeks and priced higher depending on the particular model and features selected, compared to those in the mass-production factory. NBIC had created two factories; the mass-production factory for a large market segment that is driven by efficiency considerations through long production runs. The mass-custom factory targeted a smaller segment of the market by way of a differentiation strategy. The material decoupling point is placed downstream where a customer can choose from about 8 million possible variations based on model types, colour, frame size, and other attributes to order a custom-made bicycle. Mass-custom production starts when the customer's order and specifications are received. The bicycle is shipped immediately. Such a strategy requires highly skilled workers where NBIC apply rotation and encourage the workers to train. Among the various choices via direct customer feedback, the product designers and process engineers design new products for the mass-production factory, so it then manufactures the new design based on forecasts. This strategy of moving the material decoupling point enabled the mass-custom factory to adapt to the increasing complexity because of the increased inflow of custom orders and retailers permitted to offer customisation. The NBIC decided to locate the material decoupling point (postponed frame welding, painting and assembly)

	until individually tailored orders were faxed through by 9,000 retailers. The customer's order is measured for height and weight for each product and different design types, as shown in Figure 4.2, which represents the material flow with the delayed decoupling point and the variety of design elements (Kotha, 1996).
Disadvantages of moving the decoupling point	The Japanese dealers and the international market experience long delivery times. Individual customers can choose from approximately 8 million variants including model, type, colour, frame size, and other features in which such a customisation and variety of specification complicates the flexibility of the supply chain and slows down the responsiveness measure. This strategy of movement with mass customisation requires long-term investments in advanced manufacturing technologies and human resource development. Also, to pursue such a strategy, new knowledge is necessary for refining existing skills. Such an approach relies heavily on in-house expertise to implement mass customisation. Moreover, this strategy requires an experienced marketing group to offer the individualised product (Kotha, 1996).
Research questions	***Does National Bicycle go to some lengths to improve the quality and utility of information which is transmitted upstream? Does National Bicycle transmit this information as far upstream as possible? Does it show any evidence of the zonal conception in information penetration?***
Moved information upstream	Bicycles that are made to stock are produced based on information about preferred bicycle models and colours from various retail outlets, and moved back via sales and marketing to manufacturing. This strategy is applied at the mass-production factory. In the mass-custom factory, it is directly linked to customers via retail outlets under the POS. A customer selects the options, colours, patterns and models, which are directly received by the factory. Then, these two factories are instituted under a centralised structure to enhance the sharing of information through the firm's supply chain. NBIC created an 'information network' with POS retailers so they can communicate with the mass-custom factory. The company uses its own computer hardware for the POS and its developed software. Regarding the customer's order specifications, the dealers send the information to the control room of the custom-made factory by facsimile. Then the attendant in the control room enters the information into the host computer to manage the customer's order specifications. After that, the host computer assigns each order a unique bar code label which moves with the bicycle and is controlled at each stage of the manufacturing operation. The customer's unique information regarding requirements is displayed on a terminal at each station of computer-controlled machinery, to enable workers to perform the required operation sequence. Figure 4.3 gives an overview of the whole manufacturing process that is used by NBIC (Kotha & Fried, 1993). The order process starts from a point at which the products are customised for the customers by measuring the height and weight for each individual product, and the customer can choose from a wide variety of design elements (18 models, 6 handle stem extensions, 199 colour patterns, 3 toe clip configurations, 6 brake systems, frame dimensions in 10 mm adjustments, 3 handle bar widths, 2 pedal types, 2 tyre types, 2 different name positions and 5 choices of script for the customer's name on the frame) (Towill & Christopher, 2010).
Research question	***What sort of agility does National Bicycle achieve?***
Agility characteristics	NBIC recognised that information technology and computer-integrated manufacturing are required, but are not sufficient for achieving flexibility and responsiveness (Kotha & Fried, 1993). NBIC utilised mass customisation to enable the firm to provide product variety and customisation through flexibility and quick responsiveness. This has

	resulted in an increased share of the Japanese sports cycle market, and a tangible reduction in total lead-time-to-serve. Also, it has been reported that National Bicycle practices a seasoned production in which the lean and agile processes are temporally separated (Towill & Christopher, 2010). The agility was seen in this case in its ability to reconfigure the supply chain rapidly to the variable demands. Also, this was noticed in its lead time. The target lead time is 2 weeks and was met 99.99% of the time, and such innovation enabled National Bicycle to increase its share of the Japanese sports cycle market from 5% to 29%, as a result of the reduction in serving time. Nevertheless, it kept the highly skilled staff to balance between customisation and mass production (Towill & Christopher, 2010).

Figure 4.2 shows the supply chain with the customisation of the products including the decoupling point delayed at the distribution centres.

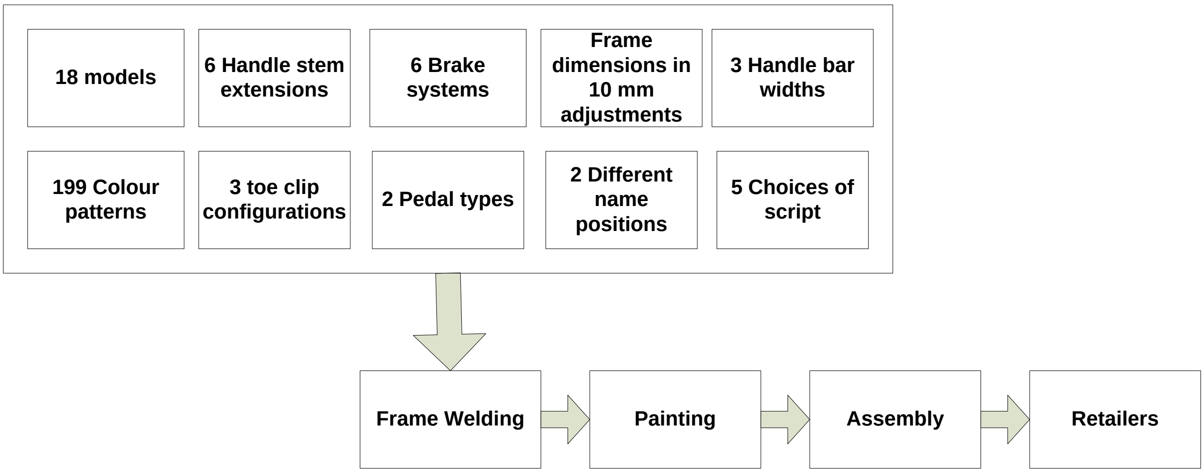

Figure 4.2: National Bicycle supply chain (adapted from Towill & Christopher (2010))

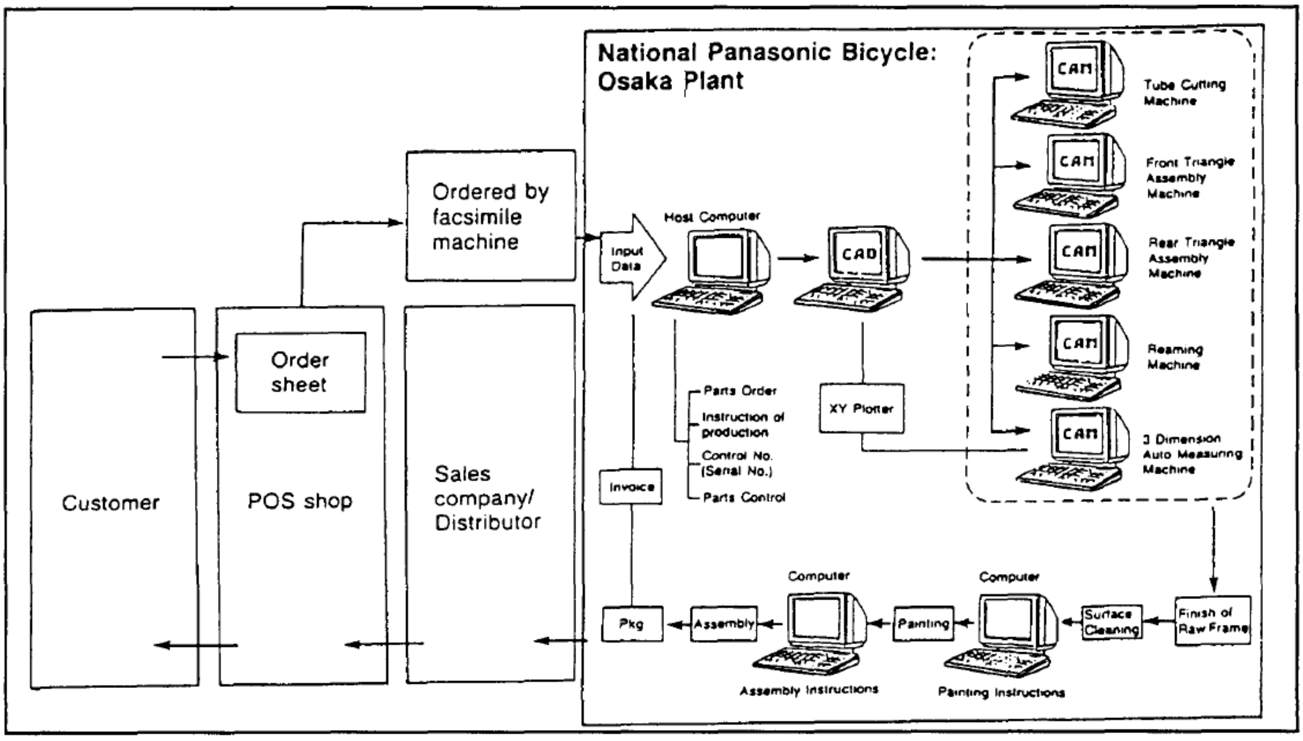

Figure 4.3: NBIC's Panasonic Ordering System at mass-custom factory (Kotha & Fried, 1993)

Two in-depth case studies by Kotha (1996) and Kotha and Fried (1993) show that mass customisation has been used to delay the differentiation, and the bicycles are made-to-order, whereby a customer ordering a custom-made bicycle can select from 8 million possible variations, based on model types, colours, frame size, patterns, models and other features. The information decoupling point is positioned directly to the factory. The order is processed through the factory, and the production process begins after the arrival of the customer's order and specifications. This positioning between the latest customisation and sharing the bicycle specification upstream enables the firm to produce the individualised bicycle quickly and ship it the same day. This shows that agility and flexibility are achieved through the positioning of the CODPs and through product variety and customisation.

4.6 Fourth Case Study: Whirlpool

4.6.1 Background

The **Whirlpool** Corporation is a Fortune 500 company and a global manufacturer and marketer of major home appliances, with headquarters in Benton Charter Township, Michigan, United States. The company has an annual revenue of approximately £11.2 billion, more than 70,000 employees, and more than 70 manufacturing and technology research centres around the world. The company markets Whirlpool, Maytag, KitchenAid, Jenn-Air, Amana, Gladiator Garage Works, Inglis, Estate, Brastemp, Bauknecht, Consul, and other major brand names to consumers in nearly every country around the world .

The Whirlpool Corporation consists of three manufacturing companies in the household cooking range industry for the final household customer, or end user (Mangiameli & Roethlein, 2001). Its manufacturers are in 12 countries and markets products in more than 140 countries. The range appliance division of Whirlpool is located in Tulsa, Oklahoma, and manufactures free-standing gas and electric ranges (Mangiameli & Roethlein, 2001). Table 4.8 provides a historical glance of Whirlpool's development.

Table 4.8: Whirlpool historical supply chain development (adapted from Slone, 2004)

- In 1911, Louis and Emory Upton founded the Upton Machine Company.
- In 1978, it surpassed $2 billion in annual revenue.
- In 1989, it surpassed $6 billion in annual revenue.
- In 2000, salespeople at Whirlpool said the company's supply chain employees were "sales disablers". Too much finished goods inventory and failing to provide the product availability to customers when needed were major issues.
- In 2000, Whirlpool North America had a new Enterprise Resource Planning (ERP) system. Whirlpool ships around 70,000 appliances a day to North American customers but after the implementation of System Analysis and Program (SAP) Development, it was able to ship only 2,000.
- In 2000, sales rose to record levels with the launch of some innovative products.
- The votes of Whirlpool's North American leadership team on 3 May 2001, chaired by Mike Todman, executive vice-president at the time, agreed on the investment that Paul Dittmann and Reuben Slone proposed to lead to a supply chain turnaround.
- Whirlpool manufactures a diversity of washers, dryers, refrigerators, dishwashers, and ovens, with manufacturing facilities in 13 countries and 3,000 workers. The sales of these appliances are in 100 countries, between big and small retailers and to the construction companies and developers that build new homes. In the US, the logistics network consists of 8 factories' distribution centres, 10 regional distribution centres, 60 local distribution centres, and about 20,000 retailers.
- In 2000, many people in supply chain roles had been with the company for years and had watched in frustration as competitors outspent and outperformed them. Part of the problem was the massive effort required by the ERP implementation, as an early adopter of enterprise systems in the industry (SAP and other vendors got their start with process-manufacturing concerns such as industrial chemicals).
- After May 2001, and within 30 days of launch, the forecast accuracy error was cut in half with only 40–45% only error (which was 100% before). The total finished goods position improved by several million dollars. These were just two of many initiatives launched in rapid succession after May 2001.
- In January 2002, Whirlpool had historic low inventories and high service levels.
- By May 2002, a blind Internet survey given to trade partners showed Whirlpool to be "most improved", "easiest to do business with", and "most progressive". After these results came

out, the VP of sales said, “You’re good now but more important, you’re consistently good”. It was a turning point in the trade’s perception of Whirlpool.

- By the end of 2003, product availability had reached over 93%, up from 88.3% in 2001. (Today it’s more than 95%.) That allowed them to attain an order till rate for key trade partners of over 96%. The number of days’ worth of finished goods held in inventory had dropped from 32.8 to just 26. They drove freight and warehousing total cost productivity from 4% to 7.2%. From 2002 to 2003, they lowered working capital by almost $100 million and supply chain costs by almost $20 million.

4.6.2 Positioning of CODPs in the Whirlpool case

Table 4.9 presents the methodology used in the analysis of the Whirlpool case. The main sources of information used are Slone (2004) and Waller et al. (2000).

Table 4.9: Positioning of decoupling points in Whirlpool case

Description	Questions used to draw meaning and verify conclusions
Research questions	***Does Whirlpool attempt to meet the requirement of agility by positioning the decoupling point as far downstream as possible? Does Whirlpool create some disadvantages by moving the decoupling point downstream?***
Material decoupling point	In the statement report by Paul Dittman, vice president of Whirlpool Corporation: “The strategic intent to strive for mass customisation is one thing, the process and systems to accomplish it are another” (Van Hoek, 2001). This highlights the managerial interest in delaying the material decoupling point, employing the postponement strategy as a way of adopting mass customisation. Figure 4.4 shows the Whirlpool supply chain (Mangiameli & Roethlein, 2001). The decoupling point is delayed until orders are received from customers. Shipments to Sears are made on this basis. Whirlpool has benefited from a cut in transportation costs, cross-docking, stockouts, inventory, and improvement in customer service (Waller et al., 2000). Using this strategy, Whirlpool retains final product customisation until a reliable order commitment takes place. Before this point, large inventories of appliances were maintained in various store locations and/or distribution centres, which expanded inventory, and added to product obsolescence (Frankel, 2006). Whirlpool and Sears had involved Boston Consulting Group to study consumers’ desires with regard to appliance delivery. Whirlpool concentrated on customer requirements initially to define requirements by segment. Also, it benchmarked its competitors to obtain cross-industry information and objective assessment of supply chain capabilities. The aim was to be considered world-class for the 27 capabilities targeted by the management and to get serious about priorities. It got help from Michigan State University, the American Production and Inventory Control Society (APICS), Don Bowersox, Tom Mentzer, Ralph Drayer, and Larry Sur to develop the supply chain “competency model” which provides the skills required in a top-tier organisation, the roles, and plan for them over time. Moreover, it encouraged the employees to be rewarded for increasing their expertise with an emphasis on developing employees’ project management skills. The focus for the consultation team was on “Plan to Sell/Build to Order”. Here, the concept is that particular high-volume SKUs should be available all the time. These are the dishwashers, refrigerators, washing machines, and other products that are requested mostly by a wide range of customers. The supply

	chain strategy was devised so that SKUs across all trade partners in all channels could be identified to ensure that the replenishment system for regional warehouses keeps them in stock. That established for small-volume SKUs, all the inventory and operating should be on a pure pull basis (Build to Order), with more flexible processes. This had helped in reducing the costs of inventory on the high-volume SKUs. They concentrated on applying lean techniques to the total supply chain using pull concepts and Kanban. They redesigned the product and made it in a smaller plant, with smaller parts, and shipped it in smaller pieces. Whirlpool pushed the end stages of production closer to the consumer and got higher leverage from the SKUs. They realised this is the kind of thing that can change the rules of the game so they can compete all over the world (Slone, 2004). Whirlpool used postponement in its downstream supply chain by delaying the shipping of a product to a Sears distribution centre until a customer order was received. Before this stage, large inventories of appliances were kept in store locations. However, marketing research showed that most customers were willing to wait several days when their purchases were for a new home. This resulted in significant savings in inventory and transportation costs through less transhipment. Hence, by eliminating these transhipments, inventories were postponed to the warehouses and moved between some Sears warehouses that needed them. It is classified as a time postponement where distribution or actual delivery of a product is delayed until customer demand is known (Waller et al., 2000).
Disadvantages of moving the decoupling point	Moving the material decoupling point and changing the strategy resulted in setting service levels by SKU because some products were of greater strategic importance than others and more profitable. They experienced some difficulties in accomplishing this since they ship thousands of products daily.
Research questions	***Does Whirlpool go to some lengths to improve the quality and utility of information which is transmitted upstream? Does Whirlpool transmit this information as far upstream as possible? Does it show any evidence of the zonal concept in information penetration?***
Moved information upstream	Customer order processing is shared upstream with the suppliers and other players of the supply chain, which supports the company's transparency in terms of the information flow (Waller et al., 2000). Whirlpool used some of the supply chain tools to enhance sharing the information upstream such as rollout of a new sales and operations planning (S&OP) process, and launching a collaborative planning, forecasting and replenishment (CPFR) pilot to enhance the forecast. With CPFR, it used Web-based tools to share forecasts with the supply chain players and collaborated on the exceptions. Also, it implemented a suite of software products from i2 for supply chain integration tools. They focused on system-to-system transactions that linked them directly to a customer's system for the purpose of transmitting orders, exchanging sales data, and submitting and paying invoices. This has allowed customers to check availability and near models, and place orders via the Internet. Moreover, they implemented event-management technology to track and ease the movement of goods through the supply chain (Slone, 2004).
Research question	***What sort of agility does Whirlpool achieve?***
Agility characteristics	Whirlpool has been reported in the literature as an example to illustrate the value of market-oriented supply chain management (Waller et al., 2000). It has used postponement to improve its responsiveness to customer demands. Whirlpool through its history has merged with many companies but has shown reduction in the supply chain stages and employed a single logistics provider,

	Penske Logistics, to help with the partners they are going to operate with in the future, so Whirlpool has become nimbler in terms of responsiveness (MacMillan, 2008). Slone (2004) concluded that Whirlpool excelled at getting the right product to the right place at the right time while keeping inventory low.

Figure 4.4 shows Whirlpool's supply chain and product flow.

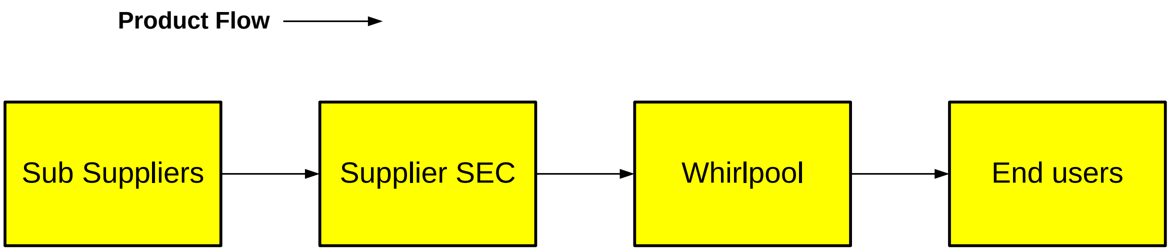

Figure 4.4: Whirlpool supply chain (Mangiameli & Roethlein, 2001)

In the literature, Whirlpool is an example of an organisation that practices supply chain management globally (household appliances), that shares the information from customers and retailers, such as Sears and Home Depot, with its suppliers through demand levelling, inventory levels and the aggregate planning of large appliances such as refrigerators, washing machines, and air conditioners. The company postponed positioning the material decoupling point until the assembly stage, waiting for the retailers' orders. The challenge for Whirlpool comes from the products' high value and the space required for storage at the local stores. It has two main distribution strategies, one for free-standing appliances, and the second for built-in appliances. Once the order is placed by customers, the goods will be sent and shipped directly. The sharing of EDI for the entire supply chain, and applying the initiatives and technologies, has helped Whirlpool's supply chain to support supply chain agility and flexibility by supporting the flow of information and repositioning the material decoupling point globally. This saved in inventory costs, transportation costs, and transhipment orders between retailers.

4.7 Analysis and interpretation of the case studies

In this section, the results of the case analyses are presented: first, the major effect in the decoupling point's positioning is discussed; and second, the responsiveness assessments are compared between the cases to test the hypothesis that by moving the material decoupling point downstream and information decoupling point upstream, an agile response can be achieved.

4.7.1 The customer order decoupling point (material and information flows)

In order to test the hypothesis, an attempt was made to capture the involvement of the customer order decoupling point through the literature review relating to the cases studied. The CODP in the material pipeline and information pipeline showed an extension of the decoupling point methodology, which the material decoupling point conforms to, that the traditional CODP and the information order decoupling point are positioned upstream by sharing the information from the customer to the suppliers in the best possible positions. The proper locations of these CODPs showed great impact on the inventory levels, stock positions, and customer order response time. These case studies transited to global markets and each was in a position to coordinate and align its supply chain through the allocation of the CODP's strategic positions, to be competitive and agile by being responsive to any changing circumstances. The product variety and complexity of the bill of material established the zonal indication through the processes of the different functions, from customer order placement, through the production stages, to the suppliers. Also, the decoupling zone is evident in the information flow through the uncertainty (and certainty) of customer orders, which fluctuates through forecasting. Sorting these information types and characteristics within the processes along the supply chain has a positive impact on supply chain agility due to redesigning the CODPs. Each information type corresponds to the characteristics of a product and its components. Such a zonal identification can separate the activities related to the certainty of customer orders and material flow, which can be supported and applied in the design stages.

The case studies suggested that the material decoupling points: MTS, MTO, ATO and ETO, are better located further downstream, also considering the related market, product, process factors, and that the position is not accurately defined but subject to the considerations outlined in Table 4.10.

A number of projects have revealed that demand uncertainty resulting from forecast errors was the key source of inefficiency in a supply chain; design changes, such as common parts, delayed product differentiation, and other postponement strategies, helped lessen the impact of forecast errors (Lee & Billington, 1995).

Table 4.10: Material and information decoupling point constraints

Material decoupling point process constraints	• The lead time must be shorter than the required delivery time • Variation in lead time or in production output make it hard to deliver completely at the agreed time • The material decoupling point is better kept downstream when it is produced for batch production with significant changeover times, or downstream of the material flow or where components are introduced by unreliable suppliers and suppliers who are difficult to replace.
Information order decoupling point constraints	• The information decoupling point is better positioned upstream to extract a reliable forecast from irregular market demand, which must be offset by high safety stocks • The information decoupling point related to the mix or different product types is better positioned upstream gradually to decrease the risk of long waiting periods for sources, and to lead to some types becoming saleable • If the potential market comprises of only a small number of customers, there is a relatively high risk of obsolescence (unless customers have a certain contractual commitment to buy) • It is better to position the information order decoupling point relative to the specification, to maintain activities specifically intended for a particular market segment or for one individual customer • It is preferable to keep the information order decoupling point upstream with respect to the lead time, so that an activity with a relatively high value can be added, compared with the lead time.

The cases studied in the literature show that to manufacture products that suited different market segments, companies would produce the main products that have the main characteristics, and parts of the finished products, and the final products were assembled at the delayed points downstream in the supply chain, with some additional components added to differentiate the products for the different market segments. The differences between the cases were that delaying the material decoupling points depended on the changes in the design of the product and the production process. So the positions of these points were at the factories, assemblers, or distributors in which they localised, customised, or assembled the differentiating modules before moving the products to the next stage.

The need for this positioning of the material decoupling points started as a way of changing the supply chain strategy to face uncertainty and competition in the markets. The companies in the case studies struggled with their supply chains in terms of delivery of materials, internal processes, and matching the product types with demand. These caused delays in replenishing stocks at the material decoupling points and led to inventory build-up.

The positions of the information decoupling points in the case studies were upstream in the supply chains, and some design principles have been noticed, as follows:

- A zone for an information decoupling point, with respect to the demand information from the customer orders, can start from sharing the information with the suppliers up to the customer, so companies can extract a reliable forecast from irregular market demand, which must be offset by high safety stocks.
- A zone for an information decoupling point, with respect to the mix information or different product types, is better positioned upstream gradually to decrease the risk of long waiting periods for sources, and to lead to some types becoming saleable so products can be designed to consist of independent modules that can be assembled into different forms of the product easily and inexpensively.
- A zone for an information decoupling point, with respect to the specification, should be upstream to a point at which the company can maintain activities specifically intended for a particular market segment or for one individual customer. This position would consist of independent modules that can be moved or rearranged easily to support different distribution-network designs.
- A zone for an information decoupling point, with respect to the timing information of the customer orders, should be positioned upstream closer to the customer so that companies are able to provide the time of delivery to the customer. This place conforms to the latest position of the material decoupling point in which the distributors can fulfil the individual customer order quickly and on time.

Making decisions like these is not easy and sharing the required information type for each echelon in the supply chain is important so people from the different areas of a company can focus their roles to support a responsive supply chain strategy. The companies were successful in their breaking down of the production process into independent processes which provided them with the kind of flexibility they required within each company's approach, such as a mass customisation or postponement.

That is, delaying the material decoupling point request and redesigning products and processes so that the stages of the production process in which a common process is used, are extended. The competition in the world market requires providing product variety for marketing and sales promotions. Such an approach has a significant impact on inventory level and supply chain performance.

The benefits of the decoupling points for each company's case are shown in Table 4.11.

Table 4.11: Benefits of the decoupling points for the companies' cases

Company cases	Benefits of extending the customer order decoupling point
Benetton (Dapiran, 1992)	1. Better response to end-user demand 2. Reduced excess inventory 3. Improved customer satisfaction 4. Getting rid of unpopular colours
Hewlett-Packard (Feitzinger & Lee, 1997)	1. Closer to customers 2. Efficient production 3. Minimised costs for transport 4. Minimised costs for logistics
National Bicycles (Kotha & Fried, 1993)	1. Reduced lead time to serve 2. Allowed customer to select the preferred features 3. More flexible and responsive
Whirlpool (Waller et al., 2000)	1. Reduction in transport cost 2. Reduction in inventory

The positioning of the material decoupling point enhances responsiveness because the companies will be able to manage customer orders with the proposed information types and delay the differentiation until the latest point, thereby helping them to address customer demands adequately (Van Hoek, 2001). These benefits are summarised in Table 4.12.

Table 4.12: Benefits of delaying the material decoupling point (adapted from Van Hoek, 2001)

Factors	Benefits of delaying the material decoupling point
Uncertainties	Reduce risk of volume and variety mix by delaying finalisation of products
Volume	Make batches of one job (job shop for customisation, flow shop elsewhere)
Variety	Presume, customise, requiring flexibility
Lead times	Offer accurate response, yet perform activities within order cycle time
Supply chain approach	Reduce complexity in operations, yet possibly add flexibility and transport costs

The location of the proposed CODP through the extreme extension was not feasible but can be feasible through the definitions and solutions provided by the research, which showed that there are two dimensions. These include the material decoupling point and order information decoupling point, and the relationships and activities between them that are related to product variety, volume, final configuration, and so on, in the supply chain. The dimensions of the information types (demand, specification, mix, and timing) indicate how the information is shared between the members of the supply chain. The information order decoupling point zone is categorised up to the dimension proposed. Each one divides the information about the order in terms of certainty into pre-information and post-information order decoupling points. Delaying the material decoupling point provides the reduction in lead time and increases delivery speed.

This thesis classified the CODP concept into an expanded two main CODP related to material and information flows. The information flow was categorised into four main underlying factors (demand, specification, mix, and timing) related to customer orders. The CODP new classification showed diversity and different CODP positions per product, and product-market combination, per product component, and per zonal concept in the supply chain (customer orders to the suppliers). The main goal for companies is to shorten the lead time to achieve the agility and flexibility required.

The CODP in relation to the information is vital to the material decoupling point as the specification detail transforms technical process information that can be handled by the material transformation processes, so the supply chain can be managed and structured in a responsive and agile way. The position of the information decoupling point is strict in regard to the implementation of adequate logistics information systems in the supply chain. The appropriate location of the information decoupling point should be supported by the intense use of modern information technology and level of centralisation through processing the information flow, as well as websites, database systems, expert systems, decision support systems, EDI, Internet, etc. (Kisperska-Moron & Swierczek, 2006).

4.7.2 Responsiveness assessment

Nagel and Bhargava define agility as "an organisation's ability to sustain and prosper in a business environment characterised by continuous changes and unpredictability". An agile organisation has a quick and appropriate movement, suiting the conditions of business. Agility is crucial when product variety, demand volatility and uncertainty are high (Nagel & Bhargava, 1994). With stable and predictable demand, a lean approach can safely be used (Christopher, 2000). Goldman et al. (1995) add that supply chain agility depends on the management of changes and uncertainties, customers' enrichment, cooperation among different supply chain entities, and effective leverage of people, information and technology. Therefore, the need to satisfy customers' requirements and preferences for a diversified product range, shorter product life cycles and the trends of mass customisation, make agility very crucial in today's business environment. Agility helps businesses to remain competitive (Goldman et al., 1995). To be agile, an enterprise must be able to perform in dynamic, turbulent, and competitive market environments.

Agility is considered an element that encourages the integration of all flexible and core competent resources of an organisation so that value-added products and services can be offered in competitive environments characterised by high volatility.

The findings from the case studies supported the hypotheses, that under information and material decoupling point extension to the upstream and downstream limits, responsiveness can be created according to the strategy applied.

Positioning the material and information decoupling points is a complex decision. It requires balancing between the response time to a customer's order, the mix or product varieties, products' specifications, and demand information. These involve local-content rules, duties, and localising the supply chain echelons at certain places to serve multiple regions. By finding the optimum position of the decoupling points, the responsiveness can be achieved.

4.7.3 The limitations of literature-based case studies

There are some difficulties in using the case studies approach which are:

1. **The availability of information**

There is much information about the cases studied, but the focus was on the papers that concentrated mainly on the cases considered. The information reported in the literature regarding questions raised for the case studies is limited. Also, it decreases the chance of making adequate inference.

2. **The sources cover a wide time period so the units of analysis are changing**

The problem of setting boundaries for units of analysis is critical. Units of analysis may differ in scope of activities, duration, and so on, but they will be bound together by the fact that they have identifiable boundaries, that they are within the same case, and that a common set of questions is applied to them (McClintock et al., 1979).

3. **Lack of rigour**

Yin (2009) discusses that the case studies are often accused of a lack of rigour.

4. **Difficult to generalise and conduct**

Case studies in general provide very little basis for scientific generalisation and are often labelled as being difficult to conduct (Yin, 2009).

5. **Descriptive, not explanatory**

It is a descriptive method, not an explanatory one so conclusions about cause-and-effect relationships cannot be drawn. The behaviour or performance of one company may not reflect the behaviour of most companies.

Despite some limitation, literature-based case studies help in:

- studying single organisations that help in testing hypotheses in terms of the theoretical adequacy of the units of analysis;
- leveraging knowledge for the research question raised that fulfils the purpose of the developmental discussion of the research;
- permitting exploration or description of the data in real companies that have been explained in the literature widely, and also helps to explain the complexities of real-life situations which might be captured through the case study design/research questions.

4.8 Discussion, Conclusions and Further Developments

The information decoupling point in terms of demand mix, variety, and specification dimension was high in the company cases that applied ATO and MTO strategies. Clearly, if a product was in the early stages of production, rather than being available ex-stock, a longer lead-time would be required.

Supply chain structure and the position of the CODP should be made on the basis of customer requirements (Pagh & Cooper, 1998). The case studies showed that, having the decoupling points apart, the information upstream and the material downstream, leads to reductions in wastage and at the same time enhances the flexibility and agility of the companies. The concept of the CODP is associated with the postponement strategies which imply the delay of the material decoupling point, which in turn reduces the degree of uncertainty, increasing customer orientation, agility and flexibility enough to meet customer demand. Consumer electronics, clothes, bicycles, and appliance industries face rapid developments in technology. Consumers force retailers to provide low cost, high quality, short delivery times, high frequencies of deliveries, and customised products at the right place and time. The margin of tolerance for wait times is low. Unpredictability in consumers' demands and changing consumer behaviours have had their effects on the retailers' profit margins in that speculative approaches and forecasting have been rendered obsolete due to uncertainties introduced by continuous changing trends.

The material decoupling points for the case studies can be located between the manufacturers and assemblers in the supply chain so that it will work on an assemble-to-order basis. In turn this will be suitable and compatible with the modular nature of the product; as a matter of fact the final assembly of the modules and the customisation steps are postponed as late as possible. This will enable firms to move the information decoupling points upstream to respond to a varied product mix, demand, specification, and timing for a range of products, whether customised or not. There will be a considerable reduction in lead time and this will depend upon where in the supply chain the final assembly is performed.

The decoupling point concept is very applicable in most of the manufacturing businesses, in the sense that the provisions required for adopting such a concept do not really result in high cost. It requires basic changes within the design of the product by having a modular design and postponing the product differentiation further upstream within the supply chain. Thus, although incorporating the decoupling point concept for so many manufacturing businesses requires modification within the supply chain, which will increase the cost in the short term, in the long term it is worthwhile to adopt this concept. Furthermore, it plays an effective role in improving the business operations within the supply chain, as well as appearing to be helpful in understanding the relationship between production systems, planning strategies and level of customisation.

The above evidence regarding agility and its link with CODPs supports the affirmative effect that having the information decoupling point upstream and material decoupling point downstream will increase the agility of the firms.

4.9 Chapter Summary

In this chapter, the analysis of the case studies and the answers to the research questions were presented: the focus was on the decoupling point concept and the responsiveness assessment. The case studies were literature-based and the evidence about the agility element was derived from the literature. The methodology was problematic in so far as the nature of these case studies did have drawbacks; the data collected for these cases was limited to change the context, to see the changes in material and information decoupling in a quantitative way, and that they apply the same material decoupling point strategy, and lead the researcher to conduct an in-depth case study using a quantitative analysis.

This chapter concludes that the extension of the decoupling point concept increases the responsiveness of the supply chain of the ATO in the industries studied as part of this research. The following chapters present an in-depth case study using simulation.

The case studies found the CODP's positions exist through zonal penetration of customer orders concurrently, through different industries; this resulted in many concurrent supply chain network configurations. Detailed and in-depth modelling is important to study this complexity and make it manageable, which will be carried out and presented in the following chapters. The next chapter, Chapter 5, predefines a modelling procedure to analyse CODP implementation, to provide its impact on responsiveness assessments. The steps for the execution of the research programme are explained in Chapter 3, which introduces the simulation study of the in-depth case study.

Chapter 5

Development of a Supply Chain Responsiveness Measurement Model

The research aim demands a demonstration of the importance of finding the best positions for the customer order decoupling points (CODPs): information and material flows using simulation and its impact on responsiveness, and thereby enhancing the modelling of the supply chain responsiveness assessment through responsive performance. This chapter describes the development of responsiveness assessment generally that is capable of representing the concept in operational terms linked with supply chain performance that is typically found in the literature. Secondly, this chapter will introduce the model development required for the analysis of the second objective.

Section 5.1 is concerned with the modelling procedures. Once a model is planned, the data requirements are known and data collection and processing can commence. Section 5.2 first describes how the required data can be collected for a field study and then outlines the processing of this data. Section 5.3 explains the information and material decoupling points' modelling construction and the variations of the processed data. Finally, Section 5.4 provides a summary of the chapter.

5.1 Customer Order Decoupling points Modelling Formulation

Before a model is created it is good practice to identify the methods by which the objectives of the design might best be achieved. Hence, this section deals with model formulation which results in a requirements list for the data collection.

Section 5.1.1 gives an overview of the process to be used to identify the data requirements for the simulation model. Section 5.1.2 describes the overall decision process. Section 5.1.3 reviews current measures of supply chain performance. Section 5.1.4 reviews possible formats of customer order decoupling point's modelling. Finally, Section 5.1.5 specifies the data requirements for the simulation model.

5.1.1 CODP model formulation process

A set of performance variables relating to the performance of the supply chain are dependent upon the type of supply chain. The information initially required for model building to enable data collection for the simulation modelling on ARENA is shown in Table 5.1.

Table 5.1: Considerations for a supply chain simulation

Supply chain stages: **e.g. Customers, Retailers (wholesalers/distributors), Manufactures and Suppliers**
Different customer demand behaviours
Different product types
For each product type, different bill-of-materials **(each product is manufactured from different raw materials and/or components)**
Minimum production lot sizes
Safety inventory levels
Information and material (components or products) flows
Distribution (delivery) lead-times
Minimum order and delivery quantities

Table 5.1 outlines the decision process that has been used to initially identify the data requirements for the simulation modelling of the supply chain.

In the decision process two parts of the decoupling points have been considered: a material flow and an information flow for the simulation model design. First, identification of the importance of significant factors is required in order to define the effect of material and information decoupling points and their variation upon system responsiveness. Then it has been identified what a simulation model should consider in a discrete event simulation (DES) model and hence regard as important when representing the impact of the CODP variations upon system performance. Both steps resulted in a shortlist of factors to be considered for the CODP model design. The final decision has been made by looking at the following two criteria: practicality of data collection, and level of impact on the simulation model. The overall decision process is described in Section 5.1.2.

5.1.2 CODP model decision process

The processes need to be subdivided into order-driven and forecast-driven between the material and information decoupling points. The processes are triggered by the customer order's arrival. The decoupling points are those that are interacting between processes, the order-driven (to order processes) and forecast-driven processes (to stock processes). Also, these are known as the safety stock, stocking points, and their main goal is to reduce the forecast errors (a factor).

The information decoupling point is "the point in the information pipeline at which the marketplace order data penetrates without modification, and the point where market-driven and forecast-driven information flows meet, the point at which information turns from the high value actual consumer demand data to the typical upstream distorted, magnified and delayed order data" (Mason-Jones & Towill, 1999).

The entire decision-making is based on information that contains a varying degree of uncertainty. In view of the above definition of the information decoupling point, it can be categorised into multiple zones related to the demand, specification, mix, timing, and inventory tasks. The information integrates customer sales and manufacturing, and is exchanged on different business levels: design, production, planning, marketing, communication, order information, and operation. Thereby the traditional material flows through assembly, packaging, distribution, and installation, and perhaps some geographical locations, all controlled by MRP or a similar control system. Figure 5.1 shows the information flow integration with the CODP concept.

The focus in this research is the issue of time and quantity dimensions, irrespective of the financial issue. The decoupling point for each pipeline is classified according to the certainty/uncertainty of each one.

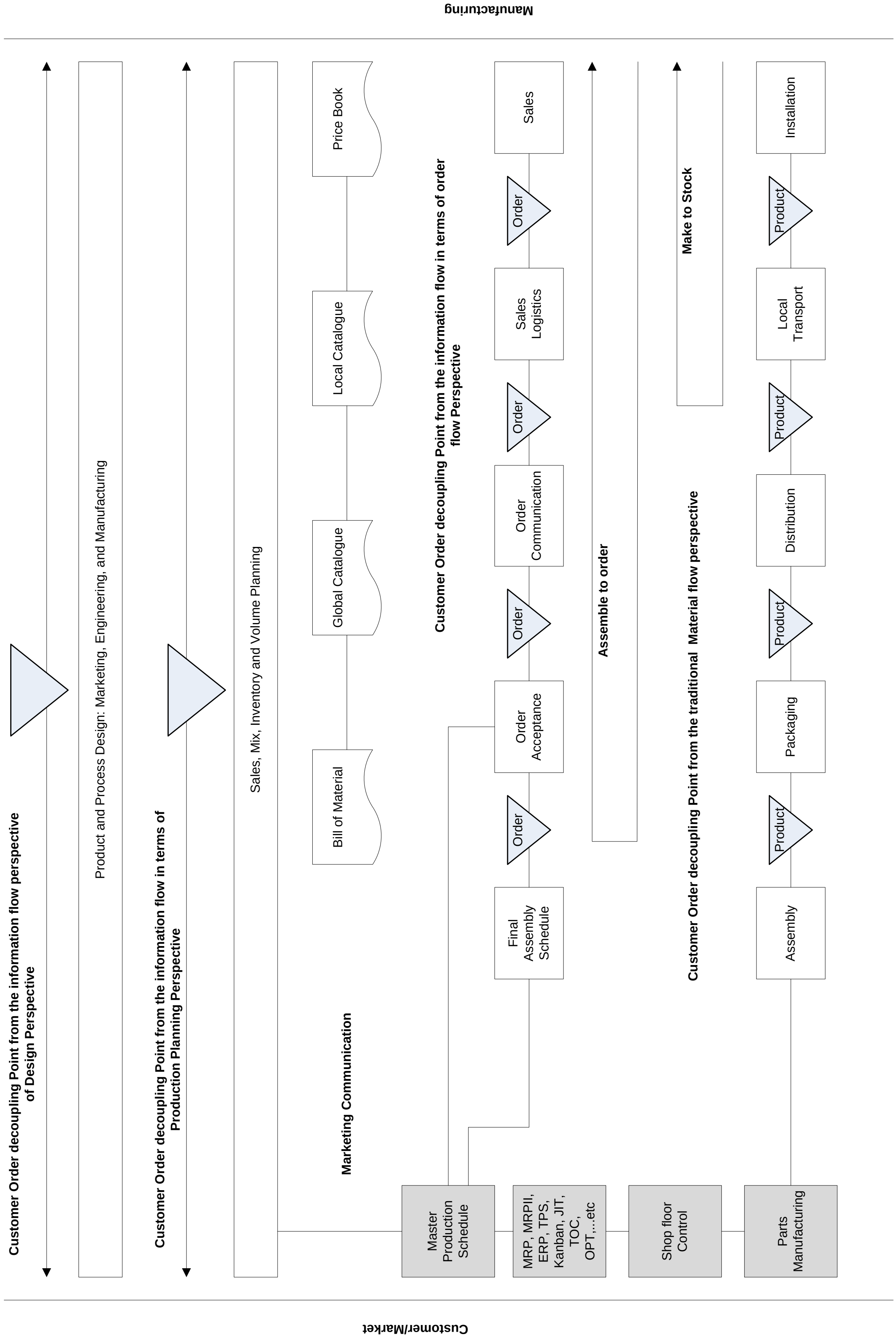

Figure 5.1: Information flow integration

Figure 5.1 shows the generic nature of the information integration that is important in the context of the CODP in relation to production operations. The information order decoupling point from the design perspective ensures real time visibility of the supply chain status for the departments including marketing, engineering, and manufacturing, that need proper coordination of the input information stream of the product and process information so they operate from the same decoupling point and any changes to the nature of the information inputs are immediately available to all the shared departments. The information decoupling point from the production and planning perspective begins with a hierarchy of decisions within the supply chain. This information decoupling point begins with the different operation levels (tactical, medium, and short) and through aggregate planning which follow the production, planning, and scheduling systems (MPS, MRP, MRP II, ERP, Kanban, JIT, TOC, OPT...etc.) that establish the production rates, capacities, mix and inventory. This decoupling point serves as the primary interface between marketing, sales, and production. The aggregate production plan provides the disaggregated production schedule of the particular material decoupling point that follows the combination of the supply chain which establishes the pull-push point in the process through the order flows. The positioning of these decoupling points ensures the right coordination of information and material inputs. This figure shows the generic nature of the material and information integration though the different perspectives which present the managerial decision-making. The effective positioning of these decoupling points determines the required production resources, the efficient use of these resources at all levels of aggregate planning, and optimises the planning system by having a planning procedure that fits through the supply chain departments.

The information considered in this research is related to the following areas:

1. Demand planning (Forecasting)
2. Inventory management (Safety stock planning)
3. Order fulfilment
4. Distribution
5. Production
6. Procurement.

5.1.3 Supply chain performance for modelling formulation process

Agility metrics are difficult to define because of the multidimensionality and vagueness of the concept of agility (Tsourveloudis & Valavanis, 2002). Applications of virtual reality for the simulation and testing of agile manufacturing have been reported by Lefort and Kesavadas (1998), Subbu et al. (1998), and other scholars who show the different views that can be suited to represent agility performance within the different areas.

The resulting factors from the literature review have then been grouped into four categories: direct, indirect, objective and subjective. Direct agility metrics affect the system directly. Indirect agility metrics might have an effect on the performance of the system. Objective indicators can be estimated directly while the values of subjective indicators are dependent on the judgement of the person assessing. Table 5.2 presents a list of grouped factors.

Table 5.2: Indicators of agility within a manufacturing context

	Objective	Subjective
Direct	Responsiveness	Reusability, Reconfigurability, Scalability
Indirect	Organisational measures: Quality, Flexibility, Customer satisfaction, Effective risk management, Innovation, Cooperation, Proactivity, Virtuality, Technology utilisation, Market orientation, Integration	

In consideration of the assumed impact of these factors on system performance and their measurability, a shortlist of the variables that are related to the decoupling points' positions and the performance of the supply chain has been produced. Table 5.3 presents the shortlist, which includes the performance measures and their definitions. These factors were included to represent the measures of responsiveness for evaluation and to help in the model and the system configuration. The list of these factors needed to characterise responsiveness which shows an identification of a final list of defined and measurable variables that is necessary for representing responsiveness quantifiably. These factors are deduced from Council of Supply Chain Management Professionals (CSCMP), based on the Supply-Chain Operations Reference-model (SCOR) (Vitasek, 2010). Also, the factors in the shortlist are recognised in the fields of performance modelling and manufacturing system design. These partial factors: total supply chain response time, cycle time, order fulfilment lead time, manufacturing lead time, delivery lead time, and fill rate, are combined to cover the most quantitative performance metrics of the overall supply chain's responsiveness.

Table 5.3: Shortlist of responsiveness measures (adapted from Vitasek, 2010)

Factor	Description
Total supply chain response time	The time it takes to rebalance the entire supply chain after determining a change in market demand. Also, a measure of a supply chain's ability to change rapidly in response to marketplace changes. Calculation: [Forecast Cycle Time] +[Re-plan Cycle Time] +[Intra-Manufacturing Re-plan Cycle Time] +[Cumulative Source/Make Cycle Time] +[Order Fulfilment Lead Time]
Takt time/cycle time	Can be defined as the maximum time per unit to produce a product in order to meet demand.
Order fulfilment lead time	Average, consistently achieved lead time from customer order origination to customer order receipt, for a particular customer order decoupling point (Make-to-Stock, Make-to-Order, Assemble-to-Order, Engineer-to-Order). (An element of Total Supply Chain Response Time) Calculation: Total average lead time from: [Customer signature/ authorisation to order receipt] +[Order receipt to completion of order entry] +[Completion of order entry to start manufacture] +[Start manufacture to complete manufacture] +[Complete manufacture to customer receipt of order] +[Customer receipt of order to installation complete]
Manufacturing lead time	The total length of time used to process raw materials and components through all upper levels in the bill of materials to an end item. It specifies the total of all individual elements of lead time, such as order preparation, queue, setup, run, inspection, etc.
Delivery lead time	The lead time taken by the product to reach the final destination, the difference between the day it leaves the warehouse and the day it reaches its destination.
Fill rate (target fill rate achievement and average item fill rate)	The percentage of order items that the picking operation actually fills within a given period of time.

Figure 5.2 shows the general integration into a typical performance measure structure.

However, researchers and practitioners have investigated the various processes with manufacturing supply chains uniquely and not the performance design or analysis of the supply chain as a whole. This chapter focuses on multi-stage supply chain modelling and agility through responsiveness assessment. The other measures are qualitative and could be useful for future research in the area of agility as it is such a large part of performance analysis.

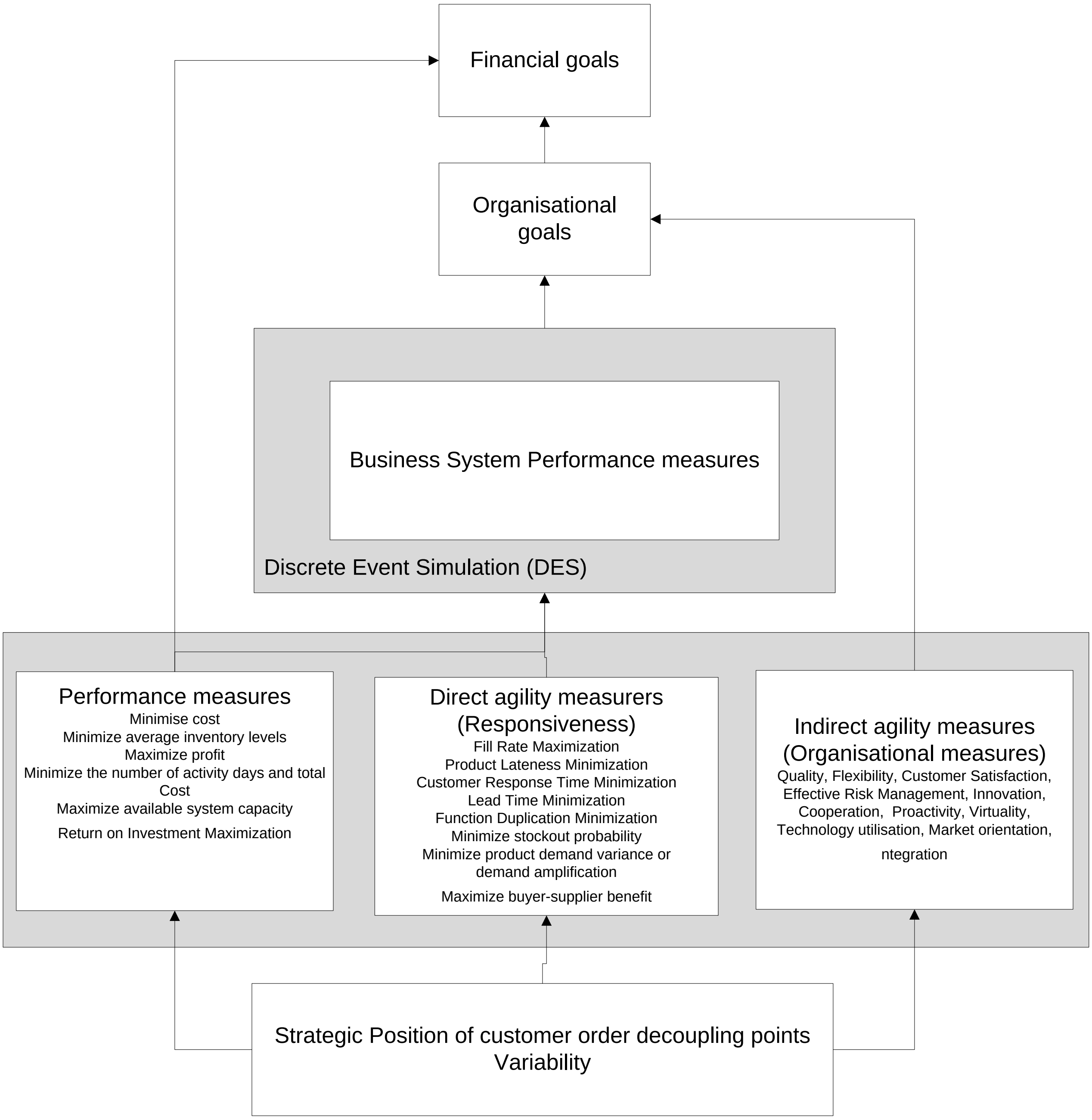

Figure 5.2: Generalised performance measures structure

Upstream of the material decoupling point, the Production Planning and Inventory Control process surrounds the manufacturing and storage sub-processes, and the interactions between them. In particular, production planning reports the design and management of the whole manufacturing process (raw material scheduling and procurement, manufacturing process design and scheduling, and material handling design and control). Inventory control depicts the design and management of the storage policies and procedures for raw materials, work-in-progress inventories, and final products. Downstream of the material decoupling point, the distribution and logistics process affects how products are retrieved and transported from the warehouse to retailers and customers. It contains the management of inventory retrieval, transportation, and final product delivery (Beamon, 1998). Figure 5.3 shows the supply chain process.

These processes act on each other to produce an integrated supply chain. The design and management of the processes determine the extent to which the supply chain works as a unit to meet required agility and performance objectives.

All the measures in Table 5.2 are determined separately for the supply chain type, make-to-order (MTO), engineer-to-order (ETO), assemble-to-order (ATO), and make-to-stock (MTS) products. The elements of order fulfilment lead-time are additive. Not all elements apply to all manufacturing process strategies. For example, for make-to-stock products, the lead time from start manufacture to complete manufacture equals zero.

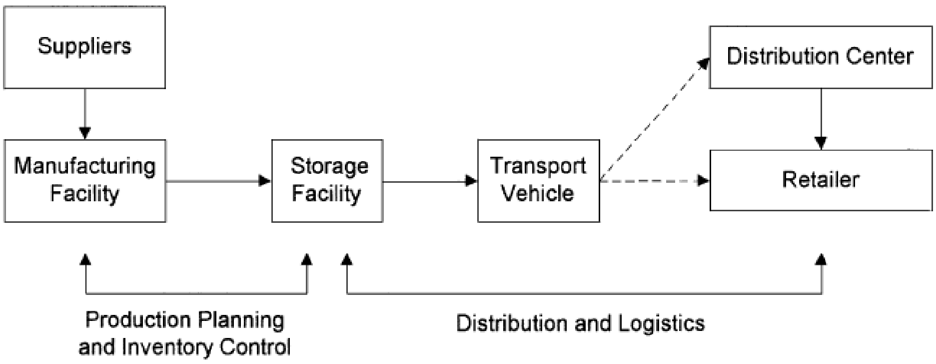

Figure 5.3: The supply chain process (adapted from Beamon, 1998)

The time between the order entry and delivery of the product is the customer order lead-time or service time (downstream process time from the decoupling point). This mainly depends on the supply chain type and the different flow of the companies.

Table 5.4 explains the order lead-time for the different decoupling points.

Table 5.4: Order lead-time for the supply chain types

DP points	Customer order lead-time
Assemble-to-Order (ATO)	The assembly and distribution time
Make-to-Stock (MTS)	The distribution time
Make-to-Order (MTO)	All production processes
Ship-to-Stock (STS)	The distribution and shipping time

Table 5.5 lists all the supply chain parameters that will be used in the study. These include the information and material-related parameters. Some of them are dynamic, which means that the information changes with time. Some are static, such that the information does not change with time. A small subset of parameters is chosen to form a dynamic performance indicator model for the entire supply chain. This research will assume that some parameters are made transparent and shareable between certain configurations to examine their impact on the chosen indicator model. A set of experiments will be explained in Chapter 8 and the information parameters collected are shown in Chapter 7.

Some of the parameters are independent in nature and their values must be supplied at the beginning of the simulation, while others are intermediate parameters with values that are derived during the simulation and are therefore not shown in Table 5.5. The derivation is gathered from the literature and forms a set of relationships or constraints between parameters defined in the simulation model.

Table 5.5: Shortlist of information parameters

Input Parameters	Factors			
CODP position	ETO	MTO	ATO	MTS
Information parameters	Supplier	Manufacturer	Distributor	Retailer
Lead time	L_S	L_M	L_D	L_R
Demand information parameters				
Final Demand Value at time t (item/day)		D_t		
Mean (item/day)		μ		
Standard deviation (item/day)		σ		
Inventory Management Parameters				
Order quantity/Replenishment quantity (items)	Q_S	Q_M	Q_D	Q_R
Reorder point (items)	R_S	R_M	R_D	R_R
Inventory level (items)	I_S	I_M	I_D	I_R
Backorder level (items)	B_S	B_M	B_D	B_R

The information flow considers the order batching that is related to the product specification, which has been discussed by Lee et al. (1997) as one of four possible causes of the bullwhip effect. The periodic order batching creates large waves in demand, with time periods of huge demands or little or no orders. The specifications information corresponds to details that are configured to a modular product: colours, options, accessories, etc.

The batching levels will be based on time intervals between order batches. The information related to demand is demand forecast updating which suggests that demand amplification happens due to the safety stock and long lead-time (Lee et al., 1997). Moreover, the information related to the mix changes is about the ability to change the variety of product produced. Mix information is often used interchangeably with process and job flexibility, and is generally produced in the experiment as the four different response time levels for the different product types may be produced during a particular time period. The response time between product mix changes fluctuates between information shared and response, and information not shared regarding the product mix. Slack (1987) discussed mix flexibility as the time required to produce a new product mix (product mix flexibility response) where T_M is the changeover time required from one product mix to another.

The last type of information is that which is related to due dates and the ability to change planned delivery dates. This type touches different areas of industrial analysis, mainly scheduling. The due date is concerned with a capable-to-promise (CTP) methodology. The response time is calculated from changing the planned due date to a new one. It will be estimated in this analysis by following an order arriving in the system in the case study. The delivery due date's information is moved upstream and represents the movement forward of the planned delivery dates that may be important in supply chain management. This accommodates rush orders and special orders, and will be described as delivery due response time. When the shared time is upstream, this means it will be reduced further and will be defined as T_D which is the delivery time that can be met for a job.

All these information types will each be a function of the response time calculation to simply measure it with the other factors in the experiment. Table 5.6 shows the experiments set for the main information considered.

Table 5.6: Information types considered in the experiment

Experiments	Factors			
CODP position	ETO	MTO	ATO	MTS
Information parameters	Supplier	Manufacturer	Distributor	Retailer
Lead time	L_S	L_M	L_D	L_R
Mix information response time	T_M			
Due date information response time	T_{DD}			
Demand information response time	T_D			
Order batching information response time	T_S			

Also, the information decoupling point levels will be based on demand and inventory management:

1. **Information related to demand**

   End-user demand information suffers from delay and distortion as it moves upstream in a supply chain. Coordination between the echelon in the supply chain through sharing the information and finding the best location for information decoupling points is important to provide a solution to counter this distortion. The demand information decoupling point is the point that separates the demand information based on demand history and other demand information. Demand information consists of end user demand, actual demand, demand forecast, and planned order schedule.

2. **Information related to inventory management**

   The inventory information will be based on the stock policy and system under study, which is classified in Table 5.7. The information in the segment will rely upon the stock policy used. Such a policy utilises information on inventory positions for the upstream and downstream points (inventory on hand, outstanding orders, backorders, and some additional information depending on the stock policy used).

Table 5.7: Information and control (adapted from Silver et al., 1998)

Control / Information	Centralised	Decentralised
Global	• VMI • DRP (some implementation) • **The serial situation** • The arborescent situation	• DRP (most implementation) • **The base stock control system**
Local	• Doesn't make sense	• Order quantities when demand is approximately level with probabilistic lead-time • Lot sizing for individual items with time varying demand with probabilistic lead-time • Individual items with probabilistic demand and lead time • Managing the most important (Class A) inventories with probabilistic lead-time

The information could be classified, as shown in Table 5.7, into two useful dimensions: local versus global information, and centralised versus decentralised. Local information implies that each location sees demand only in the form of orders that arrive from the location it directly supplies, and has its own visibility regarding the inventory status, costs, and so on. Global information implies the decision-maker has visibility of the demand, costs, and inventory status at all the locations in the system. Centralised control is identified as a push system, because the stock is pushed by the decision-maker to the locations that need it most. Decentralised control is identified as a pull system, as independent decision-makers pull stock from their suppliers (Pyke & Cohen, 1990). For example, the inventory in Figure 5.4 shows the information and customer demand stream, and it uses a continuous-review (Q_R, R_R) control policy. A useful classification for the inventory control policy is provided in Table 5.8.

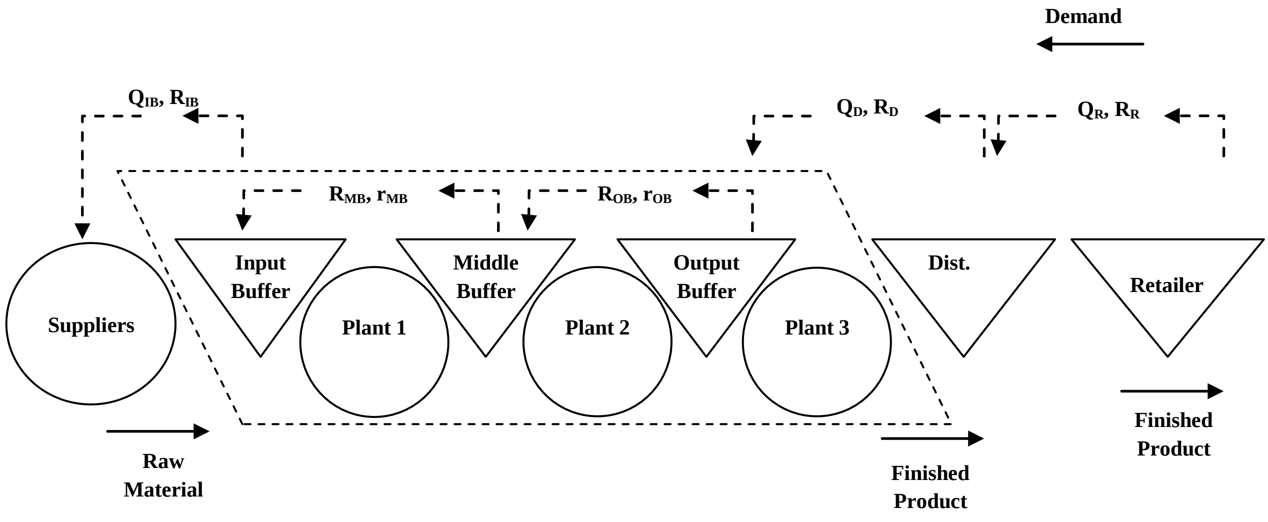

Figure 5.4: A model with inventory information flow

However, there are different variables and information flow for each inventory control policy, whether single/multiple items, single/multiple locations, and the inventory system is based on the control policy and its considered system. Some questions need to be asked regarding the inventory decisions (Silver et al., 1998):

- Should the structure and the coordination be based on long term, deterministic approximations, and a multi-echelon network in the short term?
- Probabilistic demand and lead times?
- Should the inventory stocking and replenishment decisions be made centrally or in a decentralised fashion?
- Should the inventory be held at central warehouses or should these simply be used as break-bulk facilities?
- How should a limited and insufficient amount of stock be allocated to different locations that need it?
- Where should inventory be deployed? Should the inventory be held at a central location, or pushed to the retail level?
- How important is the item: periodic or continuous review?
- What form should the inventory policy take? What specific cost and service goals should be set?

These questions will be presented for the decision-makers in the case study and more insight will help to address the variables to be considered. In addition, consideration of variables are clearly dependent upon the supply chain structure, hence the applied inventory policy will include the inventory variables.

There is a vast amount of literature referring to inventory management and its models and associated issues. When demand is probabilistic, it is useful to conceptually categorise inventories as follows:

1. **On hand stock**: the stock that is physically on the shelf, it can never be negative. This quantity is relevant in determining whether a particular customer demand is satisfied directly from the shelf.
2. **Net stock** = (on hand) – (Backorders)
   This quantity can become negative (namely if there are backorders).

3. **Inventory position** (sometime called available stock): is defined by the relation:
   Inventory position = (On hand) + (On order) – (Backorders) – (Committed)

   On order stock is the stock that has been requisitioned but not yet received by the stocking point under consideration.

   The committed quantity is required if such stock cannot be used for other purposes in the short run.

   The inventory position is a key quantity in deciding when to replenish.

   Backorders occur when an item is temporarily out of stock. Two extreme cases are either complete backordering or complete lost sales, and there could be a combination of both.

4. **Safety stock** is defined as the average level of net stock just before replenishment arrives.

Depending on the categories of the item, A, B, or C, the rules for selecting the form of inventory policy are illustrated in Table 5.8. A represents the firm’s item that has 20% of the total number of items and 80% of sales volume. B items represent 30% of the items and 15 % of sales volume. C items represent 50% of the items and only 5% of sales volume.

Table 5.8: Classification for the inventory control policy

	Continuous Review	Periodic Review
A items	(s, S)	(R, s, S)
B items	(s, Q)	(R, S)
C items	Simple (s, Q)	Simple (R, S)

R is the review interval, s is the order point, Q is the order quantity, S is the order-up-to-level

Continuous review is often called transaction reporting, and is usually not required. Transaction reporting uses manual stock card systems, for example Kardex, VISI-Record, or point of sale (POS) data collection systems (involving electronics scanners), which permit transaction reporting, and are having a profound impact at the retail level.

The periodic review, the stock status, is determined only every R time units. Between reviews there may be considerable uncertainty about the value of the stock level.

5.1.4 Format of CODP representation

Almost all real-world systems contain one or more sources of randomness and it is generally necessary to represent each source by a probability distribution rather than just its mean in the simulation model (Law, 2007).

Information sharing varies according to ordering information coordination, and demand information behaviour can be regarded as a source of system randomness. Law (2007) identifies three different approaches to specifying a distribution if it is possible to collect some data on a random input variable of interest, in increasing order of desirability:

1. The data values themselves are used directly in the simulation
2. The data values themselves are used to define an empirical distribution
3. Standard techniques of statistical inferences are used to fit a theoretical distribution form.

A time series can only reproduce what has happened historically and there is seldom enough data to make all the desired simulation runs. Empirical distribution functions use the data values themselves to define the distribution form. Fitted theoretical distributions are generated by using standard techniques of statistical inference to fit a theoretical distribution form to the data.

The different distribution types all require the same raw data. In the case study, theoretical distribution is used as it is easier to change when required to determine the effect of changing certain parameters on the simulated system. Within this research project it is intended to collect a large quantity of data, and thus represent a real working system. From the collected data, the theoretical distribution is used to fit the observed data reasonably well, and this will generate the observed data for the simulation model even if the values happen to be outside the range of the observed data, which is one of the advantages of using theoretical distribution.

To illustrate the benefits of the information decoupling point, the levels of information zones according to Table 5.6 describe the level of the information decoupling point's situation under a different information-sharing situation. From Table 5.7, the levels of information sharing for the basic optimal inventory policies for each supply chain configuration are as follows:

Level 1: This is "decentralised control", the ideal case, the deterministic demand, the demand rates are known with certainty. It is ideal and accordingly the information decoupling point position is moved upstream as far as possible. Knowing the demand information serves as a basis for establishing the replenishment quantities for the probabilistic case. Using EDI and an effective communication system requires a high level of trust across the supply chain so that the firms are willing to share potentially sensitive information. For the demand information each stocking point makes replenishments based on an actual end-item customer demand rather than on replenishment orders from the next level downstream.

Figure 5.5 shows when the stock point can make replenishment based on actual demand rather than on replenishment orders.

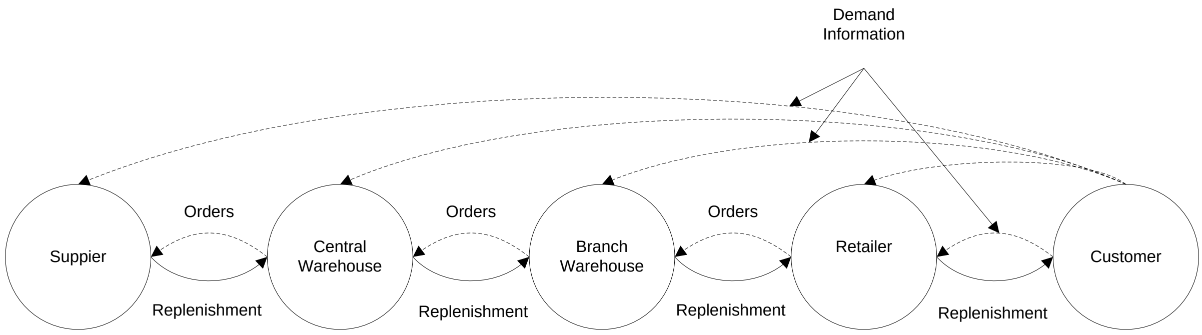

Figure 5.5: The shared demand information flow

For example, as covered in the literature, different decisions for any particular stocking point were based only on its stock position and its direct demand process. The most general (s, S) system is more appropriate for a multi-echelon situation. The following parameters are the independent variables:

Q: an order quantity is established using the end-item demand forecast for each stocking point (there are many methods in the literature about determining Q depending on the demand level, whether deterministic, time varying, or probabilistic, lot sizing, the items, the locations).

s: the reorder point is established by one of the procedures presented in Table 5.7, using end-item demand forecasts over the replenishment lead-time appropriate to the echelon under consideration.

S : is the order-up-to-level; the base stock level is determined by the relation.

$S = s + Q$: : the echelon inventory position is reviewed according to the following relation

Echelon inventory position = (echelon stock) + (on order)

The stock of a downstream echelon is the number of units in the system that are at, or have passed through, the upstream echelon but have as yet not been specifically committed to outside customers.

The on-order term is an order placed by the upstream echelon on the next higher echelon.

The echelon inventory position is reviewed after each transaction/periodic basis. The replenishment lead-time for safety stock calculation at each level must be increased by the review interval. Whenever the inventory position is less than the reorder point s, a quantity order from the proceeding echelon is ordered to raise the position to the base stock level Q.

The ordering decision is based on the end-item demand, not as a result of the orders from the next level downstream.

Level 2: the serial system; its demand information is available to all locations (global control), and decisions are made centrally (central control). The assumptions underlying the decision rules include:

1. External demand occurs only at the retailer and is a stationary process. Conceptually, it can be applied to a process that changes slowly with time where the mean and standard deviation of demand are estimated over suitable durations of time. Normal distribution forecast errors are assumed.
2. A deterministic replenishment lead-time is associated with each stage (L_W, L_R). L_R this only begins when there is sufficient warehouse stock available to fulfil retailer replenishment.
3. The policy used is of the (s, Q) form, that is, continuous review with four parameters:
   S_W = reorder point (based on the echelon inventory position) at the warehouse
   Q_W = order quantity at the warehouse
   S_R = reorder point at the retailer
   Q_R = order quantity at the retailer.

Figure 5.6 shows the serial production flow.

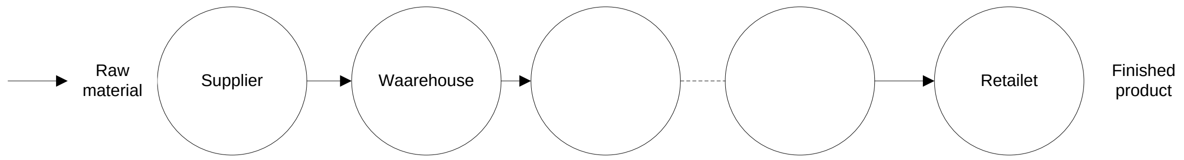

Figure 5.6: A serial production process

5.1.5 Data requirements for CODP modelling

Considering all the points discussed in Sections 5.1.2, 5.1.3 and 5.1.4, it has been decided to enhance the representations of data collected within the DES simulation model of manufacturing systems by assigning their values with some form of distribution.

To build the variables distributions, data needs to be collected during multiple visits to the chosen company. The data has to be in a suitable format for distribution design and needs to be collected over a period of time long enough to have the sample size required to achieve statistic validity.

In order to build distributions to reflect the variables' behaviour, data needs to be collected from the field study of the supply chain through a case study, which is presented in Chapter 7.

5.2 Data Collection for Responsiveness Performance and CODP

For the simulation experiments, CODP positions and all the factors considered in the previous sections need to be modelled through the case study and data collection. This section introduces the experimentation that is conducted to assess responsiveness through the use of CODP positioning in a manufacturing context and retrieve the data required to design the supply chain that is capable of representing CODPs within a manufacturing simulation model.

Section 5.2.1 is concerned with the preparation of the data collection. It discusses the choice of test site, data collection method, and measuring tool. Section 5.2.2 describes the execution of the field study and the results.

5.2.1 Preparation of data collection

Data should be sufficient for generating the requisite performance statistics but no more than that, and to the extent that serves the project's goal (Altiok & Melamed, 2007). The Arena *Input Analyzer* tool is used to provide data analysis in this project.

Section 5.1.4 has identified the model format of input distributions for simulation models designed from theoretical data. The required data are collected by conducting a field study.

Furthermore, this field study is used to investigate the level of randomness inherent in the modelling of a supply chain case based on CODPs, and the effect that different factors have on responsiveness.

In order to maintain contextual validity, the experiment has to be conducted in a real manufacturing environment. Many real life systems incorporate randomness, such as random demand in an inventory system or random processing time. Simulation with random elements is often referred to as the Monte Carlo simulation. This formally means that modelling a random system as a discrete event is introduced into events in two basic ways:

- Event occurrence times may be random
- Event state transition may be random.

The in-depth case study to be chosen must have a supply chain that consists of a manufacturing plant (machines & transport), supplier, warehouse, transportation, and that is serially connected with storage space along the production line to help analyse the CODP concept. The case study chosen according to the early classification by Hoekstra and Romme (1992) can be any of the classified manufacturing systems. The case study details and description will be analysed in Chapter 6.

5.2.2 Execution of data collection

The field study needs to be executed over a period of time in order to represent the system characteristics, and should be sufficient for generating the required performance statistics.

In addition to the variable time performance data, information needs to be collected about a number of contextual factors, which will be shown in detail for the case study, and include processing times and transfer times that affect the product flow.

The next step in the process of developing the modelling is to process the data collected. This has been done using Microsoft Office Excel 2007 and Arena Input Analyzer tool.

5.3 Model Construction and Validation

This section describes the construction and evaluation of the distributions. Section 5.3.1 is concerned with the construction of the model that allows their integration into DES.

Furthermore, the process used to verify the model is described. Section 5.3.2 discusses some observations regarding the model.

5.3.1 Construction of the model

The simulation model has been developed under Arena, release 12 (Appendix A shows a detailed case for choosing Arena). The representation of Mason-Jones and Towill (1999) has been adopted, which suggests that the CODP can be described in terms of information and material flow. According to several studies in the literature, the number of players per echelon is set at one. The retailer receives the final demand D_t, and customer demand is a stochastic, with a distribution that will be fitted from the case study. Each player stores products in a warehouse, with its inventory level set at a defined value according to the policy chosen.

5.3.2 Discussion of the modelling based on CODPs

The supply chain configuration will be examined in this study in terms of the following parameters:

1. **Number of echelon players**

   The number of echelons in the supply chain may range from three to five. In this study, four echelons (supplier-manufacturer, distributer, and retailer) have been considered.

2. **Inventory policy**

   Each supply chain has an inventory policy according to its processes and its order policy. Two inventory policies have been assumed which were described in Section 5.1.3. The reorder process for each echelon can be described as follows:

   - At time t the demand mean μ_t will follow an estimated demand distribution fitted from the case study for a single product, and its standard deviation σ according to the data collected. The demand faced for each echelon at time t is D_t.

- The order up to level will follow the chosen policy for the selected supply chain.
- The supply chain player checks the stock available according to the level of inventory information chosen in Section 5.1.3, and assigns the order quantity.
- Whenever the order is placed, the inventory level is updated, based on the selected policy.

3. **Demand information**

Based on the level of information sharing, which is basically a possible consequence of the adoption of advanced information technology, the demand information D_t is available for some players regarding the experiments that will be set up in Chapter 8.

For each scenario of the simulation run, the responsiveness measure as a direct performance measure, as shown in Table 5.3, will be assessed with its calculations and detailed in Chapter 8.

5.4 Chapter Summary

This chapter has described a structured approach to develop a model that allows the representation of certain aspects of responsiveness assessment through the decoupling points using DES modelling. Two factors have been considered for the representation: CODPs from the material, and information perspectives. The data required to design the model has been collected via a long-term field study, which will be detailed in the following chapter, processed and then used to create the model. The results of the experiment in Chapter 8 demonstrate the different levels of CODPs that exist within the case supply chain.

Chapter 6

Industrial Case Study

6.1 Introduction

This chapter introduces the design and implementation of an operational simulation model for the case study, a supply chain of a steel manufacturer, Hadeed, whose products are sold worldwide, though most of its customers are in Saudi Arabia. The objective of this simulation study is to understand the different aspects of the Hadeed supply chain and to analyse a number of factors that have an influence on supply chain performance in terms of decoupling points' positions, by tracing the material and information flows. It should be noted that any simulation study cannot cover everything in a supply chain system, and this study is based upon the addressed objectives and the selected items in that system. In this chapter, the different simulation steps are applied in a real case study in order to analyse the decoupling points' positions and how to test the hypotheses in a real problem situation.

The main aim of the study is to present an illustrative example problem. The upstream and downstream linkages, in different processes and activities that produce value in the form of products and services in the hands of the ultimate customer, are the objectives of supply chain management (Christopher, 1999).

6.2 Selecting the Case Study

As discussed in the research design, the experimental research used relies upon the theoretical framework of positivism. Also, the focus in this case is on using quantitative methods. The choice was to conduct the case study at Hadeed as a field experiment focusing on make-to-stock (MTS) and discrete production, compared to the literature cases studies which focused on assemble-to-order (ATO) and/or make-to-order (MTO), to analyse and verify the theoretical concepts to achieve the goal of the study.

In the case of field experiments, the setting where they are carried out is a natural and realistic environment. When the natural environment is an organisation, they are better known as "experimental organisational research" (Bryman, 1989).

Due to the limited number of cases that can be studied in case study research and the expense of a simulation study, it is more appropriate to have one case study of a polar type or extreme situation where the phenomena of interest is “transparently observable” (Pettigrew, 1990). Also, several authors, explicitly or implicitly, support the notion of selecting one single case study to examine a phenomenon, such as Mitchell (1983), Merriam (1988) and Stake (1995).

6.3 HADEED Company

The Metals Group is a major part of the Saudi Basic Industries Corporation (SABIC), which has a diversified manufacturing portfolio in Saudi Arabia. Today, it is wholly owned by Hadeed (Saudi Iron & Steel Company), the leading steelmaker in the Gulf region. Since 1983, Hadeed has produced long steel products for the Kingdom’s construction industry and contributes to the infrastructure and development of some 34 countries across the region and beyond. Its output now includes flat, hot and cold rolled steel for expanding Saudi and regional engineering and manufacturing industries. Hadeed is the first fully integrated steel producer in Saudi Arabia, producing rebars and wire rods since 1983, in the Jubail Industrial city. SABIC is the foremost non-oil company in the Middle East. It was established in 1976 on a 4.4 sq. km. plot in Al-Jubail Industry City and was the first complex in the kingdom of Saudi Arabia, coming on stream in 1983 with an original design capacity of 800,000 (metric) tonnes/year.

The success of any industry depends on the extent of its competitiveness in the international markets. The steel industry is the backbone of industrial progress for any community. Hadeed was established as a strong steel industry. It is an integrated plant that uses the direct reduction process and adopts state of the art technologies to produce long products including rebars, wire rod, light section and flat products. A significant achievement of Hadeed is being ranked the fifth in the world among iron producers that use the direct reduction process. It also occupies a strategic position among the largest steel producers in the world. Today Hadeed is the largest steel company in the Middle East, one of the largest fully integrated complexes of its kind in the world, and an active member in the International Iron and Steel Institute.

SABIC’s vision is to be a leading global manufacturer and marketer of hydrocarbon and metal products, which include basic and intermediate chemicals, polymer resins and polyesters, fertilisers, metals and industrial gases. Through successive technical enhancements and expansion, Hadeed's annual production capacity has risen to exceed 3.5 million tonnes of finished iron and steel products.

The production process goes through three stages. The first is in the direct reduction plant where the iron ore or the raw material is treated to extract the oxygen atom from the material exported from Sweden and Brazil. The second stage takes place in the steel plant, where the material is melted and shaped in the semi-final shape, called billets, before it is sent to the rolling mills. In the rolling mills, the third and final stage, the billets are reheated and reshaped into the finished products. Then, the products are transferred to the dispatch area before it is shipped to the customer.

The annual production capacity of Hadeed is about 4 million tonnes of both long and flat products. These products are of the finest quality in the world. Consequently, in 1994 Hadeed's products received the ISO 9002 certificate.

Many internal and external projects were built using Hadeed's steel. Some internal projects are:

- the two Holy Mosques expansion
- King Fahad airport, Dammam
- The Ministry of Interior building, Riyadh
- SABIC main buildings in Riyadh and Jubail
- King Fahad Sports Stadium
- Al-Faisaliyah Tower, Riyadh
- Kingdom Centre, Riyadh.

Some of the external projects are:

- Communication Tower, Kuwait
- Emirates Tower, UAE
- Arab Tower, Dubai
- Abu Dhabi National Bank.

Egypt, Hong Kong and the United States are other exporters of Hadeed's products. Hadeed's vision is to be the main supplier of steel products in the Middle East and North Africa.

6.4 HADEED Company Products

The feedstocks are Iron ore, Scrap iron and Steel. Hadeed produces iron and steel products; these products are produced in many different shapes, sizes, thicknesses, and lengths, and can be classified into the following categories:

1) **Rebars**: produced in different thicknesses (6,8,10,12,14,16,18,20,22,23,25, and 40 mm). Figure 6.1 is a picture of flat bars.

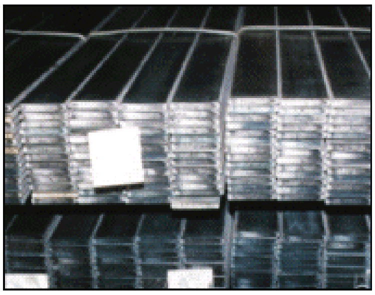

Figure 6.1: Flat bars

2) **Section bars**: produced in different shapes and thicknesses: 14 mm, 12.7 mm in thickness and equal angle, unequal angle, channel, flat, and square shapes. Figure 6.2 is a picture of section bars.

Figure 6.2: Section bars

3) **Rod**: produced in different diameters (5.5 mm up to 16 mm). Figure 6.3 is a picture of wire rods.

Figure 6.3: Wire rods

4) **Billets**: this is the original form of the above three categories before being shaped and cut. Figure 6.4 is a picture of billets.

Figure 6.4: Billets

6.5 Case Study Modelling

Two main aspects of Hadeed are considered in this case study: material flow and information flow. The following sections have been designed for the material flow that takes place through four main zones in the integrated steel plant: iron making (Direct Reduction Modules), steelmaking (Steel Plant: Electric Arc Furnaces), steel casting (Steel Plant: Billet Casters) and rolling mills (Bar Mill, Rod Mill, Section and Bar Mill, Bar and Rod Mill Plants). These four zones consist of a group of ten production stages, detailed in Figure 6.5.

The Direct Reduction Plant receives the raw material and feeds iron ore direct to the steel plant, which converts the raw material into billets at the end of its production. Mill Plants convert the billets into the finished products: rebars, sections, and rods. The distribution echelon consists of the warehouses and the transportation networks that move the final items to the customers. The logic behind these divisions was an attempt to make the development of the model more efficient. Figure 6.5 shows the highest level of the Hadeed supply chain and the decoupling points along the supply chain. Figure 6.6 shows the potential positions of the material decoupling points.

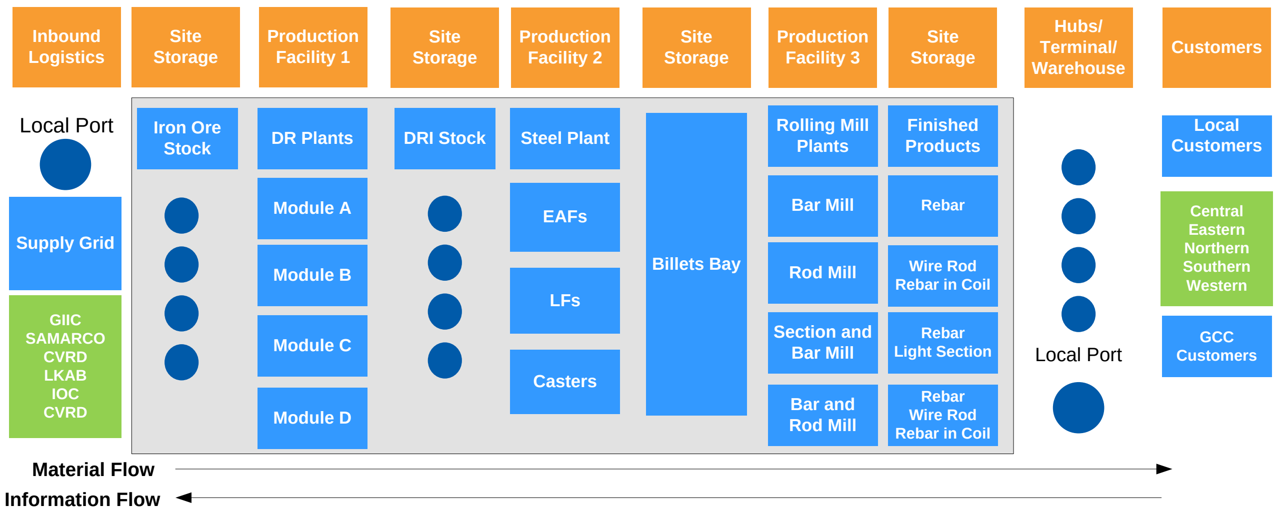

Figure 6.5: Hadeed supply chain flow schematic

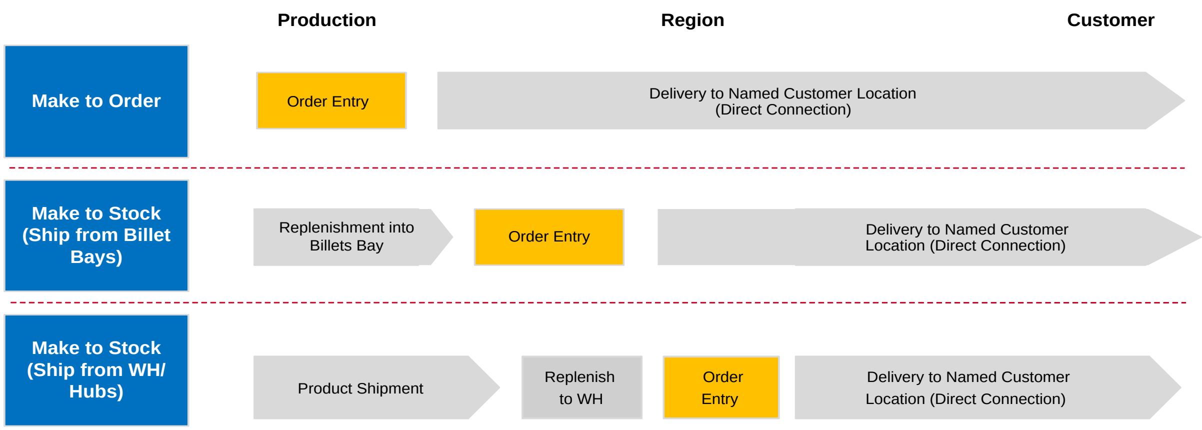

Figure 6.6: Positions of the material decoupling points

The Hadeed case is complex as it is composed of multiple echelons that are subject to different events, for example: Order arrival, Inventory updating, Order triggering, Order shipment.

The following sections of this chapter discuss how elements of the Hadeed case study are modelled.

6.6 Material Flow Process Modelling

Figure 6.5 shows the Hadeed network, which focuses on flows within its supply chain.

There are only two categories of major raw materials, i.e. iron ore and scrap, whose flow has been modelled as one combined product since they have the same inputs for the next stages in production, as shown in Figure 6.5. The material flow has been considered unidirectional, starting from iron ore and resulting in finished steel. The numerous categories of finished long steel products have been grouped into four categories, namely bars, section bars, rods, and billets. The model does not differentiate the finished products of steel based on sizes and grades since they are made to stock. They are only represented by tonnage.

In the model, the production plant is considered as a unified whole, consisting of the main equipment as well as auxiliaries. The details of the individual sections, machines and equipment are not considered. In the case study, where a number of production shops of different capacities exist, they are represented in the model as the same number of production shops with an average capacity, keeping the total capacity the same. For example, there are three blast furnaces in the steel plant, each having the same capacity and size. These have been represented in the model as three blast furnaces of an average size and capacity. Similarly there is no distinction made in the model between the variety of sizes and grades of material being fed to a shop.

A generic structure of a production line consists of twelve stages through the material flow. The integrated production flow, therefore, is influenced by the information flow feedbacks. Configurations will be changed during the experimentation to interact the simulation model with different scenario inputs to see the behaviour of production and inventory.

6.6.1 The direct reduction plant

There is always sufficient raw material in storage so the steel plant never starves. Also, the process from the ship's arrival and to the steel plant is a continuous process that starts with delivering the raw material (iron ore) and goes through different chemical processes that intend to remove the oxygen (O_2) from the iron ore; this step will help the steel plant to save energy in melting direct reduced iron (DRI). This model generates the iron ore arrivals to the steel plant, the next echelon. A module has been created to generate the scrap arrival and iron ore. It is assumed in this case study that there is unlimited inventory since there has not been any starvation in the steel plant, and the fact that it is a continuous process that will not add a value in our modelling. The study models the handling of raw material in an integrated steelmaking plant, considering the operations of receiving, unloading, stocking, handling and supplying the different raw materials related to the production process within an operational perspective. The aim of the modelling of this process is to help in the decision making of controlling the ore inventory. This part of the production plant is not random or stochastic, but deterministic, while exhibiting behaviour considered satisfactory by management and steelyard team alike. The unified supplier to the steel plant including the capacities and processing time has been considered in this part of the model without going into the details of the continuous processes, as it is not of interest in this study. Figure 6.7 shows the sub-components and the flow of the first stage of production at Hadeed.

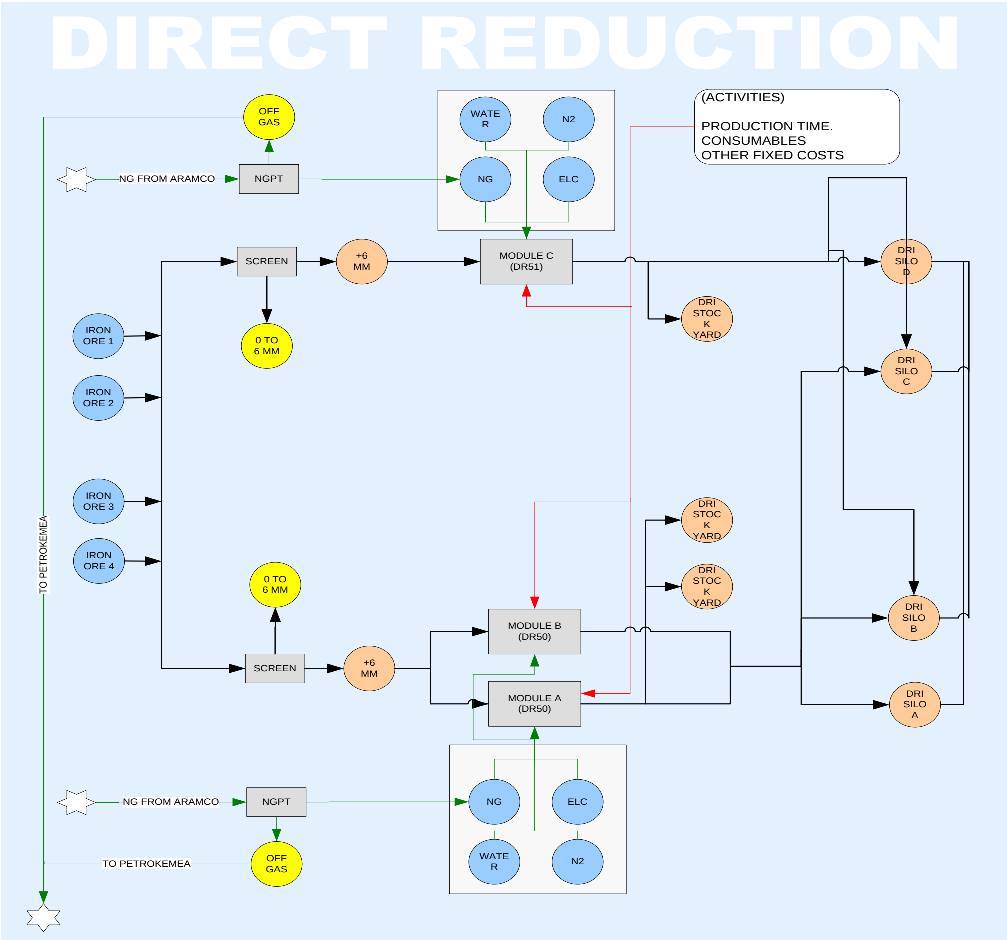

Figure 6.7: DR sub-assemblies and material flow

Table 6.1 provides the supplier and capacity of raw material received by ship.

Table 6.1: Hadeed suppliers

Raw Material Supplier	Capacities
Brazil	
Vale	1.44 Mt/y
Samarco	1.66 Mt/y
Canada	
IOC	0.5 Mt/y
Sweden	
LKAB	2.4 Mt/y
Bahrain	
GIIC	1.9 Mt/y

The discrete aspect has been used in the continuous system to simulate and analyse the performance of the processes at this stage and afterwards, which makes the material flow discrete, treating it as a series of 'portions', obtaining results that are statistically similar to the behaviour of the real system.

6.6.2 The steel plant

Steel is produced at Hadeed from liquid iron ore by using the basic oxygen process. Iron ore arrives at the steel plant and is poured into 150-tonne ladles, and then the sulphur is removed through one of two units. It is then charged into one of three basic operating system vessels where the iron ore is converted into steel. At this stage alloying elements are added to control the finished steel's properties. This 150-tonne unit of steel is called a cast. Additional secondary steelmaking processes are then carried out depending on the grade (selected according to the end use of the steel being made). Typically around 50 out of over 1,300 grades are produced each week. These processes are carried out at one of three Ladle Arc Furnaces (LAFs) and two Vacuum Degassers (VDGs). The chemical analysis, homogeneity and temperature of the steel must all be closely controlled to ensure that the steel is fit for purpose. It has been assumed for simplification in this model not to consider the different grades and the varieties of a product due to their complexity and wide range.

After steelmaking has been completed the cast is sent to one of three continuous casting machines where it is cast into a precise solid section for dispatch for further processing or end use. Groups of casts, called sequences, of identical or similar grade are processed through the casters without a break. The timing of arrival at the casters is critical; if a cast is delayed the sequence may be broken, incurring a costly and time-consuming machine reset and the logistical problem of holding or recycling the delayed cast of steel.

The steel plant is arranged in a series of bays. Movement of both empty and full ladles is carried out using cranes (within bay movements) and steel cars (between bay movements). Figure 6.8 shows the subcomponents and flow of the second stage of production at the steel plant.

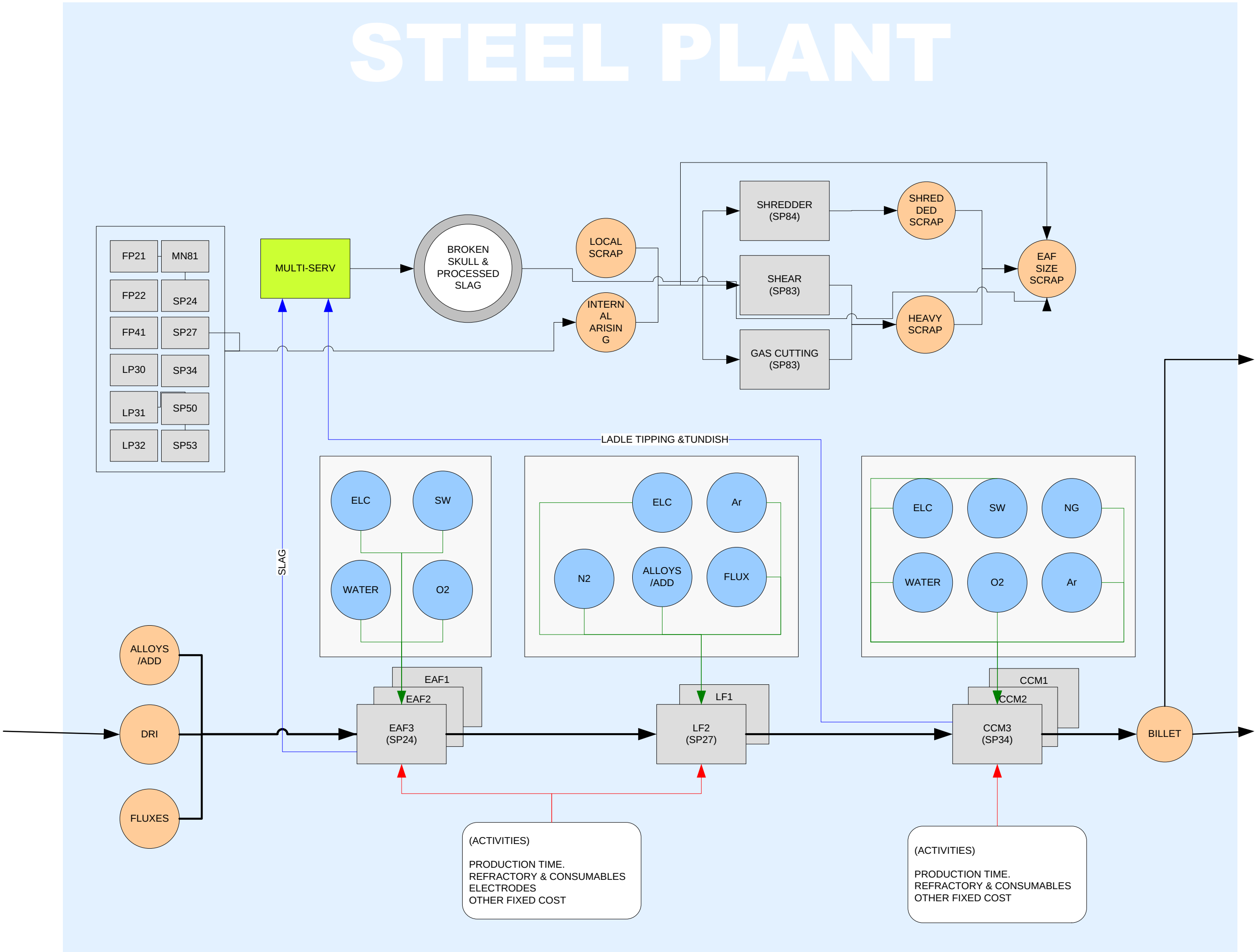

Figure 6.8: The steel plant sub-assemblies and material flow

6.6.3 Billets bay

The billets bay is one of the major stocks where billets are saved and marked after exiting the steel plant and before sending to the rolling mill. The capacity of the billets bay is approximately 120,000 tonnes divided into two sections: A and B near to the rolling mill; and C and D near to the steel plant. It has been modelled using assign and hold modules in Arena to control the release of the production at the steel plant and rolling mills. Usually, billets are produced from casters:

1. Go to Rod Mill, and caster
2. Go to Bar Mill, and caster
3. Go to Sections and Bar Mill
4. Go to Barod Mill.

6.6.4 Milling

Having created the billets, they are moved to the milling plants according to product type, either rod or bar. The process modules have been used to show the milling production followed by an assignment to update the inventory level of the warehouses following the milling processes. Rolling mills' long product has four units: Bar Mill, Rod Mill, and sections Bar Mill and Barod Mill. Each mill has been modelled using a process module followed by an assign module. Figure 6.9 shows the subcomponents and flow of the third stage of production at the rolling mills' plants.

6.6.4.1 Bar Mill

The Bar Mill converts 130 mm^2 steel billets into reinforced concrete bars for the building industry as per internationally recognised quality standards. It can produce bars of 14 mm to 40 mm in size. Billets come from a steel plant to the billets bay of the rolling mill. The billets are reheated to the desired rolling temperature and then rolled into rebars of 12 to 40 mm diameter by 12 m as a standard length with a standard bundle weight of 2 tonnes. The annual production capacity of the Bar Mill is around 1.2 million tonnes of rebar.

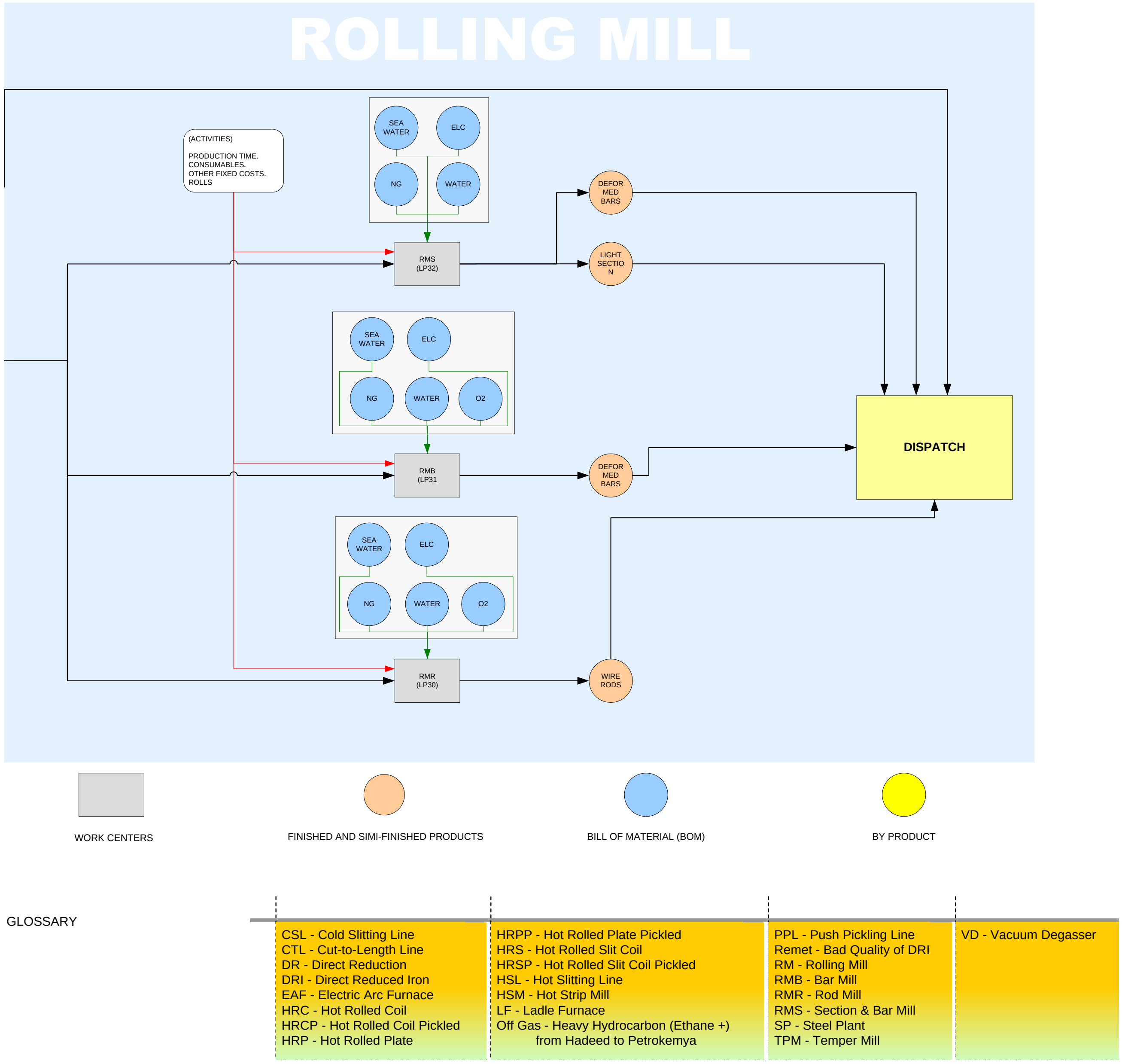

Figure 6.9: The rolling mill plants' sub-assemblies and material flow

6.6.4.2 Section and Bar Mill

This converts 130 mm^2 steel billets into concrete reinforcing bars and light sections for the building industry as per internationally recognised quality standards. This flexible mill has an annual production capacity of over 800,000 tonnes of light sections and rebars. The sizes of rebars range from 10 to 32 mm. The light sections include angles in sizes of 30 x 15 x 4 to 75 x 40 x 5 mm, squares of 10 to 25 mm and flat bars in sizes of 25 x 5 to 100 x 6 mm. The total production capability is over 70 profiles.

6.6.4.3 Rod Mill

The Rod Mill converts steel billets into plain, deformed reinforced wire rods for the building and manufacturing industry as per internationally recognised quality standards with sizes between 5.5 mm and 16 mm, and the annual production capacity of the Rod Mill is approximately 800,000 tonnes. It can be plain or rebar in coil.

6.6.4.4 Barod Mill

The Barod Mill has two lines, one for bars from 8 mm to 40 mm, and the other for wire rod plain coil from 5.5 mm to 16 mm, also wire rod rebar in coil from 6 mm to 16 mm.

6.6.5 Logistics

The dispatch section has the responsibility of submitting the final product to the customer in the correct size and quantity. This section deals with sales by receiving inquiries concerning orders. Production planners update the data in SAP daily to notify dispatch staff to release material. Dispatch submits around 10,000 tonnes daily. They control from 260 to 300 trucks daily and each truck can carry 30 tonnes.

6.6.6 Long finished products

1. **Billets**: are semi-finished steel products. They are obtained by continuously casting steel or rolling ingots on a rolling mill, and are used as a starting material in the production process of other long products.
2. **Bars (reinforcement bars)**: are rolled from billets. Merchant bars and reinforcing bars (rebar) are two common categories of bars. Merchant bars include rounds, flats, angles, squares, and channels that are used by fabricators to manufacture furniture, stair railings, and farm equipment. Rebar is used to strengthen concrete in highways, bridges and buildings.
3. **Rods (wire rods)**: are semi-finished products used as feed for wire mills or raw material for nuts and bolts. Some wire rods are also sold to building contractors and other steel processing plants. Sizes: 5.5 mm to 12 mm (wire rods).
4. **Rebar in coil**: are ring-shaped coils. They are used in the automotive, construction, welding and engineering sectors. Round steel bars with diameters ranging from 5.5

mm to 16 mm that are hot-rolled from billets and coiled at the end of the rolling process. Sizes: 8.0 mm to 12 mm (rebar in coil).

5. **Structural sections**: are shapes produced in a rolling mill from reheated billets. They include wide-flange beams, bearing piles, channels, angles and tees, and are used mainly in the construction industry.

6.7 Information Flow Modelling

The discrete events modelling of the information flow is presented according to the experiments and factors considered in Chapters 5 and 8. The information flow follows the definition of the information decoupling point as the point that separates the order information that relates to actual orders versus distorted data in terms of order requirements (mix, demand, timing, and specification). The model is an extension of the information decoupling point idea to position and track varieties of information decoupling points and break down the information based on its certainty in relation to the order. A delay module is used to represent the response time for each dimension to analyse and verify the information flow in relation to the measures of responsiveness. The case study was used to demonstrate the different types of information data available to help investigate responsive performance using the simulation tool, which helps in finding the cause and effect relationships of events. Figure 6.10 is a conceptual representation of the information decoupling points for each type of information flow that is considered in the analysis.

Hadeed uses supply chain management with the APO system, which mainly focuses on the planning side and consists of five processes that are harmonised across all SABIC SBUs. The positions of the information decoupling points have a serious impact on planning and order fulfilment data on SAP. Since the main material decoupling point strategy is MTS at Hadeed, with a shorter service time, the forecast-driven activities are so important, that is, demand planning, and inventory management. The aim of the following sections is to track the information tasks that influence the material decoupling point position. Hadeed produces few large sizes of their products as MTO, but this case study analysis is restricted to one pure material decoupling point. For the information decoupling points, the proposition above in regard to information flow analysis has been followed in the case study and limited to supply chain management with APO modules and its applications.

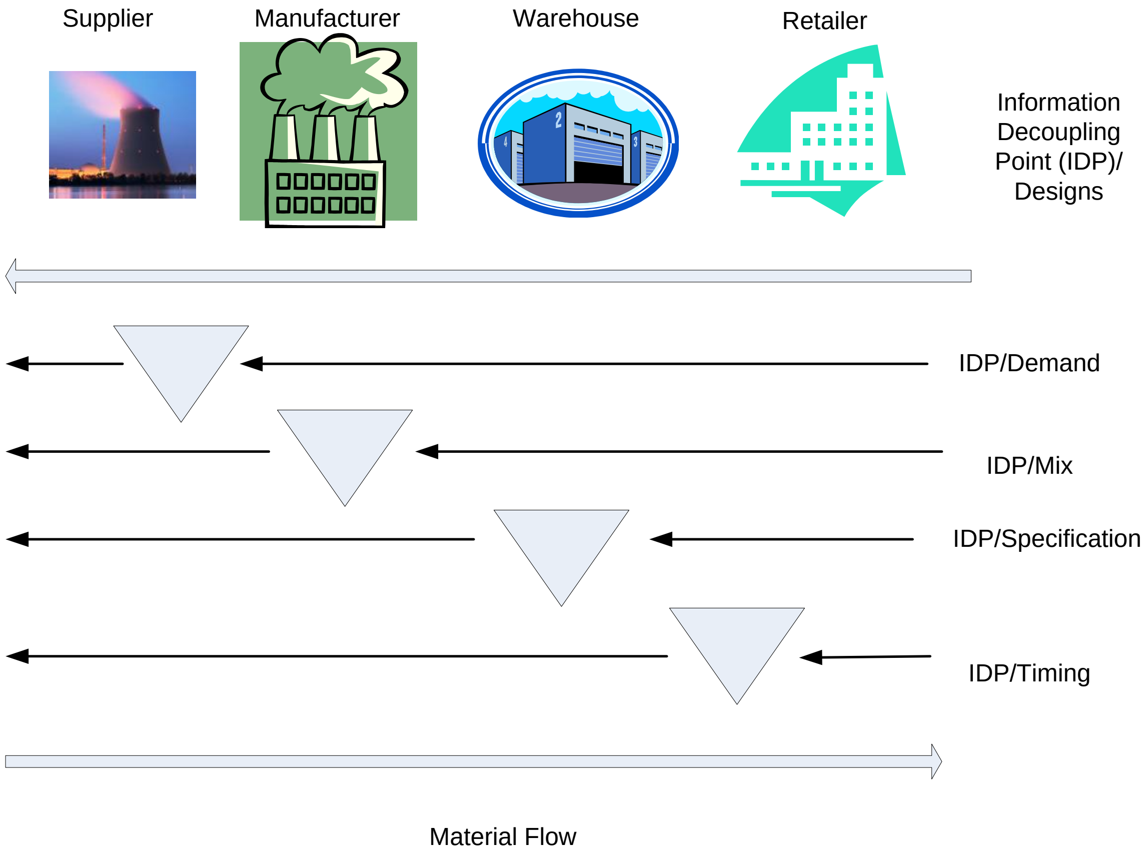

Figure 6.10: Information decoupling points' positions for each information type

The structure of the following sections is based on the information decoupling point's analysis and on the events analysis. The data for the analysis is based on the case study, and the modelling started with the order-related information based on the mix, demand, specification, and timing. Viewing the information order in a discrete event way as a series of interactions helps in specifying the response time needed for an event.

Hadeed uses SCM with the APO system, which mainly focuses on the planning modules. There are more than 400 transactions in SCM and a truly deep and vast body of software applications, which is beyond the scope of this project. The focus here is on the range of penetration of information flow within the supply chain, and the modelling focuses on the lead and response times for each of the information decoupling points as mentioned above, and how to represent the dynamic aspects of them are shown in the following sections. The type of information flow shown in Figure 6.10 is concerned with the following, which are discussed in Chapter 7:

- Demand
- Mix

- Specification
- Timing.

The formulation of the information decoupling points considers the customer's requirements in terms of the order and product characteristics. The case study of Hadeed was analysed to identify the decision points that affect the information penetration positions and influence the responsiveness and certainty of acknowledging the orders. The sequence of the information flow events will differentiate depending on the type of material decoupling points (MTS, MTO, etc.) and the kind of industry and products. The study of these decisions involving the order entry to the system is viewed simply as an order point, which supports the decision making that consequently will maximise the responsiveness and agility of the firm. Figure 6.11 shows the modules of the Hadeed case in general as per supply chain management with APO.

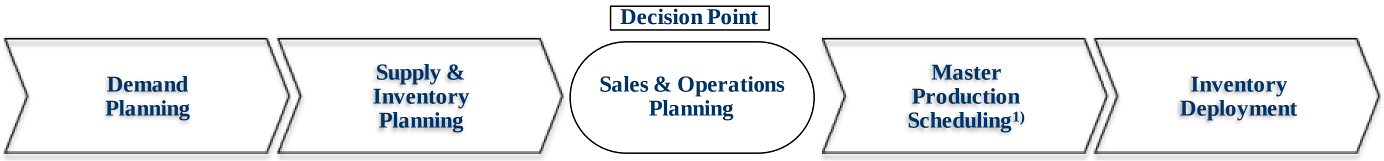

Figure 6.11: Supply chain management with APO at Hadeed

The information flow basically goes through the supply chain management process with APO modules. Figure 6.12 (a, b) shows workflows and the planning processes for the order from entry till the displacement between the different departments.

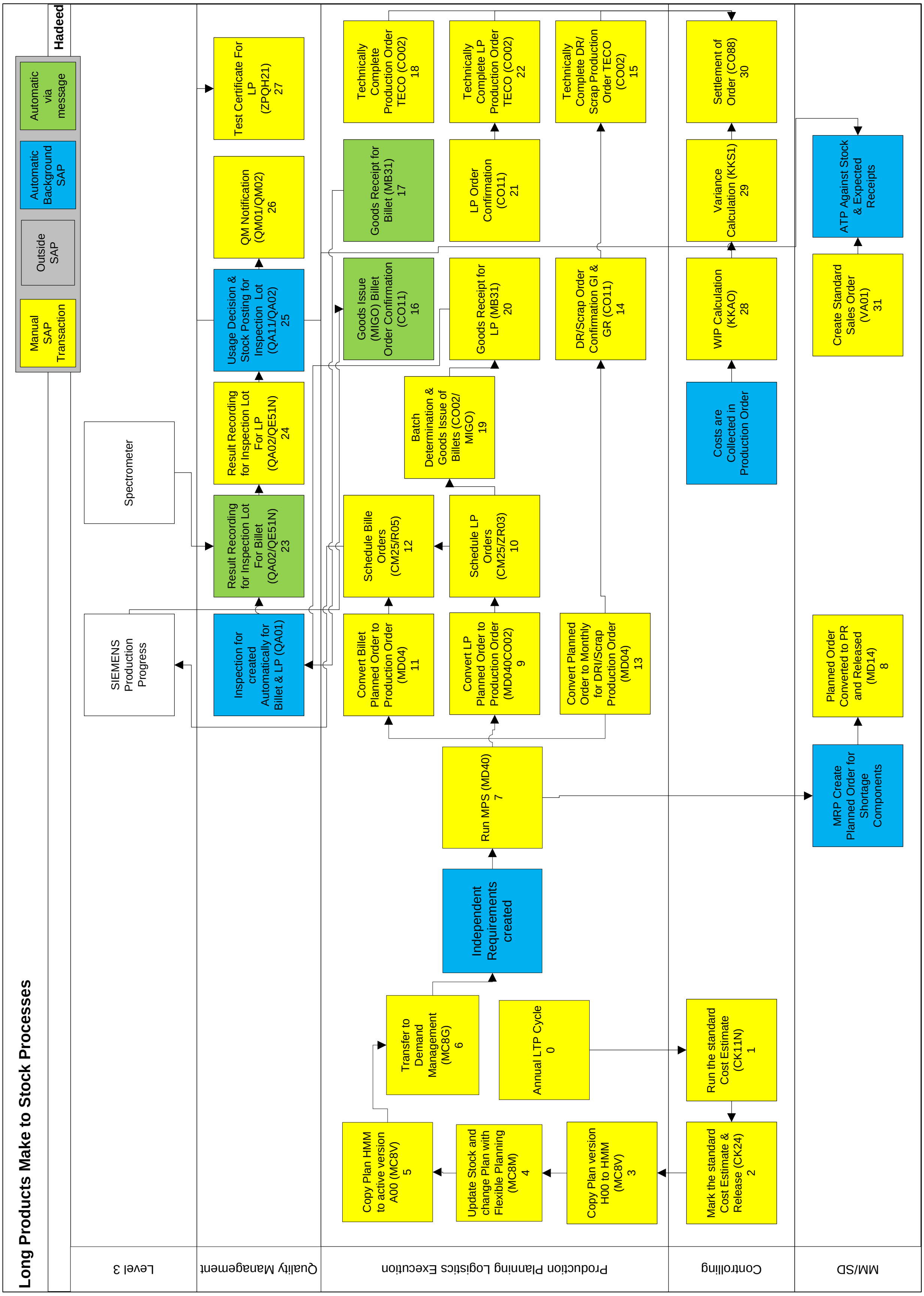

Figure 6.12: Order control system (a)

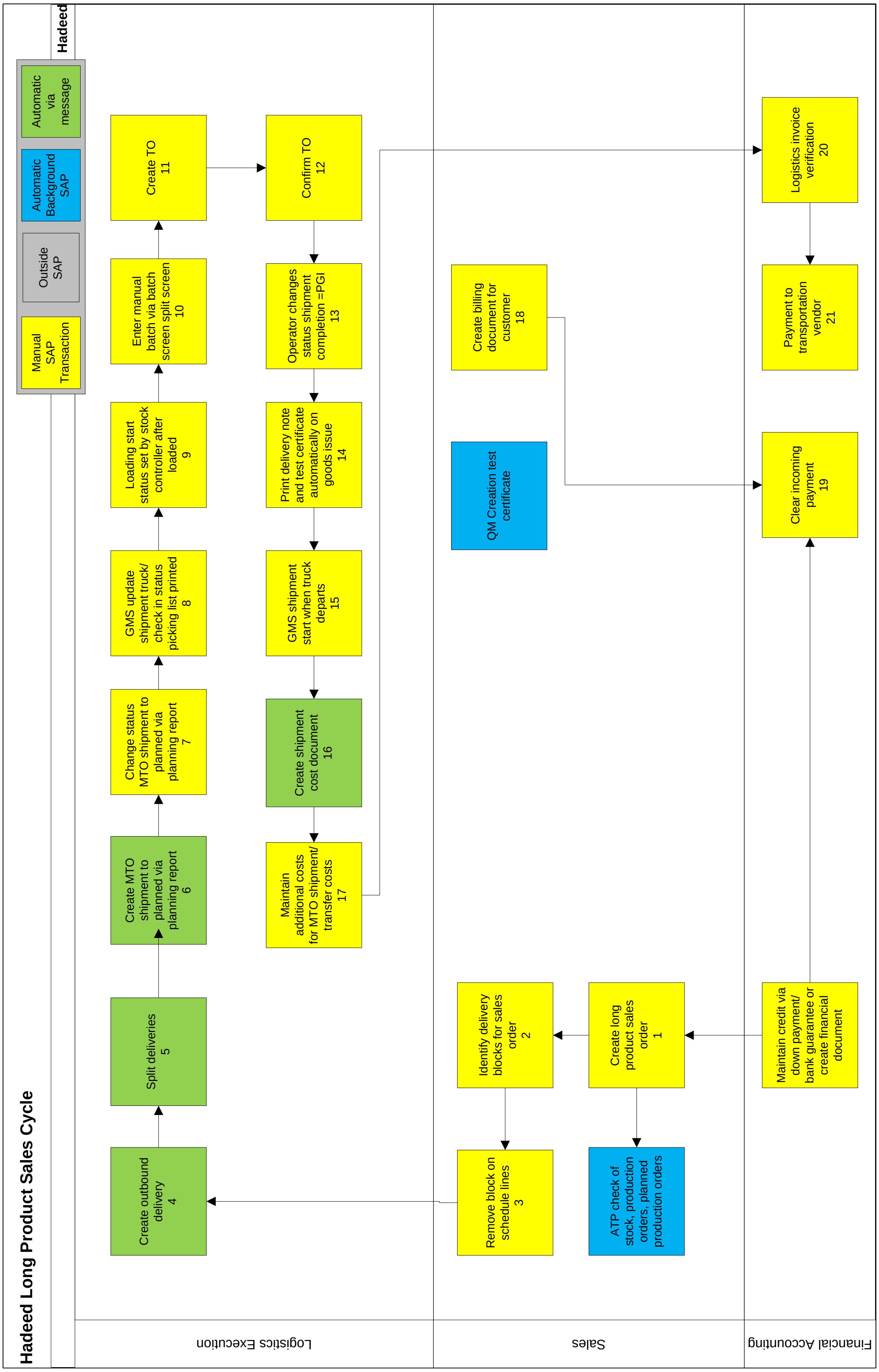

Figure 6.12: Order control system (b)

6.7.1 Information flow-mix/specification

This part of the information regarding the order is controlled by the Supply Chain Planning Master Production Scheduling and Level 3 Production Planning. Hadeed forecasts the end product mixes with the planning process as outlined in Figure 6.13. The product mix in the material flow starts at the steel plant according to the master schedule of the end products. The information about the grades and the production orders is released in advance before receiving the customer orders. If there is a need to change or reconfigure an order, the planning horizon could include the changes for the next run.

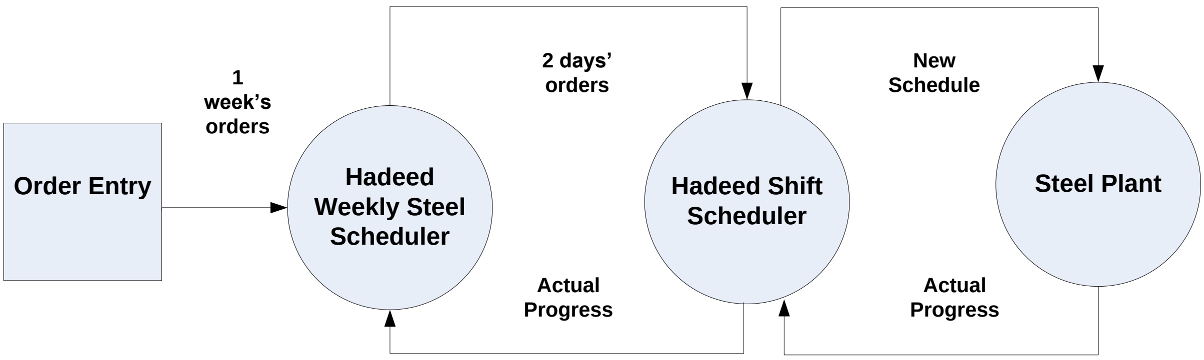

Figure 6.13: Order entry at the steel plant

The master production scheduling represents the short-term detailed planning of the agreed Sales and Operation production plan. Production planning produces a monthly plan for the steel plant which includes the varieties of products sequenced, based on a detailed production system according to the available Bill-of-Material (BOM), routing, and cascading requirements for each of the plant work centres.

The final output of the master production schedule is a daily production schedule for the plant. For the steel plant schedule, the different composition grades will be listed in the same schedule but in different containers (tundish). For the rolling mill schedule they produce the different grades in the same campaign by taking into consideration the optimum operating conditions (for example, the campaign usually starts with high carbon grade).

6.7.2 Information flow – demand

The demand information in the decoupling point is the point of sale. The optimal case is having the customer demand information shared and upstream. This will affect the base-stock supply chain. All echelons base their replenishment on local stock and work-in-progress levels, local sales, downstream incoming orders and actual marketplace demand.

The demand information for the planning is controlled by a Supply Chain Planning module – Demand Planning module. The bases for the demand planning are historical data, sales force estimation and contracts, statistical forecasting, etc. The output is the creation of a realistic unconstrained demand within strategic boundaries for a rolling 18 to 30 months' plan.

6.7.3 Information flow – quantity

According to the demand plan, production capacity, logistic capacity, and inventory targets, the quantities can be shared upstream in terms of the planning, and downstream for the base case and scenarios. The sales and operations planning is a consensus decision-making process based on a feasible plan between the Demand Planner, the Supply and Inventory Planner, the Logistics Representative and the Business Manager for the products under his responsibility. The supply and demand balance scenarios are discussed, focusing on the inventory position, the fulfilment of the original unconstrained demand plan as well as production and logistics capacities. The outcome is an agreed Demand Plan, Supply Plan and Logistics Plan.

6.7.4 Information flow-timing/quantities

Global Available-to-Promise (gATP) offers a logic which enables SABIC to promise its customers reliable delivery dates based on resource availability and allocation decisions. The ATP and CTP quantities compute the quantities needed for the material decoupling point. gATP provides the business with the required information instantaneously to make accurate decisions.

gATP is a fundamental function of APO. It confirms whether a customer's request for a given product in a given quantity at a given time can be honoured. The function triggers an online search through the existing current data as represented in SAP live Cache. Figure 6.14 shows the gATP logic at Hadeed.

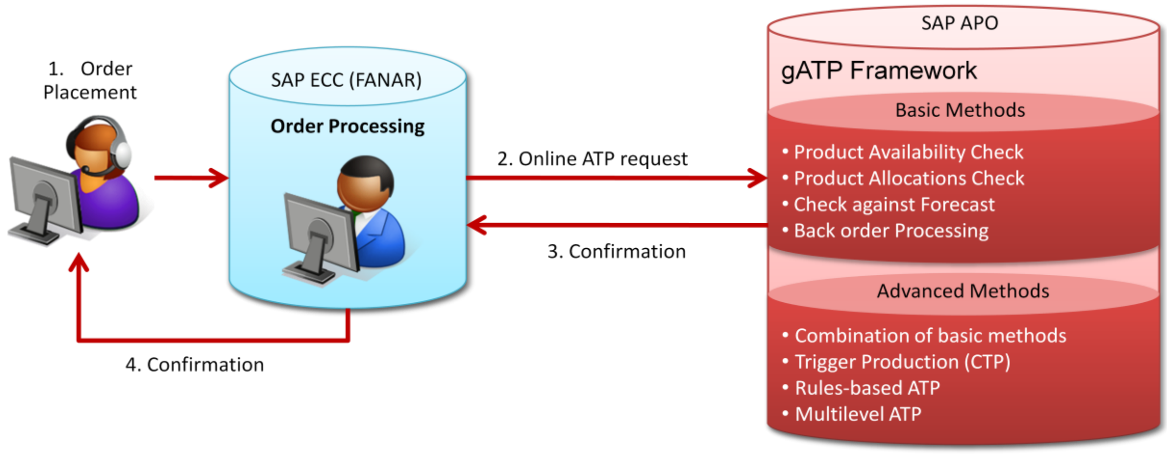

Figure 6.14: gATP logic at Hadeed

The sales order entry is performed in R/3 either manually (for orders by telephone) or per EDI, and then followed by an ATP check that is carried out in APO during the sales order entry. Backorder processing is performed in APO, and the results are sent back to the sales order to R/3. gATP combines information from both the planning and the execution. Global ATP in SAP Supply Chain Framework is represented in Figure 6.15. During the sales order entry, gATP checks the product availability and generates reservations. During delivery, gATP checks the product availability only.

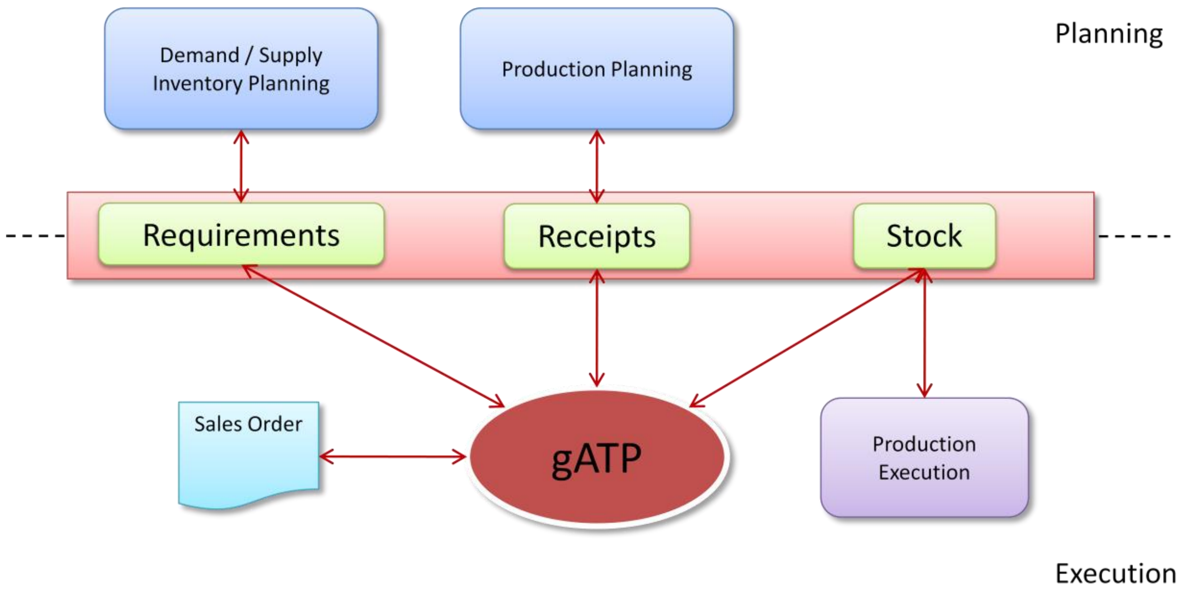

Figure 6.15: Global ATP in SAP supply chain framework

6.7.5 Delay/response time analysis of the information flow

To analyse the response time or delay time of this information, the methodology is to consider the point in time that a request for an order is about to join the queue of orders, which resembles the transactions to the CPU or disk. The expected total waiting time of an order is based on the historical data collection for the orders requests at Hadeed, and usually the ordered quantities are received in advance and fulfilled according to agreement with the customers based on contracts. However, it is simply modelled as a delay module for each type of information proposed. Arriving orders are modelled as entities that arrive and wait in the queue until all the orders are fulfilled within the agreed period of time.

If the purchased items can be ordered within the order lead-time offered to customers, this does not constrain the flexibility of the Master Production Schedule (MPS) as they can be purchased to customer order (Browne et al., 1995), so the mix information has not made any changes to the orders since the orders are satisfied within an agreed period of time. The same case applies for the specification or grades of products, as Hadeed creates all the production jobs (with varying routing and material requirements) on an annual basis with rigid schedules in response to customers' product specifications, contract and agreement. In the Hadeed case the information flow with the types of information could not be an effective approach.

The model for the information flow was simulated for the month as a demand of an inter-arrival time of the orders to generate the total volume of demand with having two main products flows: one for the rebars and the second for the rods. Product demands are inclined to be stationary at most of the inventory points.

Most of Hadeed's sales volume is to several customers with whom long-term relationships have been established. All long-term sales contracts are restricted for one or more calendar years. The total volume that the customer is committed to order in a year is specified in the contract. The replenishment lead-time is more than three months.

6.8 Chapter Summary

In this chapter, the Hadeed case was presented as a study for the simulation experiments. It included a presentation of the Hadeed profile and its material and information flows. The data collected has relied upon four resources: interviews, observations, documents, and questionnaires. Appendix C describes the Hadeed supply chain in detail with the rotation during the visits. The analysis of the case study was based on interviews with company employees, and data analysis. Having the necessary data from each echelon in the Hadeed supply chain allowed for simulation preparation and understanding the processes that govern the Hadeed supply chain. It also helped in exploring the characteristics of the case simulation design. This chapter addressed the preparation of the data collected and the framework developed in Chapters 5 in order to address the research questions. It analysed the case study to support and prepare for the experimentation and scenarios analysis for the next chapters. It showed the possible material decoupling points, and the type of rigid information flow reflecting the high demand environment driven that relies upon demand planning and forecast, as orders from customers are based on contracts and agreement.

Chapter 7

Simulation Modelling for Responsive Supply Chain

The impact of the CODPs' positioning on responsiveness is assessed using simulation modelling and following the methodology discussed in Chapter 5, also applying the input factors that are important in terms of having a major impact on responsiveness to explore the combined effects of these factors on output. This chapter describes the development of simulation modelling, an investigation using the case study, the planning for data collection, and serves to assess the accuracy of the manufacturing system simulation model, considering all input factors, and simulation experimentation.

Section 7.1 is concerned with the formulation of the experimentation-run characteristics and data requirements. Section 7.2 describes the planning, execution and processing of the system data collection. Section 7.3 explains the construction of the simulation model. Finally, Section 7.4 provides a summary of the chapter.

7.1 Experiment Formulation

Kelton et al. (2010) state that before starting any analysis, the analyst should design a complete set of experiments to conduct, and they identify three types of analysis which should be considered when structuring the experiment to be performed. These are:

1. **Candidate analysis**: this is normally done during the early design phases of a system. It identifies the best candidate systems from a large group of potential designs. These usually lack details.
2. **Comparative analysis**: this is normally the next logical step in selecting the final system design. It compares a finite set of designs and identifies the best one.
3. **Predictive analysis**: this deals with only a few systems – often only one. It estimates the actual performance of the system.

Since this case study is to be conducted using an existing system, the second type, comparative analysis, will be applied and the experiments will compare the best design for the goal of maximising responsiveness. Hence, this section discusses the experiment's formulation while Chapter 8 explains the experiment's construction.

Section 7.1.1 discusses the choice of the initial main simulation model that builds the foundation of the experiment. Section 7.1.2 describes the simulation software that has been used to develop the model. In addition, it discusses the reasons for choosing Arena as the most suitable software for creating the models. Section 7.1.3 concentrates on the derivation of experimental factors and performance measures required from the simulation model to enable the assessment of the CODP-based model. Section 7.1.4 develops a conceptual model for each of the simulation experiments

7.1.1 Choice of initial simulation model

It was also required that the manufacturing systems represented in the simulation model are already established to allow data collection for modification, enhancement and validation of the initial simulation model.

The initial simulation model has been built to represent a similar system to the one used for the in-depth case study, to derive the best combination of CODPs and parameters. This has been done for contextual validity. The simulation model represents the automated production line of Hadeed which can be further classified as a high production, MTS, flow/serial line, with a product layout according to Groover's (2001) classification of production systems. The simulation model reflects the supply chain/production system that represents Hadeed's processes. The host company is located in Saudi Arabia and is still in operation. Access has been granted for information and data collection. Chapter 6 describes the case study for the simulation modelling.

7.1.2 Simulation software and suitability of Arena for the problem under consideration

For creating the models for the supply chain systems under consideration, Rockwell Automation's Arena version 12 was selected over other available software for the following reasons:

1. It has the ability to model the dynamics aspects of manufacturing systems
2. The Arena package was readily available
3. It has the ability to represent performance measures
4. It has the ability to support decision-making variables
5. It has the ability to close the gap between different levels of the simulation model.

A simulation software survey conducted by Swain (2009), which is shown in Appendix A, presents Arena as the most popular choice for manufacturing system analysis, being suitable for detailed and complex modelling of large manufacturing systems. Also, Arena supports the usage of theoretical distributions for representing the variables. Although using a distribution within Arena is relatively simple, an effective modelling of such stochastic elements requires accurate input distributions. (More about simulation modelling in supply chains can be found in Appendix A.)

7.1.3 Preliminary experimental design

The system analysis process should generally follow a well-defined sequence of steps: problem formulation, project planning, system analysis, model creation, data collection and analysis (Seila et al., 2003). Once the model is built, simulation runs can be carried out to evaluate system designs and decisions. This is the first step of the experimentation and analysis.

Seila et al. define the term experimental design as "the selection of input parameters values and other conditions, decisions, or policies that can be specified in the model". Several common measures of performance can be obtained from a simulation study, which can be grouped into different categories. Law (2007) addresses the general performance measures of simulation in manufacturing, which are listed in Table 7.1.

Table 7.1: Examples of common measures of performance obtained from a simulation study

Measure
Throughput
Time in system for parts (cycle time)
Times parts spend in queues
Times parts spend waiting for transport
Times parts spend in transport
Timelines of deliveries (e.g. production of late orders)
Sizes of in-process inventories (work-in-progress or queue sizes)
Utilisation of equipment and personnel (i.e. production of time busy)
Lengths of time that machine is broken, starved (waiting for parts from previous workstation), blocked (waiting for a finished part to be removed), or undergoing preventive maintenance
Preparations of parts that are reworked or scrapped

The performance measures that have been chosen for the simulation experiments are listed in Table 7.2, some of which are built into Arena.

Table 7.2: Chosen performance measures

Measure	Format
Total supply chain response time	Time series, histogram, mean, standard deviation, minimum and maximum
Takt time/Cycle time (time in system for parts)	Time series, histogram, mean, standard deviation, minimum and maximum
Order fulfilment lead-time	Time series, histogram, mean, standard deviation, minimum and maximum
Manufacturing lead-time (throughput)	Time series, histogram, mean, standard deviation, minimum and maximum
Delivery lead-time (times parts spend in transport)	Time series, histogram, mean, standard deviation, minimum and maximum
Fill rate (target fill rate achievement and average item fill rate)	Average
Times parts spend in queues	Time series, histogram, mean, standard deviation, minimum and maximum
Times parts spend waiting for transport	Time series, histogram, mean, standard deviation, minimum and maximum
Sizes of in-process inventories (work-in-progress or queue sizes)	Time series, histogram, mean, standard deviation, minimum and maximum
Utilisation of equipment and personnel (i.e. production of time busy)	Average

The next step in the preliminary experimental design is the choice of experimental factors. Law (2007) explains that input parameters and structural assumptions composing a model are called *factors*, and output performance measures are called *responses*. Table 7.3 shows the factors and levels for the experiments.

Table 7.3: Experimental factors for simulation experiments

Factors for experiments	Levels			
Number of players for echelon	No. of suppliers, manufacturers, distributors and retailers			
Inventory policy	Order quantity/replenishment quantity			
Demand information/response time	Standard deviation of demand/response time			
Material CODP positions	ETO	ATO	MTO	MTS
Order batching sizes/response time	Batch quantities/response time			
Lead times	Lead times for the echelon players			
Variety/specification response time	Response times for the product types			
Due date response time	Response times for the dates changes			

7.1.4 Conceptual model design

To be able to design a simulation model that represents a system in an appropriate way, a thorough understanding of the system has to be developed first. This can be achieved by means of a conceptual model. Although effective conceptual modelling is vital, it is also the most difficult and least understood stage in the modelling process (Law, 2007). Some attempts have been made to provide such a framework that goes back to Shannon (1975) who describes four steps: specification of the model's purpose; specification of the model's components; specification of the parameters and variables associated with the components; and specification of the relationships between the components, parameters and variables.

Robinson (2004) offers a definition for a conceptual model: "The conceptual model is a non-software specific description of the simulation model that is to be developed, describing the objectives, inputs, outputs, content, assumptions and simplifications of the model." This definition highlights the non-software specificity of the conceptual model and the components of such a model. In the model domain the aims are to agree on the model, determine an appropriate level of simplification/abstraction, communicate the model, validate the model and identify data requirements (Robinson, 2006). A range of methods has been proposed for representing and communicating simulation conceptual models; the most popular techniques are: event graphs (event worldwide), activity cycle diagrams (activity worldwide), and Petri Nets (process worldwide) (Seila et al., 2003).

An alternative to these methods is to use the graphical modelling of a simulation software package. In this research, the graphical modelling with Arena was used, which does not require detailed coding of the model but a basic outline of the components of the model and some of the details associated with it.

Within the field of discrete-event simulation it is apparent that there is no agreed way of describing simulation models. This is somewhat different to the case in system dynamics modelling where models are either represented using causal loop diagrams, or stock and flow diagrams (Sterman, 2000).

As the systems under study are existing facilities, previously developed layout plans could be used as the basis for the conceptual modelling. The layout plans include the required information about the process flow and the components involved in the process. The data collected includes a description of the processes in terms of tasks and processing times. The following sections show samples of the collected data through observation, documents that have been validated by comparison between them, questionnaires, and inspection of the real systems of the case study.

7.2 Data Collection System

Data collection is an important step for any simulation study. In this project, the supply chain for the considered case, the Hadeed plant, had been visited multiple times in order to understand the system and to collect the required data. The data was collected through interviews with engineers and by observation methods. The main idea was to understand the system with the proposed factors such as customer demands, as-is supply chain operations, and as-is performance. A variety of data has been collected and will be explained in the following sections, including: demand history, time required for each process, production policy used at each echelon, and lead time of the echelons.

7.2.1 Planning the data collection system

Effort should be made to set a systematic approach for the data collection process in order to integrate data from different sources. Appendix C shows the involved rotations for data collection and Chapter 6 presents the case study description. The approach goal for data collection was to examine the combinations and make the model transferable, which allows solving the model with different input data (from other settings, testing hypothetical scenarios). In this section a summary of the data collected for the simulation study is presented. The supply chain is divided into a number of segments as shown in Figure 7.1. The sequence and description of supply chain echelons are:

1. **Suppliers**: supply the raw material (iron ore) in large amounts from different countries (Brazil, Bahrain and Canada) to Hadeed.
2. **DR Plant**: converts the iron ore to direct iron ore, which is basically removing the oxygen atom from the iron ore.
3. **Steel Plant**: turns solid “raw” materials into liquid steel using furnaces and going through different processes, and ends by solidifying the poured steel in billets using casters.
4. **Milling Plants**: Bar Mill, Rod Mill, Section and Bar Mill, and Barod Mill; these four milling plants produce the final products from the billets into either bars or rods.
5. **Logistics**: dispatches the finished products to the customers.

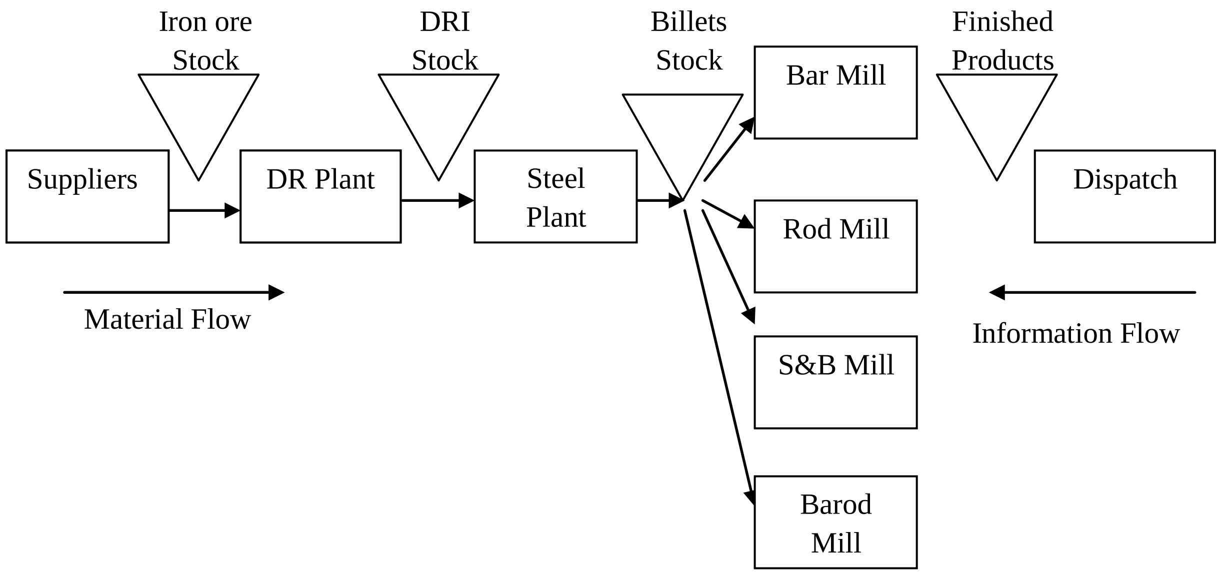

Figure 7.1: Hadeed supply chain

The main data collected for each echelon are:

- Entities inter-arrival times (customer demands, billets arrival)
- Processing times and capacities (for each resource)
- Failure times/repair times
- Production quantities

- Inventories between echelons.

7.2.2 Execution of the data collection system

Table 7.4 illustrates the collected data for each echelon for production operations in terms of processing times and capacities.

Table 7.4: The operation time and capacities for each echelon and its resources

Echelon	Operation time	Capacity (tonnes)	Capacity (billets)
Suppliers Ships at port	4 hrs unloading	165,000	90,164
Direct Plant		170,000	92,896
Module A	180 tonnes/hr		
Module B	180 tonnes/hr		
Module C	132 tonnes/hr		
Steel Plant			
EAF 1	75 min	150	82
EAF 2	75 min	150	82
EAF 3	55 min	150	82
LF 1	20-35 min	150	82
LF 2	20-35 min	150	82
Tundish	25-30 min	150	82
CCM 1	70-80 min	14	8
CCM 2	70-80 min		
CCM 3	70-80 min		
Bar Mill	42.92 sec/billet	152.36 t/hr	
Bar & Section	64.43 sec/billet	103.92 t/hr	
Rod Mill	67.3 sec/billet	97.73 t/hr	
Barod Mill	124.48 sec/billet	77.8 t/hr	

The capacity of each resource is in tonnes and is seized by the operation time. For simplification and unification of the simulation modelling, a conversion table is provided in Table 7.5. For example, the furnace capacity is 150 tonnes, which means that the lot size is 150 tonnes for scheduled time, which according to Table 7.5 equals 80 billets after casting.

Table 7.5: Conversion table

1 tonne DRI	**=**	**1.4 tonnes iron oxide**
1 billet	**=**	**1.83 tonnes**
1 cast (heat)	**=**	**80 billet = 150 tonnes**
Truck load	**=**	**25 tonnes/truck**
30 tonnes	**=**	**15 bundle or 16 coils**
15 bundle	**=**	**1 band**

The average quantities produced on a daily, monthly and yearly basis are shown in Table 7.6.

Table 7.6: Production quantities

Echelon	Average Daily Production	Average Monthly Production	Average Yearly Production
DR			2,937,387
Module A	180 tonnes/hr		
Module B	180 tonnes/hr		
Module C	132 tonnes/hr		
Steel Plant	9,244	43,524	2,912,125
Bar Mill	3,608 (2,021 billet)	99,796	1,197,550
Bar & Section	2,494 (1,339 Billet)	68,163	817,950
Rod Mill	2,345 (1,284 Billet)	56,413	676,960
Barod Mill	1,364 (796 Billet)	9,504	423,260 (Rebar) 106,960 (Rod)
Dispatch	9,114	45,300	3,232,550

Table 7.7 shows the inventories for all the materials and capacities between echelons in tonnes.

Table 7.7: Inventories quantities

Material	Min	Optimum	Max
Iron ore	500,000	870,000 (71,617)	1,300,000
DRI	200,000	350,000	500,000
Scrap	150,000	200,000	250,000
Billet	130,000	135,000	150,000
Rebar	60,000	75,000	90,000
Coil	20,000	25,000	30,000

Table 7.8 shows the transfer times between the echelons and capacities.

Table 7.8: Transfer data between stations

Transfer	Capacity	Time
Port-to-Hadeed (length = 12,759 metres)	2,200-3,000 tonnes/hr	43-45
Silos to day bin	200 tonnes/hr	2
Tundish to casters	22-25 tonnes/hr	56
Basket charging		3 min
Delivery to customer		
To Dammam	1 day	
To Riyadh	2 days	
To West	4 days	
To North/South	4-5 days	

The full capacity of the production line is in tonnes/hour for any product type without considering machine and conveyor breakdowns. Therefore, the product quality/specification for the type is not included in this project. Based on the collected data, the production line works 24 hours/day. Down time data are presented in Table 7.9.

Table 7.9: Down times for components

Component	Down time (hrs/month)
Steel Plant	22
Rod Mill	58
Bar Mill	53
Section and Bar Mill	53
Barod	72

7.2.3 Processing the collected data

This stage of the input analysis is the focal point in the data modelling. The probabilistic model is fitted to empirical time series data. Independent observations were modelled as a consequence of Independent identically distributed (IID) random variables. The task was merely to identify (fit) a “good” distribution and its parameters to the empirical data. As stated, the software used was Input Analyzer, the built-in Arena facility for fitting distributions to empirical data (Altiok & Melamed, 2007). The sample data was fitted into distributions via Input Analyzer. It served in recommending the class of distribution and associated parameters.

7.3 Simulation Modelling Approach

This section explains the simulation modelling of the case study and testing the position of the information flow decoupling point upstream in the supply chain and the physical material decoupling point downstream. It discusses the representation of the material and information decoupling points of the Hadeed case study and aims to fulfil the objectives of the research programme, which are given in Chapter 1.

The simulation models are developed to investigate how varying the decoupling point's position impacts on the responsiveness of the supply chain, that is, to respond to the needs of the customers. The developed structured approach (Chapter 5) focuses on the responsiveness characteristic.

Section 7.3.1 describes the logic of the material flow in the simulation model. Section 7.3.2 shows the representation of the information flow logic and its coordination with the material flow. Section 7.3.3 introduces the simulation model description including the assumptions made during the model's development, the model logic's description, and the model variables used.

The focus on responsiveness was considered during the development of the structured methodology, as it is the most applicable performance measure in simulation modelling for business competition in the steel industry. A working definition of responsiveness has been inferred from the work of various authors on the subject (Aitken et al., 2005; Christopher et al., 2004, 2005; Jones, 2006; Stalk & Hout, 1990) as:

"The ability to reduce the cycle time of the supply chain, filling an order faster than competitors, and reducing processing time decisively and within an appropriate timescale to be able to respond to customers' demands and changing requirements."

The focus is on the cycle time to find the best configuration that satisfies the customer's needs for delivery requirements while forwarding the information flow upstream and fixing the material decoupling point.

7.3.1 Material flow representation

Models in material flow simulation, which is an application of discrete event simulation, are growing in size and level of detail (Chwif et al., 2000).

The Hadeed case study simulation focuses on the highest level of the supply chain. The raw material is transferred through the sequence of echelons, which is already detailed in Chapter 6. Figure 7.2 shows a simple format of the material flow.

The model logic was developed to maintain a sufficient number of units (Arena entities) through the processes. The material flow was initially modelled as sequential processes or a production line to achieve the goal of the Hadeed line of final production outputs. Figure 7.3 shows a run of four days based on a push-regime production line without considering any information feedback.

The goods flow is decoupled at two points: (1) the first and current strategic decoupling point is before the shipment from Al-Jubail to the customer/retailer (see Figure 7.2); (2) the second potential position is between the rolling mills and the steel plant (see Figure 7.4). The second is a quasi-feasible CODP. This is applied for some sizes and is possible as the processes could be driven with planning and forecast, and the orders could be delivered directly after finishing the milling process.

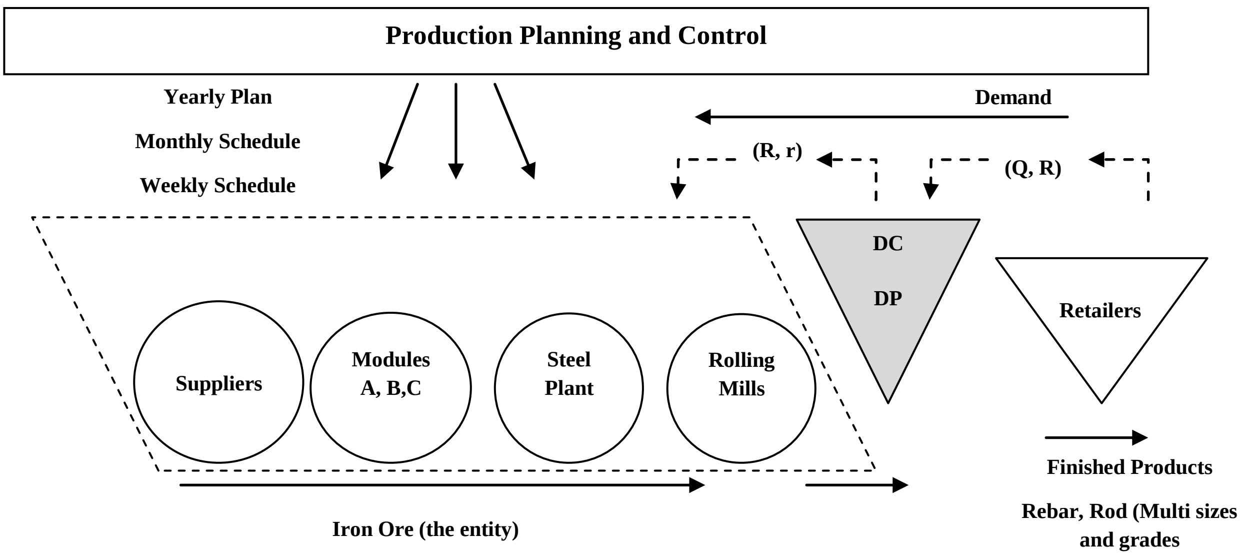

Figure 7.2: Hadeed supply chain (distribution centre as a decoupling point)

The first position of the material decoupling point (Figure 7.2) is at the distribution centre separating the upstream subsystem based on the make-to-stock processes and the system on the right of the decoupling point based on the order fulfilment processes. Figure 7.4 shows the second experiment, which represents the second possible material decoupling point position at the billet bay as an assemble-to-order strategy.

The material flow was obtained from the Hadeed case as a base structure for the model. The material flow dominates the lead time for the production delay up to the decoupling points, and the logic was developed using discrete-event simulation software (Arena 12). The configurations of the factors considered to be varied in these experiments (Chapter 8) are as shown in Table 7.10. The design for the experiments is detailed in Chapter 8. This chapter presents an empirical study of the case using the simulation.

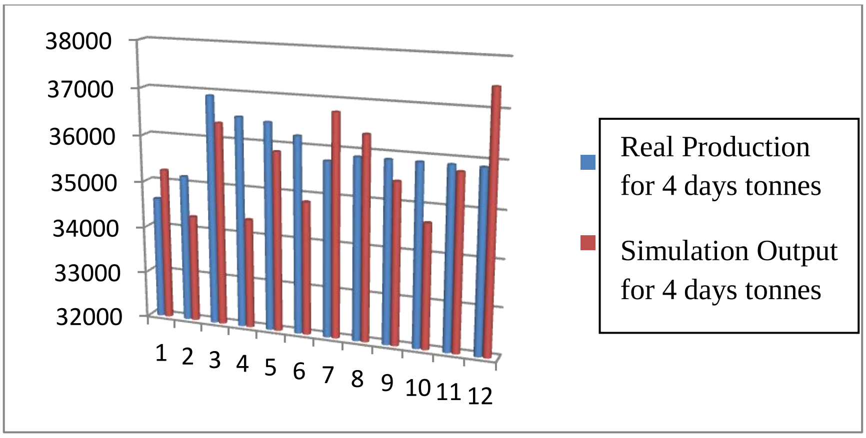

Figure 7.3: Real production rate in tonnes and simulation output run for 4 days

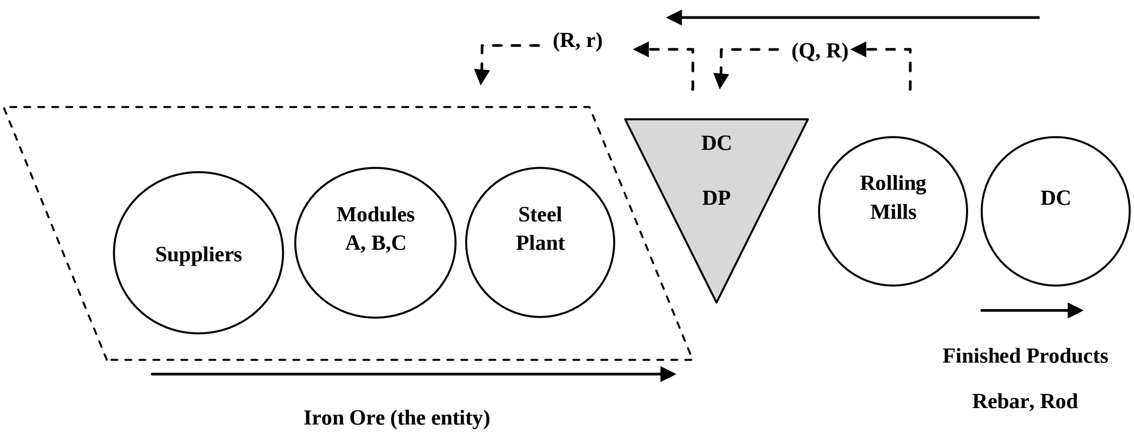

Figure 7.4: Billet bay as a decoupling point

Table 7.10: Two positions of the material decoupling point

Configurations	Positioning the MDP at the billet bay	Positioning the MDP at the warehouses
Test model	MTS to billet bay	MTS to the warehouses
Factors to be varied	Order arrival at billet bay	Order arrival at warehouses

7.3.2 Information flow representation

The purpose of this section is to identify the relationship between the customer order-related information (Demand, Mix, Specification, and Timing) and the production flow decisions in the supply chain (Production, Capacities, Inventory Position). Also, it is an introduction to the experiment's configurations. The information flows from the final customers/retailers, rolling mills, steel plant, modules, to the raw material suppliers. Figure 7.5 shows the flow process of the information and the simulation model environment of the Hadeed supply chain. The inventory management has been considered in the simulation model. Chapter 5 presented the inventory policies and the replenishment of an order up to the level that is used in the Hadeed case, which is usually in a make-to-stock production.

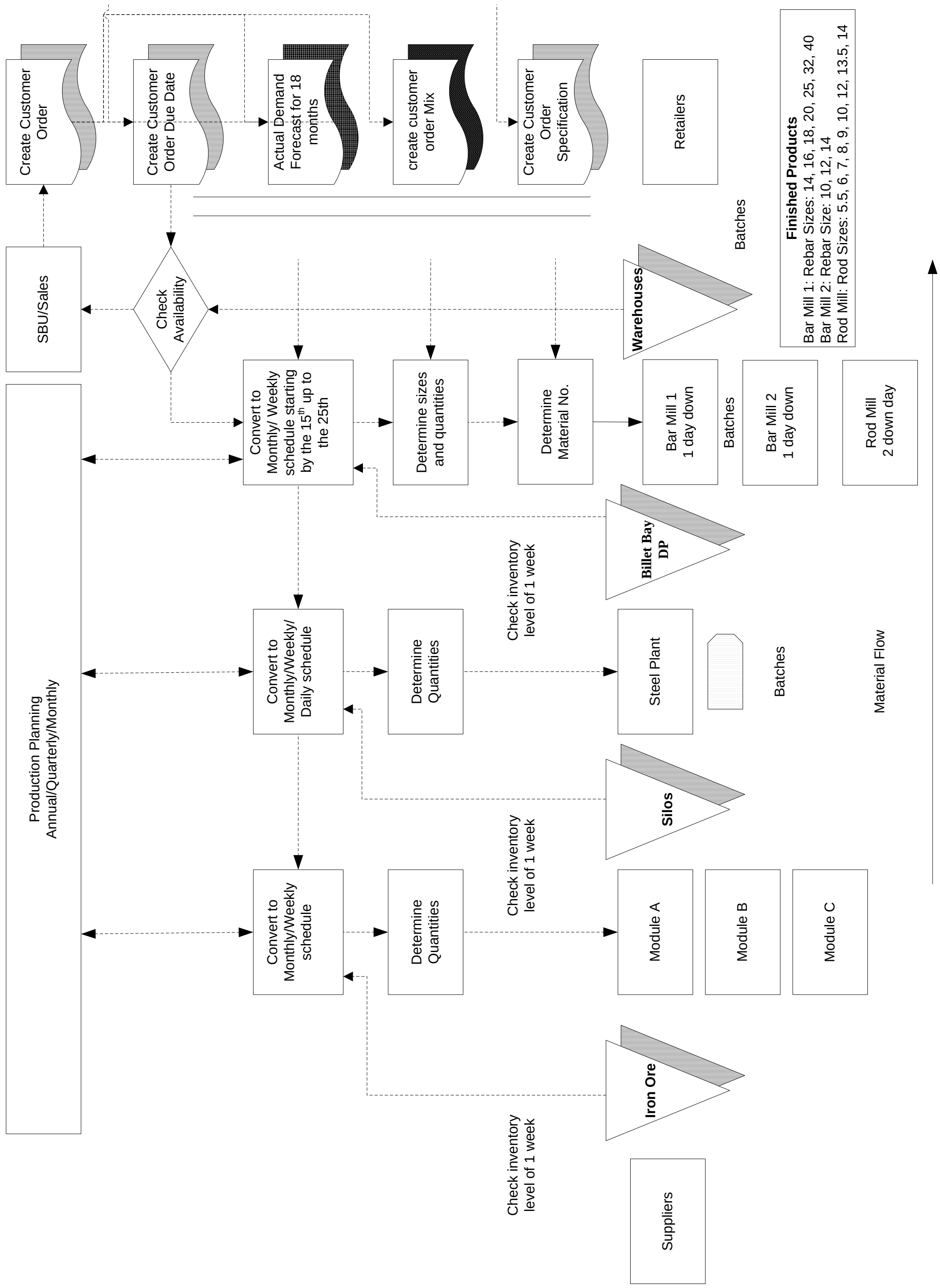

Figure 7.5: Customer order information flow at Hadeed

The subsections below explain the role of each type of information and its link to the production and material flows.

Table 7.11 shows the types of customer order information and the configuration of the information flow types.

Table 7.11: Types of customer order information

Information Type	Specific Information
Demand	Planned demand converted to monthly schedule
Product specification	Quality mix for each size
Due date	Final customer delivery date
Mix	The products variety

In the Hadeed case study the delay of these information types, from final customer order placement until the orders take effect at the scheduling department to begin manufacturing the orders, are subject to a variable information delay. The production at Hadeed is based on planning and scheduling, which incur delays in the system requiring this information. The scheduling and inventory planners use this time to determine the inventory levels and the proper way of scheduling the production orders according to size and quality priorities (the product specification for each size). These types of information conflict with the scheduling department, which is responsible for fulfilling these information requests.

For the rolling mills, Hadeed creates a monthly schedule based on an annual plan, and monthly confirmation from SBU for sales requirements and production lines. For the steel plant and the Direct Reduction Plants, Hadeed creates monthly schedules based on an annual plan and production confirmation. However, Hadeed creates the production schedules for each production line based on the monthly schedule created. The scheduling department uses SAP (Planning Production model) and APO to create the scheduling and optimise the production runs. For inputs, Hadeed uses the confirmed monthly sales orders and maintenance schedules. For outputs, it uses the production orders and schedules. It considers capacity constraints according to the historical data of each plant and annual plan. The sequence for each grade/product depends on the priority for the sales and production capability. For the steel plant the schedule is optimised by utilising the tundish (container), using the same grade or similar compositions grade in the same tundish. For the rolling mill schedule it optimises the scheduling by sequencing the sizes and grades based on the optimum operation conditions.

7.3.2.1 Inventory management at Hadeed

The shared information is the production plans, production schedules and production parameters. The unshared information is the customers' details and prices. Regarding the inventory information, the model uses a continuous review policy that replenishes when the inventory levels reach certain limits. The model uses (Q, R) control policy to manage its main inventory to face customer demand. The information at the retailers is converted to quantities orders, a replenishment of quantity Q is ordered from the distribution centre whenever the inventory position down-crosses level R. The inventory levels are one of the targeted measures to monitor the variations in demand and replenishment for the proposed scenarios. Chapter 5 introduced the inventory control policies and the parameters considered.

7.3.2.2 Demand information flow

Demand is the driving power of Hadeed as the retailers generate the demand and pass the information to the SBU (Strategic Business Unit)/sales team whose main task is to ensure the products are available at the warehouse when the customers want the products.

The demand is produced by the production planning department/SBU and the period of the plan for all the plants based on the forecast is 18 months. From this demand information, a monthly schedule can be produced to help in generating customers' order arrivals to the system. Two demand arrivals were created in the model to reflect the two main products: the rebar and the rod. This information type flows to the scheduling department which controls the plants. The schedule is updated monthly for the rolling mill and the planning period starts by the 15th of the month up to the 25th of the month. This is done separately from the other plants. The plan reflects a monthly schedule for the rolling mill as a rolling forecasting system. Another schedule is produced for the steel plant after checking the billet bay inventory. The steel plant produces monthly, weekly, and daily schedules. The logic of the scheduling optimisation is not included in the model. A delay module is used to represent the scheduling activities and whenever a change in the schedule is required.

This type of information is converted to sizes and quantities at the rolling mill, and to quantities for the steel plant and modules. The demand plan gives the global suppliers an idea about the demand volume to arrange for ocean shipments. It is assumed that Hadeed never starves for the raw material, and the modelling of the ships' arrival or their lead times are not considered in the model (see Section 7.3.3.10).

The information flow regarding demand is delayed in the order queue and controlled by the delivery, the inventory, and the schedule. Figure 7.6 shows the demand rate for the rebar and rod in quantities for the year from January-December 2008. The time series shows that the demand's behaviour is stationary. The demand information has been used to determine the theoretical distribution of the demand arrivals and quantities, which are fitted using Arena's Input Analyzer program. The demand inter-arrival time for the bar was fitted by an exponential distribution as 6.67e + 003 + EXPO (155) days, and the rod inter-arrival demand was fitted by a beta distribution as 818 + 234 * BETA (0.212, 0.0793) days.

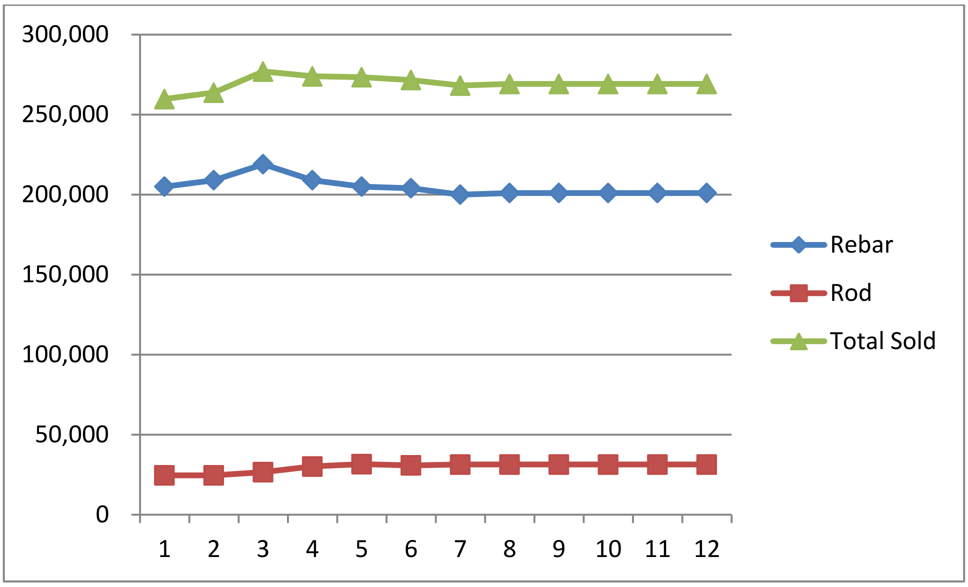

Figure 7.6: The demand rate at Hadeed (tonnes)

The demand in the first case was satisfied from the distribution stock, which is the actual case. The demand in the second case was produced from the billet bay and delivered to the customer, and is subject to a tolerance period that the customers would wait before receiving an order.

7.3.2.3 Timing (due date) information flow

The information flow regarding the due date at Hadeed is given after checking the inventory at the warehouses. If an inventory is available, it will be satisfied and the due date assigned. Otherwise, the orders need to be passed to the second echelon through the scheduling and the due date; and will be based on production and delivery times.

When the final customer places the initial order with Hadeed, SBU and sales departments check the inventory and satisfy the customers that the products demanded are in stock. Otherwise, the orders are transferred to the scheduling planning department. Promising to fulfil orders is the main task of the supply chain. Hadeed uses the ATP/CTP procedure embedded in SAP, but the disadvantage of this method is that it is not flexible when there is no inventory available. However, the model assigns a due date when the order is entered. If there is no inventory available, the scheduling delay will be added plus the rolling and delivery lead-times.

The main controller of the production rate is the ordering rate. The order lead-time is variable and can be affected by a number of factors in the ordering, scheduling, production, and/or delivery processes.

Setting a due date can take place either at the order's arrival as an immediate response, or in case of shortage the batch order processing can be promised and this has been assumed to be a fixed period of 30 days.

Another factor that determines the due date is the distance or shipping time. In the model, since Hadeed delivers locally, the shipping time to the main retailers is categorised by regions. The trucks travel to the central and eastern regions in 1 day, and north, south, and western regions in 4 days, and these have been added to the model as a delay part of the due date information.

7.3.2.4 Mix/products variety information flow

The essential duty of the production planning section at Hadeed is to produce a periodical (weekly, monthly and yearly) plan that is a compromise between the demand (certain and forecasted) and the production capacity of the company. This plan mainly assigns certain sizes of finished products to be produced in each of the four mills available in the long products production area. They are the Rod Mill, Bar Mill, Section/Bar (S/B) Mill, and Bar and Rod Mill (Barod Mill).

In production planning, it has been found that the most demanded sizes, and therefore the most produced and dispatched sizes by each mill, are:

- The Rod Mill: 5.5, 7, 8, 9, 10, 12 and 14 mm (Coils)
- The Bar Mill: 16, 20, 25 and 32 mm (Rebars)
- The S/B Mill: 12 and 14 mm (Rebars)
- The Bar and Rod (Barod) Mill: Bar Mill: 12, 16 and 32 mm (Rebars); Rod Mill: 5.5 and 9 mm (Coils)

- The S/B Mill: 10, 12 and 14 mm (Bars).

An Excel sheet was designed showing the weekly production plan for each mill. This plan specifies the size, the amount and which are to be produced. The forecasted weekly demand during the period January-December 2008 was used as an estimation of the consumption of each size. In addition, the actual production capacity of each mill was used as a limitation to process the proper tonnage to cover that demand.

The milling plants produce to stock the planned different sizes based on the schedule. If an item is demanded, it is compared to the schedule and if it cannot be satisfied from the stock, or planned for the next run, the order will be delayed for an extra month to be included in the next month's schedule. This means the sizes information is controlled by the scheduling department and not transmitted upstream of the billet bay.

Consumption: Data on all amounts of each size dispatched during the period (Jan-Dec 08) were collected. Then, it was divided by 365 (days in one year) and multiplied by 7 (days in a week) to approximate the weekly demand.

Production: The production quantities for each size are fixed for all sizes in the mills, and calculated using the actual production capacity figures of each mill. A delay is added to model the setup time during the size change, and the downtime is taken from the production lines' capacities.

Information related to the sizes is beneficial for the rolling mill, hence this type of information is used for the rolling mills and is not forwarded to the steel plant, except the quantities details.

7.3.2.5 Specification information flow

The same principle for the mix applies to the specification, as the rolling mills are the only plants that benefit from specification information in their production. It is used only in determining quantities information for the steel plant, which is anyway given automatically by the demand information for the steel plant.

7.3.3 Model Description

The models are composed of two main sub-models, one for material flow and the second for information flow. A snapshot of the Hadeed model is displayed in Figure 7.7.

7.3.3.1 Entities

There are different players called entities that move around the model, and change status. They are the dynamic objects of the simulation. For example, customers and iron ore were entities of the model, which affect and are affected by the system and make a difference to the performance measures.

7.3.3.2 Resources

Entities go through these resources, which are a group of servers, each of which is called a unit of the resource. Some of the resources are parallel, such as the modules, the furnaces, and the casters. Table 7.12 shows the resources of the Arena model including the time and capacities for each resource.

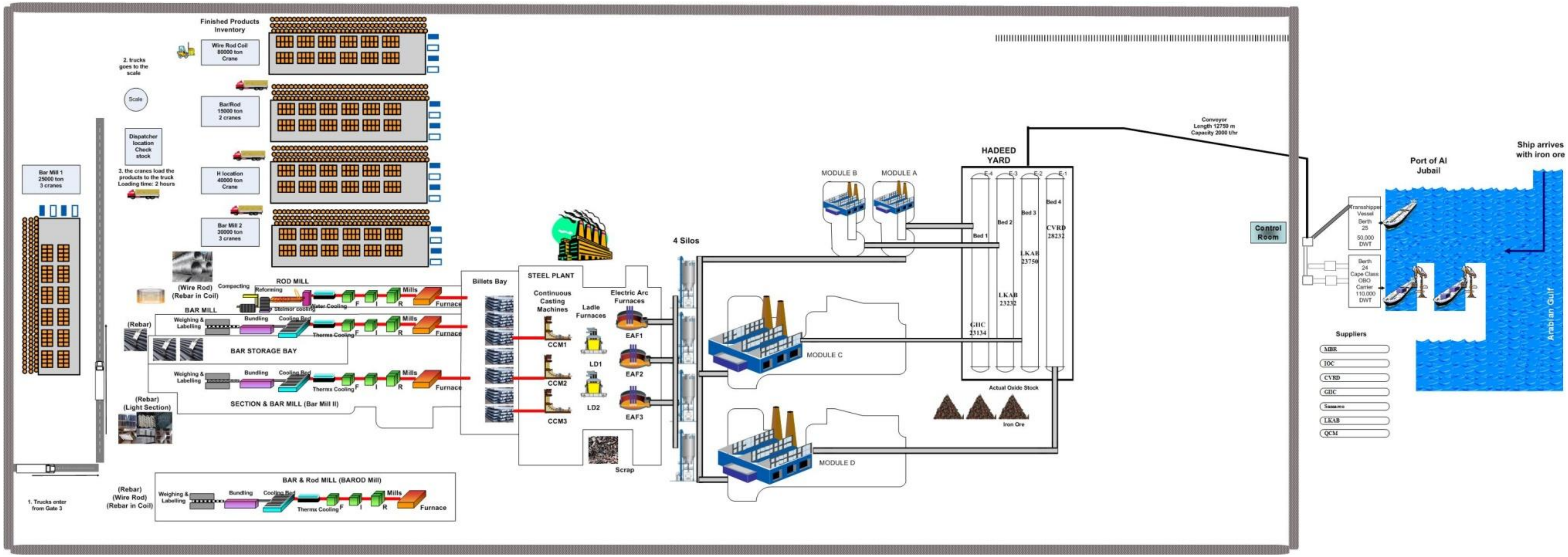

Figure 7.7: Snapshot of Arena model for Hadeed case

Table 7.12: Hadeed production resources

Resources	Total time	Capacities (tonnes)
Port_R: Ships unload iron ore	4 hrs	165,000
Module A_R, Module B_R, Module C_R: Three direct reduction plants		170,000
EAF1_R, EAF2_R, EAF3_R: Three electric arc furnaces	75 min, 35 min	150
LF1, LF2: Two ladle furnaces		
Caster 1, Caster 2, Caster 3: Three continuous casting machines	75 min	14
Bar Mill	42.92 sec/billet	152.36 t/hr
Rod Mill	67.3 sec/billet	97.73 t/hr
Light Section & Bars	64.43 sec/billet	103.92 t/hr
Bar and Rod (Barod) Mill	124.48 sec/billet	77.8 t/hr

7.3.3.3 Queues, buffers, storage

There are queues where entities are waiting when they need to seize a unit of a resource that is occupied by another entity. Before each resource in Table 7.12 there is a queue and the focus of the model is on the buffers (queues) that are shown in Table 7.13, which represents the places at Hadeed that have buffers with capacities between the echelons.

Table 7.13: Hadeed inventories

Buffers	Capacities (tonnes)
Iron Ore stacks in the storage area Iron ore is stacked in the storage area inside Hadeed facilities before transporting it to the Direct Reduction facilities	600,000
Silos for storing directly reduced iron (Sponge Iron) Directly reduced iron is stored in 4 silos	5,000
Billets Bay Billets are stored in the billets bay after cooling them	150,000
Rebar Storage Area	55,000
Light Section & Bar Storage Area	30,000
Rod Mill Storage Area	55,000
Bar and Rod (Barod) Storage Area	40,000

7.3.3.4 Statistical accumulators

The model kept track of various intermediate statistical-accumulator variables as the simulation progressed. The measures shown in Table 7.13 and the following measures were under observation:

- The number of parts produced so far
- The total waiting time in the queue so far
- The number of parts that have passed through the queue so far
- The longest time waiting in the queue so far
- The longest time in the system
- The total time spent in the system.

All these variable are initialised at zero.

7.3.3.5 Events

"An event is something that happens at an instant of simulated time that might change attributes, variables, or statistical accumulators" (Kelton et al., 2010). In this case study, the events will be as follows:

- **Arrival**: a new part enters the system, resources
- **Departure**: a part leaves the system, or finishes the service
- **The end**: the simulation is stopped at 30 days
- **Warm-up period**: 10 days is certainly enough for the model to have settled out.

The core modules used in the model were: Create Assign, Decide, Process, Dispose, Hold, Delay, Resources, Queues...etc. Also, see Appendix B, which details the function of these modules. Appendix D shows the simulation model in SIMAN view.

The point of view that has been used for both of the models is based on the realism of the case study. The scheduling is based on push system before the decoupling point or make-to-stock, and pull system is used after the decoupling point for the order fulfilment process. A push system is essentially used for a mass production kind of system as Hadeed uses in response to the customer order processes. The logic of the models was a manufacturing push system before the decoupling point to mimic the scheduling processes, and pull logic after the decoupling point to mimic the ordering processes.

The main inventory is subject to order arrival, inventory updating, replenishment order triggering, and order shipment.

Next, three model segments are described in some detail.

7.3.3.6 Demand management segment

The demand segment translates the details discussed in Section 7.3.2.2 to the model. The customer arrives; their details are put into the system with an inter-arrival time, customer identity and a bespoke set of requirements (demand quantity, size, due date, and specification). On arrival, a customer's identity is entered into the Assign module, a delay occurs due to the order entries and if the customer can be satisfied from the inventory, a due date is assigned and the demand is taken from the inventory. Otherwise a scheduling delay will be added to the customer order lead-time to reflect the schedule adjustment that will happen in case of a delay.

The information flow starts with the orders aggregated and placed with the sales (3 days delay) at the sales department, and the orders are presented in a queue. Then the sales department transmit the orders to the scheduling department as a weekly schedule. A queue of the sizes and specification orders is delayed until the schedule is updated (if it is not available in the inventory, a delay of 30 days is estimated).

7.3.3.7 Inventory management segment

The inventory management is modified to control the production operation and demand fulfilment. Hold modules are used to stop production if the inventories reach the maximum limit, and replenish when it reaches the reorder points for the inventory positions of the modules, silos, billet bay, and warehouses. The logic is connected with the demand segment, and the demand that is satisfied is taken from the strategic inventory. The Assign module is used to keep track of the inventory information which tracks on-hand inventory level fluctuations between the maximum and reorder point, and also triggers replenishment orders.

In the first experiment the strategic inventory buffer is the distribution centre with a reorder point of 20,000 tonnes for rods and 60,000 for bars. The modelling of procurement to the inventory point is based on manufacturing and transportation time and level constraints. An (R, Q) inventory control policy is used to control the replenishment process at the buffer. An (R, r) policy is used to control production. In the second experiment the billet bay has been put in as a strategic inventory with a reorder point of 120,000 tonnes.

7.3.3.8 Scheduling/production management segment

This segment manages the main constraints for the processes between echelons, and manages the raw material consumption and finished goods production by keeping track of a circulating control entity that modulates the suspension and resumption of production.

These segments are linked to manufacture a product, remove a product, and update the buffers. In the first experiment production is made up to the main stock and in the second experiment is made up to the billet bay, and the manufacturing of bar or rod will start after receiving an order as ATO.

In determination of a scheduling delay, the simulation model is stopped running and held to represent the size or specification change for the third experiment if a change is required.

7.3.3.9 System variables and expressions

The variables utilised in the simulation model are found in Table 7.14.

Table 7.14: Variables used in the model

Variable	Units	Initial values
Silos Inventory	tonnes	20,000
Billet Bay Inventory	tonnes	120,000
Modules Inventory	tonnes	500,000
Bar Inventory	tonnes	60,000
Rod Inventory	tonnes	20,000
Total Bar Customers	customers	0
Total Rod Customers	customers	0
Bar Inventory Position	tonnes	0
Rod Inventory Position	tonnes	0
Bar Reorder Point	tonnes	60,000
Rod Reorder Point	tonnes	20,000
Delayed Bar Customer	minutes	0
Delayed Rod Customer	minutes	0
Complete Bar manufacturing time	minutes	0
Complete Rod manufacturing time	minutes	0

7.3.3.10 The system's assumptions

The following assumptions are made during the model development:

- There is always sufficient raw material so the process never starves; the ship's arrival and its unloading process model are not included.
- Processing is carried out in batches of billets to simplify the modelling, which is measured in tonnes (1 billet = 1.83 tonnes).
- Data is collected based on the distribution of the historical data gathered. The distributions are found using Input Analyzer (in ARENA environment) for data fitting.
- The failure is also gathered as distribution from the historical data, which indicates maintenance or breakdown.
- The model runs for 30 working days for each schedule run according to the available capacities.
- The scheduling activities or its optimisation are not included but a delay module is assumed to represent the scheduling delay for any change required.
- The batches are calculated from the histories based on the proportions for each size specification.
- The failures of the production processes that may occur are assumed to be 1 day for Bar Mill, 1 day for section and Bar Mill, and 2 days for Rod Mill.
- The inter-arrival times between successive customers' demands are IID uniformly distributed between 6,667 and 7,300 tonnes.
- The supply chain is assumed to have initial inventories of 500,000 tonnes before the modules, 20,000 tonnes at the silos before the steel plants, 130,000 tonnes at the billet bay before the rolling mills, 60,000 tonnes bar and 20,000 tonnes at the warehouses.
- There are two main finished products in the supply chain: the rebar and the rod, and one raw material (iron ore), which is represented in tonnes (assuming the continuous flow as discrete).
- All the supply chain is initially full at time zero. A continuous review (R, Q) and (R, r) inventory policy is used. Also, it is assumed that there are no backorders in the system and no shortage of raw material (no starvation) to cause any production stoppages.
- The delivery time is assumed based on the retailers' locations in the regions (Central: 2 day, Eastern: 1 day, Northern: 3 days, Southern: 4 days, Western: 4 days, Gulf Cooperation Countries (GCC): 1 week).

- The conveyors, forklifts, and trucks' movements within the Hadeed facilities are not considered, assuming the materials are available for the next process.

7.4 Chapter Summary

This chapter specified the data needed for the factors and parameters chosen in order to define a working simulation model. The chapter showed the experimentation formulation, and discussed the software used for the experimental design. Also, it presented the planning for data collection, which summarised samples of the major data gathered and did not present the vast majority needed to model the random variables. The fitting input distribution was done via Input Analyzer. Lastly, the chapter discussed the development and construction of the simulation model. The next chapter will introduce the experimentation of the simulation model involving the Hadeed case study in more detail.

Chapter 8

Experiment Execution and Analysis

To assess the impact of the customer order decoupling points on responsiveness through the case study simulation model developed in Chapter 7, this chapter investigates the experiments of the current and suggested systems' models of the Hadeed case study. Also, the validation and verification of the simulation models is considered. Ranges of scenarios are investigated by the modification and enhancement of the simulation models. Moreover, the chapter interprets the results of the experiments and discusses the zonal concept related to the scenarios investigated.

Section 8.1 introduces the experimentation, including verification and validation. Section 8.2 explains the range of scenarios investigated. Section 8.3 explains the results of each experiment in each scenario. Section 8.4 interprets the final results of the experiments and shows the zonal concept related to the scenarios investigated. Finally, Section 8.5 provides a summary of the chapter.

8.1 Introduction to the experimentation

In the previous chapter, the case study was introduced and the simulation modelling discussed. The model was mainly divided between two sections: material flow for all the echelons, and information flow including all the information types considered. The logic behind these divisions was to make the development of the model more efficient. Utilising this approach enabled modifications to be made in one sub-model without affecting the other sub-model. An initial Arena model was implemented. The simulation was run with the base case study for the actual scheduling delays and the size batches being processed.

The case scenarios are explained in section 8.2 which are mainly either to produce up to the rolling mills and store the finished products at the warehouses, or to the steel plants and store at the billet bay. The final Arena models developed with the alternate scenarios and experimental designs are finalised and introduced. Section 8.3 reports the results from these different scenarios and experimental designs, which are also compared with the actual Hadeed model. However, this chapter is exercising the model for the inputs from Chapter 7 and factors from the experiments to see how they affect the output measures of responsiveness and performances measures.

All the information types are set as shown in Figure 7.5 and as mentioned in the previous chapter. The design of experiments investigates the different configurations between the material decoupling points and the information flow, and finding its impact on the performance measures. The set of experiments investigates moving the different information options up to the proposed points whilst the material decoupling point is fixed at the strategic physical inventory for each scenario design.

8.1.1 Verification and validation

The simulation model, as many systems that must be modelled, contains some random inputs and is therefore stochastic. Since queuing, demands, and inventory systems are included in the model, it has to be modelled stochastically (Law, 2007). Stochastic simulation models also make random output. Hence, there must be an estimate of the actual model including a percentage of the accepted errors as it is known in the simulation (Law, 2005, 2007).

A walk-through of the assumptions (section 7.3.3.10) was carried out with Hadeed's production and control manager. This helped to ensure that the model's assumptions were correct and complete for the considered overview. Moreover, Hadeed's managers agreed with the feasibility of the actual and suggested systems and accepted the results of the model for the current system. The interaction with the other factory departments was promoted. However, the model was constructed in Arena to reduce the programming time and resulted in an easier model's verification. Also, the debugging function in Arena was an important tool in terms of the verification. Moreover, pilot runs were made based on the basic model discussed in Chapter 7. Animation was used to verify the model logic to trace the entities flow, a snapshot of which is shown in Figure 7.7. It was an effective verification tool. The simplifying assumptions about the system were balanced to keep the real uncertainty and make a valid representation of the system. This ensured that it was possible to measure or reliably reduce error. The output of such a simulation model will be an approximate answer to the problem rather than an exact answer (Sargent, 2007).

The main model validation check was through comparison with the existing system of Hadeed and its performance measures. This was reviewed with Hadeed managers to check the correctness of the model results. The validation process started with examining the fit of the model to Hadeed's set of important performance measures, which was mainly throughputs and the order fulfilment lead-time. This simulation model therefore went through multiple cycles of model construction, verification, validation, and modification.

The purpose of the simulation model is to determine the impact on responsiveness for the proposed systems. The information flow types such as demand, mix, due date, and scheduling policies were the factors that affected the performance of the model. The model was initially tested for the base case and was verified to accomplish the same tasks as the real system. The test was performed in terms of what quantities were produced to achieve the targeted levels, the inventory levels, response time and cycle time of the current situation.

The results from the proposed configurations were compared to the base case to determine the performance and differences between the suggested systems and the current situation. To validate the simulation model as the case study, the production output was compared as shown in Figure 7.3. The levels of the inventories at the different stock locations calculated by the model were very close to the real situation. The base model indicated that the simulation run and the modification results are valid results. The main performance quantitative measure in terms of the verification of the model was the throughput to verify the goodness of the model. Also, the utilisations of the resources were estimated and showed they were quite close to the actual case.

Validation activities started from the data collection stage by comparing the parameter values and performance metrics from the Hadeed case study with their model counterparts. Efforts were made to collect high quality data on the system through conversations with subject-matter experts, observation of the system, and by interacting with the manager from the beginning of the case study until the end of the simulation study. The validation process depends on the complexity of the system being modelled and because the considered version of the highest level of Hadeed was the observed system during the case study, it would be relatively effective and possible to validate since the location and nature of the company was known. However, any model is a simplification of reality, hence the simulation of Hadeed was an approximation and there is no such thing as absolute model validity, nor is it even desired. The time and effort spent during model-building development was valid according to the cost-effectiveness and time limitation. Increasing the validity of the model beyond a certain level is expensive and requires extensive data collection, which may not even lead to better insight about the system or give significant decisions. Also, the simulation model was developed for the set of purposes declared in the objectives in Chapter 1.

Figure 8.1 shows the relationships between the timing of validation, verification, and establishing credibility (Law, 2007). The interactive debugger tool allowed stopping the simulation at any selected point in time, and examining and possibly changing the values of certain variables of any types of errors. This tool is included in Arena. Also, the batch-running mode helped in tracing the model, which produces a large amount of output and warns if any error can occur during the long run. Observing the animation was helpful to check the model running and part of the validation process. In other words, using Arena or a commercial simulation package reduces the amount of programming required and takes care of the system considered as it contains powerful high-level tools that increase the credibility, verification, and validity of the model.

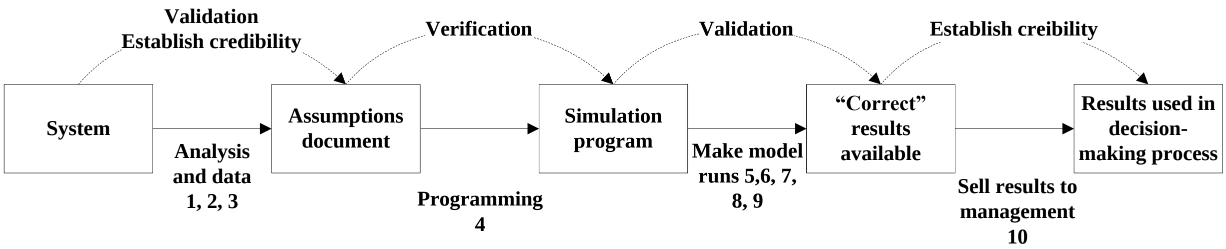

Figure 8.1: Timing and relationships of validation, verification, and establishing credibility (adapted from Law, 2007)

8.1.2 Performance metrics

In this section, the main performance measure is the response time of the supply chain. As mentioned in section 7.1.3, the response time for this study is the reduction of the cycle times. Other measures are estimated during the simulation run. Table 8.1 shows the performance measures that were deducted from Table 7.2 to be shown in the simulation output for the experimentations.

Responsiveness is defined in Section 7.3.

The cycle time can be defined as the maximum time per unit to produce a product in order to meet demand (from customer order receipt to completed manufacturing) (Vitasek, 2010).

The replication length would be terminated for the experiments at 30 days since it yields sufficiently close values to the actual case of Hadeed, so the experiments are set for 30 days and ten replications of each model run. In a similar vein, the length of a warm-up of 10 days was determined by observing experimentally when the time variability of the throughput and utilisation statistics was eliminated. For a replication of one month by the simulation run, the examination of the Arena model verified that the runs and replications were processed to completion with very close results to the actual case performance throughput. The model runs are based on the historical data which provides the performance measures, all the resources were set to have the same capacity constraints as the real case, and the system was working 24 hours a day, 5 days a week, with scheduled maintenances.

Table 8.1: The performance measures

Measure
Total supply chain response time
Takt time/cycle time (time in system for parts)
Order fulfilment lead time
Manufacturing lead time (throughput)
Delivery lead time (times parts spend in transport)
Fill rate (target fill rate achievement and average item fill rate)
Utilisation of equipment (i.e. production of time busy)

8.2 Range of Scenarios Investigated

In simulating the production line of Hadeed, four scenarios were deemed to be important, to test the hypothesis of the research that having the physical customer material decoupling point as far downstream as possible and positioning the customer information decoupling point as far upstream results in better responsiveness. Several scenarios, which include differing decoupling point positions, were necessary.

The first two scenarios are modelled with the material decoupling point placed at the warehouse producing a make-to-stock design with two information decoupling points' configurations; the first scenario is placing the information decoupling point downstream and the second scenario is placing the information decoupling point upstream. This option allows for being efficient and productive. It is popular for mass production, although it presents the real danger of excessive stock with loss of revenue. However, if the responsiveness shows that this configuration can keep up with customer needs, then this option obviously increases Hadeed's profits. This is going to be tested in the experiments designs.

The last two scenarios are modelled as a configuration allowing the material decoupling point to be pushed upstream, before the rolling mills at the billet bay. The strategy makes the production system an assemble-to-order design with two information decoupling points' configurations; the third scenario is placing the information decoupling point downstream and the fourth scenario is placing the information decoupling point upstream. The last two scenarios ensure that there are always enough inventories for the rolling mills based on the orders, and no excessive inventory at the warehouses or lost sales. The danger here is that the customer may have to wait. However, this could be more or less responsive than the previous scenario. Hence, there would be two configurations, as in the previous case, which have the material decoupling point at the billet bay, and two information position scenarios are proposed: one upstream and another downstream of the billet bay.

The purpose of the experiments is to verify the theory mentioned by assessing the most responsive scenario based on the responsiveness assessments and performance measures considered.

The scenarios that need to be modelled will follow mainly the same assumptions that involve the same resource capacities and plants, except for the differences in strategic inventories in the scenarios, the affected modelling logic in the material and information flows, and replenishment elements. The changes in the logic compared to the actual case are limited to the information type's delays and the positions of the inventory either at the warehouse after the rolling mills or at the billet bay after the steel plants. More details about the parameters and the various configurations are explained in the following sections. However, the first two scenarios follow the make-to-stock strategy. The last two scenarios follow the assemble-to-order strategy. The following scenarios and experiments discuss these material and information decoupling points' positions, and alternative operating policies that represent the proposed systems to investigate the best design that will lead to maximum responsiveness. Table 8.2 presents the range of scenarios investigated.

Table 8.2: The range of scenarios to be investigated

Scenarios	Design of experiments
1. Material decoupling point at the warehouses, the information decoupling points positioned downstream.	The same echelons as the actual case study, the same inventories capacities and policies as the actual case. MTS material decoupling point position. The order information is positioned downstream. The replenishment and order flow follow the order information types and its time responses of the information decoupling point position.
2. Material decoupling point at the warehouses, the information decoupling points positioned upstream.	Similar to the above scenario except the order information decoupling points are positioned as upstream as possible according to the information types considered. This affects the information flow logic in the simulation model and its time responses of the information decoupling point positions.
3. Material decoupling point at the billet bay, the information decoupling points positioned downstream.	The same echelons as the actual case study, the same inventories capacities and policies as the actual case. ATO material decoupling point position. The order information is positioned downstream at the billet bay. The replenishment and order flow follow the order information types and its time responses of the information decoupling point position.
4. Material decoupling point at the billet bay, the information decoupling points positioned upstream.	Similar to scenario 3 except the order information decoupling points are positioned as upstream as possible according to the information types considered. This affects the information flow logic in the simulation model and its time responses of the information decoupling point positions.

8.3 Design of the Simulation Experiments

Once the basic model is judged to be valid, the next step is the design of simulation experiments. The experimental design of the scenarios shown in the previous section is discussed here. The results for each scenario for each experiment are explained in this section. The final results are given in section 8.4 and a comparison is made of the actual Arena simulation model results. The research questions were driving the direction of the simulation study. However, for each of the system configurations, the following were specified:

- Length of each simulation run: 30 days
- Length of the warm-up period: 10 days
- Number of independent simulation runs using different random numbers: 10 replications.

Experimentation of the simulation scenarios consists of generating system histories and observing system behaviour over time. They are extended for the case study to form the experiments design shown in Table 8.2: the performance measures in section 7.1.3 and from Table 8.1 will be computed for each design for their averages across the complete independent replications of each alternative system. The statistical method for collecting the outputs for the desired performance measures is based on IID observations by making independent replications. Both boxes under Initialise Between replications are checked to cause both the system variables and the statistical accumulators to be cleared at the end of each replication. The reason for clearing after each replication is to get statistically independent and identically distributed replications for termination analysis. The following design and scenarios are presented as the best different types of comparison possible for the case study, and which are appropriate to satisfy the objectives of the thesis. The factors considered in the model are determined due to the goals of the study rather than because of any inherent form of the model. All the factors are quantitative except the material CODP positions, which show a categorical factor that represents the main inventory position. The major goal of the experimental design in simulation is to determine which factors have the greatest impact on the responsiveness of the Hadeed supply chain. There are major topics in the field of statistics and whole books on the design of experiments and response surface methodology. However, the design of experiments here is prepared so the simulation can be carried out across the scenarios with the different configurations to see which configuration is giving the best responses and performance.

The system designs that can achieve the maximum responsiveness will be tested compared to the actual system on the basis of measures of responsiveness and performance. For each proposed system, 10 replications of 30 days will be made (24 hours a day) with 10 days of each replication being a warm-up period design. Regarding the starting point for the simulation runs, the assumptions were to start with sufficient capacity in the inventories in the long run. All the processing times, arrival rates and transfer times are as the actual Hadeed case study. The following subsections simulate the different scenarios (system designs), which are described in Table 8.2.

8.3.1 The material decoupling point at the warehouses scenarios

8.3.1.1 Positioning the customer order information decoupling point downstream and postponing the material flow downstream at the warehouses

The modelling was based on positioning the material decoupling point at the “warehouse” and the information decoupling point also at the “warehouse”. The material flow is run up to the main inventory position at the warehouse. The information flow starts from the customers to the warehouse in which the information decoupling point controls the main inventory and order, including the information types downstream. Table 8.3 shows the factors specified for the system design related to this scenario. For the material flow, the entities flow as a push system until they reach the warehouse inventory. This scenario is similar to the actual case in Hadeed. Regarding the customer order information flow, the customer arrives with their demand quantities, as depicted in figure 7.5. The model begins with the customer order, and the flow proceeds from here to the inventory check and delay factors that are tightly coupled and limit the customer order flow. The information decoupling point was modelled in Arena, as buffers delay the customer entities, replenishment process, and inventory management while decrementing from the inventory positions and fulfilling the orders. The decision logic for the information flow was revealed from the same flow presented in Figure 7.5. The check process for the customer information entities is as follows:

- After the orders are created in the model
- If the ordered quantities are available:
    - Check if the order mix (quantities and sizes) is available,
        - Check if the order specification is available
            - Decrement from the warehouse inventory
            - Replenish inventory when it reaches the minimum inventory level
            - Assign the due date, delay the order based on the delivery time;
        - Check if the order specification is not available
            - Implement delay in batches to give time to reschedule with steel plant and identify a needed requirement;
    - If the order mix (quantities and sizes) is not available,
        - This incurs a mix information delay that is assumed for adjusting the monthly schedule, and delays production from the steel plant
        - Restart the steel plant when the signal is received in the model through the Hold module;
- If the ordered quantities are not available:
    - This incurs a mix information delay that is assumed for adjusting the monthly schedule, and delays production from the steel plant,
    - Also, it will incur a demand information delay that is assumed for adjusting the modules and the iron ore supplies
    - Restart the modules plant when the signal is received in the model through the Hold module.

Table 8.3: The experiment factors for the first scenario

Input Parameters	Factors
CODP position	**MTS**
The configuration of the CODP	**Positioning the CODP at the warehouses**
Experiments	**Factors**
Information parameters	
Mix information delay time	$T_M \rightarrow$ UNIF (336, 672) hours
Due date information delay time	$T_{DD} \rightarrow$ UNIF (24, 96) hours
Demand information delay time	$T_D \rightarrow$ UNIF (504, 1008) hours
Order batching delay time	$T_S \rightarrow$ 168 hours

The scenario involves keeping the information flow position downstream and postponing the material flow. Table 8.4 contains the statistics generated by Arena for the supply chain of the Hadeed case study.

Table 8.4: Performance measures for the first scenario

Measure	Mean	Minimum	Maximum
Total supply chain response time (hours)	1,517	1,062	1,970
Takt time/Cycle time (time in system for parts)	100.15		133
Order fulfilment lead time	757	756	759
Manufacturing lead time	133	66	201
Delivery lead time (times parts spend in transport)	48	24	96
Fill rate (target fill rate achievement and average item fill rate)	0.67		
Utilisation of equipment	0.63	0.57	0.64
Throughput	287,235		

The simulation run determined that the total supply chain response time is on average 1,517 hours, which as defined in Table 5.3 as the time it takes to rebalance the entire supply chain after determining a change in market demand. The total throughput calculated for one month is 287,235 tonnes. The average flow time or cycle time is 100 hours which is defined in Table 5.3 as the maximum time per tonne unit to produce a product in order to meet demand, which means that each tonne needs approximately 4 days on average to travel from supplier to completion of manufacturing. The information flow is positioned according to Figure 7.5 and the logic explained in this subsection, which shows the information flow in terms of the information types, inventory updating and scheduling delays.

Table 8.5 shows that the average inventories are constant and within the ranges of the real situation. Because of the high demand and constant supply situation, the above results show a match between supply and demand that reflects the current situation. This is also part of the verification of the model since this scenario is similar to the actual case at Hadeed.

Table 8.5: Results from the first experiment

Measures	Average output of model (tonnes)
Output Rebar	136,488.8
Output Rod	58,363
Billet Bay Inventory	139,172
DR Modules Inventory	540,387
Silo Inventory	212,194
Warehouse Bar	60,191.39
Warehouse Rod	20,642.17

8.3.1.2 Positioning the customer order information decoupling point upstream and postponing the material flow at the warehouses

The modelling was based on positioning the material decoupling point at the “warehouse” and the information decoupling point upstream. The material flow is run up to the main inventory position at the warehouse. The information is shared upstream with the steel plant and the module’s plants based on the information types. Table 8.6 shows the factors specified for the system design related to this scenario. For the material flow, the entities flow is a push system until reaching the warehouse inventory. This scenario is similar to the actual case in Hadeed. Regarding information flow, the information types are shared upstream with the steel plant and the demand will be shared up to the modules plant. The customer arrives with their demand quantities, as depicted in figure 7.5, and is modelled as customer entities that start the stream from the create module, and proceed to the inventory check and delay factors that are tightly coupled and limit the customer order flow. The delays encountered due to scheduling and batching will be lessened because of information sharing and the time needed for coordination. The information decoupling point was modelled in Arena, as buffers delay the customer entities, replenishment process, and inventory management while decrementing from the inventory positions and fulfilling the orders. The decision logic for the information flow was revealed from the same flow as in Figure 7.5. The check process for the customer information entities is similar to the logic in the first scenario, except the delay for changing batches is less than the previous scenario, at a minimum of two days to adjust the weekly schedule with the steel plant to determine the required batches that need to be considered in the weekly schedule. Also, the mix information delay is less than in the previous case due to mix information sharing. The demand information delay that is assumed for adjusting the modules and the iron ore supplied is also less since the demand information is shared upstream with the modules plant.

Table 8.6: The experiment factors for the second scenario

Input Parameters	Factors
CODP position	**MTS**
The configuration of the CODP	**Positioning the CODP at the warehouses**
Experiments	**Factors**
Information parameters	
Mix information delay time	T_M → UNIF (48, 168) hours
Due date information delay time	T_{DD} → UNIF (24, 96) hours
Demand information delay time	T_D → UNIF (168, 336) hours
Order batching delay time	T_S → 48 hours

The scenario involves moving the information flow position upstream and postponing the material flow downstream. Table 8.7 contains the statistics generated by Arena for the supply chain in the Hadeed case study.

Table 8.7: Performance measures for the second scenario

Measure	Mean	Minimum	Maximum
Total supply chain response time (hours)	846	803	1,279
Takt time/Cycle time (time in system for parts)	91		99
Order fulfilment lead time	336	288	384
Manufacturing lead time	116	51	173
Delivery lead time (times parts spend in transport)	48	24	96
Fill rate (target fill rate achievement and average item fill rate)	0.93		
Utilisation of equipment	0.95	0.85	0.97
Throughput	299,469		

The simulation run determined that the total supply chain response time is an average of 846 hours. The total throughput calculated for one month is 299,469 tonnes. The average flow time is 91 hours as the maximum time needed per tonne unit to produce a product in order to meet demand, which means that each tonne needs approximately 4 days on average from travelling from the supplier until manufacturing is completed. The information flow is positioned according to Figure 7.5 and the logic explained in this subsection, which shows the information flow in terms of the information types, inventory updating and scheduling delays. The specification and associated sizes-related information is less than in the previous scenario since the scheduling activities are shared between the rolling mill and the steel plant to ease determining specification and size. The average inventories are constant and within the ranges of the real situation. This scenario shows better responsiveness and performance measure than the previous scenario.

8.3.2 The material decoupling point at the billet bay scenarios

8.3.2.1 Altering the material decoupling point to an ATO strategy and moving the information flow downstream

The modelling was based on positioning the material decoupling point at the "billet bay" and the information decoupling point also at the "billet bay". The material flow is run up to the main inventory position at the billet bay. The information is shared upstream with the steel plant. Table 8.8 presents the factors specified for the system design related to this scenario. For the material flow, the entities flow as a push system until reaching the billet bay inventory.

Table 8.8: The material decoupling point factors for the third scenario

Input Parameters	Factors
CODP position	**ATO**
The configuration of the CODP	**Positioning the CODP at the billet bay**
Experiments	**Factors**
Information parameters	
Mix information delay time	$T_M \rightarrow$ UNIF (24, 48) hours
Due date information delay time	$T_{DD} \rightarrow$ UNIF (24, 96) hours
Demand information delay time	$T_D \rightarrow$ UNIF (96, 168) hours
Order batching delay time	$T_S \rightarrow$ 24 hours

This scenario is a proposed case compared to the actual case in Hadeed. Regarding information flow, the information types are shared upstream with the steel plant. The customer arrives with their demand quantities, as depicted in figure 7.5, and is modelled as customer entities that start the stream from the create module, and proceed to the inventory check and delay factors that are tightly coupled and limit the customer order flow. The delays encountered due to scheduling and batching will be lessened because of information sharing and the time needed for coordination. The modelling of the information decoupling point in Arena is similar to the previous two scenarios as delays to the customer entities, replenishment process, and inventory management while decrementing from the inventory positions, which are the billet bay and fulfilling the orders to the rolling mills. The decision logic for the information flow was revealed from the same flow as in Figure 7.5. This incurs a mix information delay that is assumed for adjusting the monthly schedule and holds the production of the steel plant.

The scenario involves moving the information flow position downstream to the billet bay and pushing the material flow upstream to the billet bay. Table 8.9 contains the statistics generated by Arena for the supply chain of the Hadeed case study.

Table 8.9: Performance measures for the third scenario

Measure	Mean	Minimum	Maximum
Total supply chain response time (hours)	941	725	1,193
Takt time/Cycle time (time in system for parts)	245		334
Order fulfilment lead time	936	888	1,284
Manufacturing lead time	196	151	274
Delivery lead time (times parts spend in transport)	48	24	96
Fill rate (target fill rate achievement and average item fill rate)	0.23		
Utilisation of equipments	0.21	0.18	0.33
Throughput	53,877		

The simulation run determined that the total supply chain response time is an average of 941 hours. The total throughput calculated for one month is 53,877 tonnes. The average flow time is 245 hours as the maximum time needed per tonne unit to produce a product in order to meet demand, which means that each tonne needs approximately 10 days on average from travelling from the supplier until manufacturing is completed. The delay here is due to the WIP time, including queue time at the billet bay, and waiting for production orders for the milling plant. The information flow is positioned according to Figure 7.5 and is a similar logic to the previous sections except for the delay factors, which show the information flow in terms of information types and inventory updating and scheduling delays at the steel plant before the billet bay. The specification and associated sizes-related information are less than in the previous scenario due to the scheduling activities, but the effect in this scenario is that there was a delay in the material flow to the rolling mill for determining the specification and order sizes for production and setup times for switching between the mixes. The average inventories are below the ranges of the real situation. This scenario shows good responsiveness but low performance compared to the previous scenarios.

8.3.2.2 Altering the material decoupling point to an ATO strategy and moving the information flow upstream

The modelling was based on positioning the material decoupling point at the "billet bay" and the information decoupling point upstream. The material flow is run up to the main inventory position at the billet bay. The information is shared upstream with the steel plant and the modules plants, based on the information types. Table 8.10 shows the factors specified for this system design in relation to this scenario. For the material flow, the entities flow as push system until the billet bay inventory. This scenario is a proposed case as well as the actual case in Hadeed. Regarding information flow, the information types are shared upstream with the steel plant. The customer arrives with their demand quantities, as depicted in Figure 7.5, and is modelled as customer entities that start the stream from the create module and proceed to the inventory check and delay factors, which are tightly coupled and limit the customer order flow. The delays encountered due to the scheduling and batching will be lessened because of information sharing and time needed for coordination. The modelling of the information decoupling point in Arena is similar to the previous three scenarios as delays to the customer entities, replenishment process, and inventory management, while decrementing from the inventory positions, which is the billet bay and fulfilling the orders to the rolling mills. The decision logic for the information flow was revealed from the same flow as in Figure 7.5. This incurs less mix information delay which is assumed for adjusting the monthly schedule and holds the production of the steel plant.

Table 8.10: The material decoupling point factors for the fourth scenario

Input Parameters	**Factors**
CODP position	**ATO**
The configuration of the CODP	**Positioning the CODP at the billet bay**
Experiments	**Factors**
Information parameters	
Mix information delay time	$T_M \rightarrow$ 24 hours
Due date information delay time	$T_{DD} \rightarrow$ UNIF (24, 96) hours
Demand information delay time	$T_D \rightarrow$ UNIF (48, 96) hours
Order batching delay time	$T_S \rightarrow$ 24 hours

The scenario involves moving the information flow position upstream to the billet bay and pushing the material flow upstream to the billet bay. Table 8.11 contains the statistics generated by Arena for the supply chain in the Hadeed case study.

Table 8.11: Performance measures for the fourth scenario

Measure	Mean	Minimum	Maximum
Total supply chain response time (hours)	825	621	963
Takt time/Cycle time (time in system for parts)	232		325
Order fulfilment lead time	923	841	1,182
Manufacturing lead time	173	142	255
Delivery lead time (times parts spend in transport)	48	24	96
Fill rate (target fill rate achievement and average item fill rate)	0.25		
Utilisation of equipment	0.23	0.19	0.34
Throughput	62,543		

The simulation run determined that the total supply chain response time is an average of 825 hours. The total throughput calculated for one month is 62,543 tonnes. The average flow time is 232 hours as the maximum time needed per tonne unit to produce a product in order to meet demand, which means that each tonne needs approximately 10 days on average for travelling from the supplier until manufacturing is completed. The information flow is positioned according to Figure 7.5 and is a similar logic to the previous sections except for the delay factors, which show information flow in terms of the information types, inventory updating and scheduling delays at the steel plant before the billet bay. The specification and sizes-related information is similar to the previous scenario, but the demand type of information is shared between the steel plant and modules plant, which lessened the demand sharing delay. The same issue as in the previous scenario is the delay in the material flow to the rolling mill to determine the specification and size orders for production, and setup times for switching between the mixes. The average inventories are below the ranges of the real situation. This scenario shows good responsiveness but low performance compared to the previous scenarios.

8.4 Experimental Design Analysis and Interpretation for the Four Scenarios

Table 8.12 shows the different alternatives with the measures and the times. All the results in hours were rounded to the nearest integer number here and in the experiment results.

Table 8.12: Different alternatives with the different performance measures

Measure	Actual case study	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total supply chain response time (hours)	2,237	1,517	846	941	825
Takt time/Cycle time (time in system for parts) (hours)	97	100	91	245	232
Order fulfilment lead time (hours)	789	757	336	936	923
Manufacturing lead time (hours)	131	133	116.24	196	173
Delivery lead time (average times parts spend in transport from complete to customers)	48	48	48	48	48
Fill rate	0.63	0.67	0.93	0.23	0.25
Average utilisation of resources along the production line	0.61	0.63	0.95	0.21	0.23
Throughput in tonnes	269,379	287,235	299,469	53,877	62,543

It can be seen that scenario 2 (positioning the customer order information decoupling point upstream and postponing the material flow at the warehouses) has relatively the best responsiveness and performance measures compared to the actual case study and the other three scenarios, based on the considered performance measures. Scenario 3 has the worst performance measures in the throughput: order lead-time, utilisation, and manufacturing lead-time. The Hadeed case currently has the slowest response time compared to the other scenarios. Figure 8.2 presents the different alternatives with the specified performance measures.

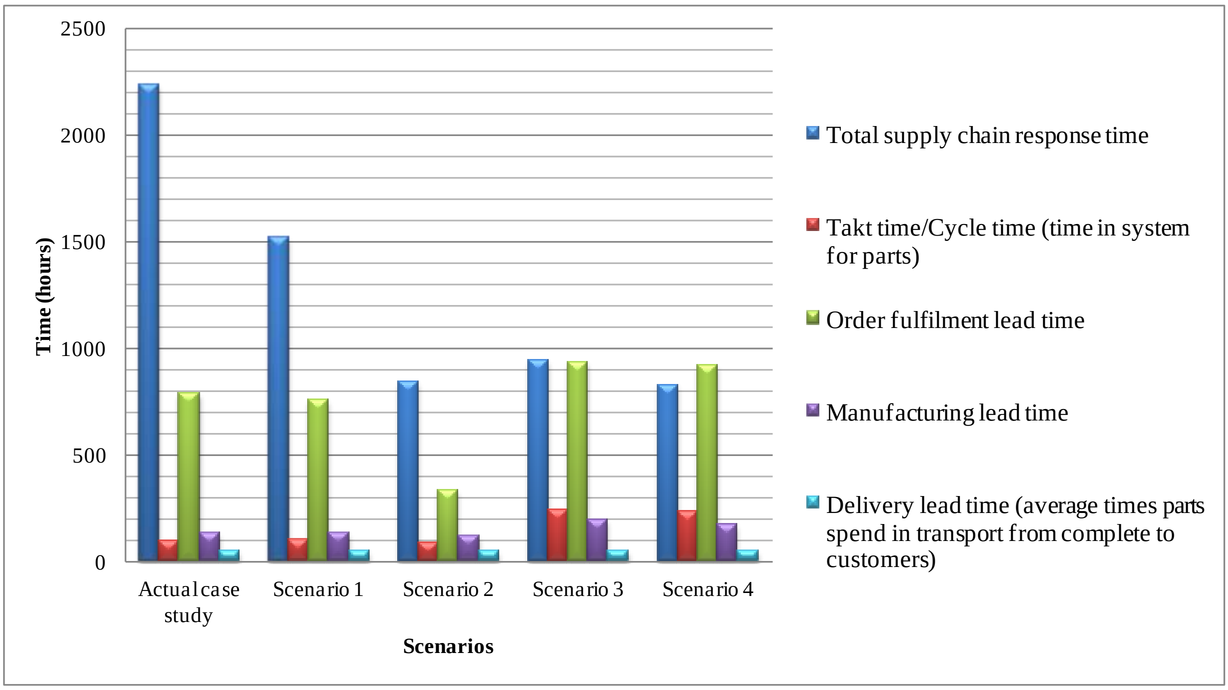

Figure 8.2: Comparison between the scenarios

In conclusion, postponing the material decoupling point to the latest point possible and pushing the information decoupling point with its information types upstream to the furthest points possible in the supply chain, verifies the theory that it performed the best responsiveness when taking into consideration the other performance measures also. The focus was not on the responsiveness measure, as realistically an MTS type of industry such as the steel industry, takes throughput as one of the main performance measures, so adopting the two customer order decoupling points positioned at the farthest point in each flow (scenario 2) showed that the supply chain is a more efficient and responsive scenario than the others. The analysis of the scenarios actually shows the second scenario as the more realistic and feasible scenario. The last two scenarios were feasible but not realistic for consideration as a recommendation to Hadeed's managers. The inclusion of the last two was to test the theory of the decoupling points' movements and their effect on performance and responsiveness measures.

Any demands, mixes, specifications, and due dates change the results in a scheduling change and eventually lead to a delay in the order lead-time and the manufacturing lead-time in all cases. The correction or satisfaction from the inventory, or a slight change in the schedule, was set as the input factor for the experiments.

In terms of flow time, a significant impact was found in the second experiment, which performed at the fastest flow time, as information delays upstream were lessened due to the coordination and sharing of information. The main effect is inside the plant where the setup change times will increase if there is no sharing of information. Production planning and control are generally the main processes that can reduce the order fulfilment lead-time in terms of expediting the orders schedule, and coordinating between the production department and sales team. More timely information sharing and coordination in the scheduling and planning activities, if a change is required, will reduce the need for extensive forecasting and slightly decrease the demand amplification within the supply chain. Moreover, the information flow was found to be integrated with the material flow in increasing responsiveness when the scheduling time can be reduced and the planning efforts can be minimised. However, this type of supply chain, which relies on scheduling and planning efforts, can only be improved if an advanced system is used that reduces the scheduling lead-time so that variability can be removed.

The main method that would improve the order fulfilment is improving the logistics or delivery system. A strategic logistic issue is that Hadeed relies on truck deliveries. Establishing a train network is a major logistic solution for Hadeed. This should link between the industrial cities at Al-Jubail. It would increase the delivery speed and reliability in Hadeed's supply chain.

Thus, the only way to improve the current situation is to reduce the order lead-time by considering the information types and moving them upstream to ease sharing between departments and reduce delays and delivery time. Any improvement in these will affect responsiveness and reduce the order lead-time. The location of the plant in the eastern region, and most of the customers being in the central, north, west, and south, makes delivery challenging. The delivery times in the simulation experiments were constant and could not be reduced due to actual case constraints.

Through experimentation it became obvious, when the different information was pushed upstream in the supply chain, through the modelling as customer entities, and classified under the four types of information: mix, specification, due date, and demand, to the latest sharing points possible, and through postponing the material decoupling point to the latest point in the supply chain, that responsiveness was maximised. Also, the other performance measures and decoupling zones were represented as customer entities upstream in the echelons, and the information decoupling points made buffering points in the modelling and acted as decision-sharing points that affect the performance and responsiveness of the supply chain. Figure 8.3 shows the zonal decoupling area where the customer order information delay will be reduced if sharing is achieved between the responsible echelons. Through the scenarios' observation and modelling, the decoupling zone was distinguished when considering the mix (size) change, quantities, inventories, due date, and specification. The position when triggering the inventories, and knowing when to hold and start to produce through the simulation, which led to the CODP positions in terms of information types flowing upstream and the major martial point downstream, depends on coordination between the departments within these zones in relation to the four different operational factors that affect the customer order information flow.

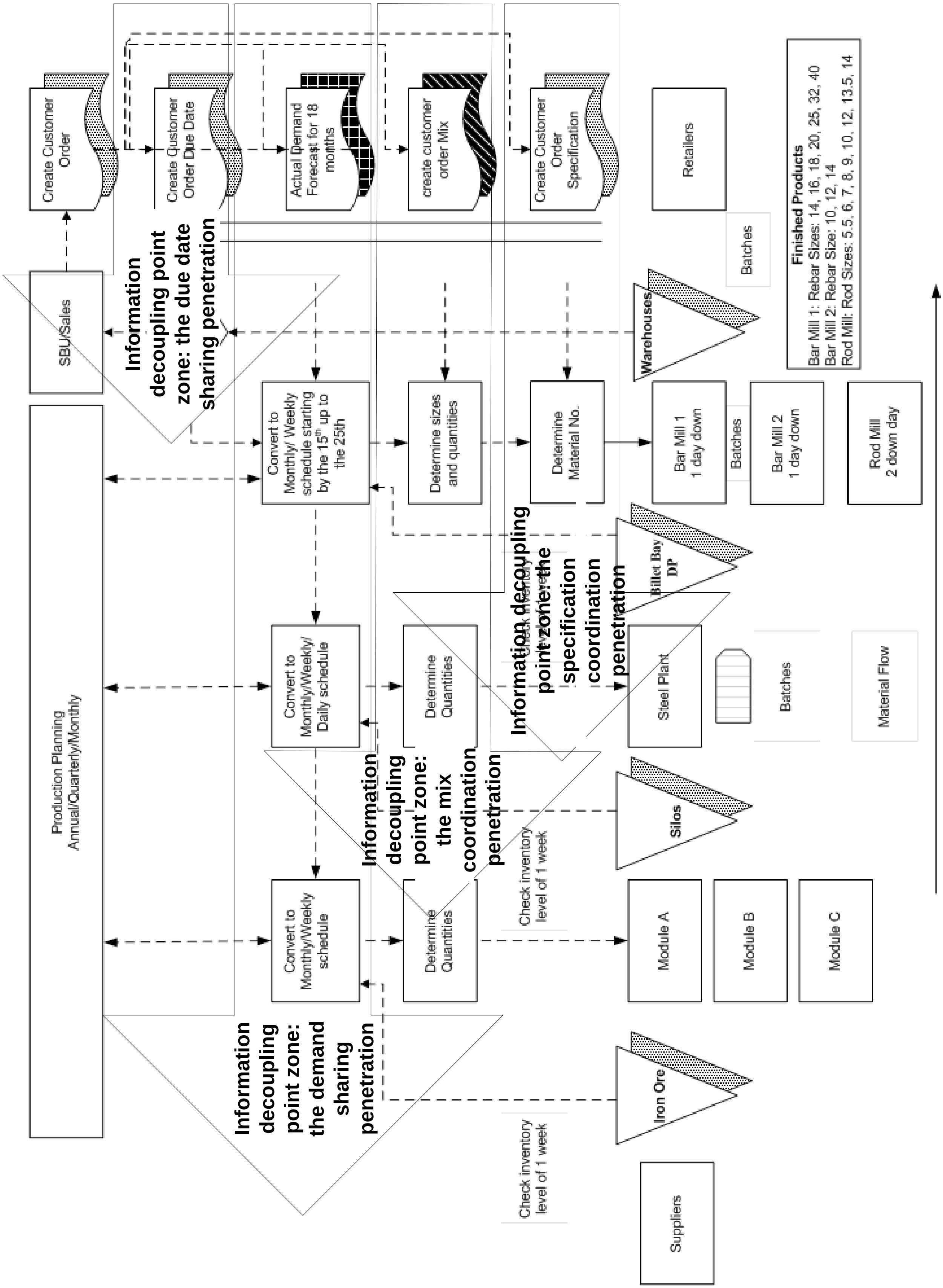

Figure 8.3: The zonal concept in relation to the scenarios

8.5 Chapter Summary

This chapter has presented a collective analysis of the results obtained from the simulation experiments described. Within this analysis the impact of the material and information customer order decoupling points on the responsiveness and performance measures has been investigated. Furthermore, four alternatives or representations have been investigated and compared to the actual case study. The collective analysis of the experiment results produced two key findings:

The first finding: postponing the material decoupling point downstream to the latest point possible and positioning the information decoupling points upstream, including all the classification of the information types, maximises responsiveness and improves the performance of the supply chain.

The second finding: the information decoupling points' classification and entries showed a zonal area that can be represented in the supply chain to ease the coordination for the mixes, specifications, demand, and due dates changes, which were the main factors in the simulation experiments to be considered during the modelling and through the variability of the supply chain systems between demand and supply.

This chapter concludes the research programme. Chapter 9 now concludes the thesis. It presents the key findings and conclusions from each of the research stages and highlights the contribution to knowledge made by the research. Finally, the limitations and concerns are discussed and recommendations are made for future work in the research field.

Chapter 9

Discussion, Conclusion and Future work

9.1 Introduction

The research conducted in this thesis explored the responsiveness of the supply chain. A review of the literature proved vague in terms of measuring agility, with the focus on the customer order decoupling point (CODP) and its zonal concept, as it was presented with various theoretical perspectives which made it less effective. The research has combined the CODP with responsiveness to serve a supply chain to become more agile and integrate the decoupling point with responsiveness assessment. This research can be used by academics as well as industrialists to utilise the CODP to help in analysing their supply chains and maximise its agility.

This chapter explains how the research objectives were met. It discusses the methodology chosen to achieve the objectives, the suitability of the adopted methodology and the potential for improvement on the methodology. The contribution to new knowledge is also described, together with a discussion on the application of new knowledge for academics and industrialists.

9.2 Fulfilment of Research Objectives and Discussion

This section discusses the objectives of this research and the methodology used to meet the objectives as shown below:

9.2.1 Objective 1: Identify the characteristics of CODP methodology, and the zonal concept, from the material and information decoupling points, their positions, and the extent to which that can be used to analyse the agile supply chain.

The review of literature on leanness, agility, leagility, the decoupling point’s concept, postponement, and product variety, identified the dimensions used to characterise and understand the decoupling point’s classification, positioning, and extent. Two main positions of the decoupling point were identified by extending the information decoupling point to include four further dimensions of customer order information related to product mix, product specification, lead time, and demand volume, while the material decoupling point conforms to the traditional decoupling point.

The CODP methodology was also extended to include two separate decoupling points: one of which conforms to the traditional CODP that was cited in the literature, and the other is related to customer order information as covered in Section 2.6.7. The material decoupling point refers to the stages or types of supply chain/manufacturing system (MTS, ATO, ETO, and MTO) and employs postponement and delivery strategies.

The literature has linked the CODP to a specific customer order methodology (cf. Hoekstra & Romme, 1992; Mason-Jones & Towill, 1999; Mason-Jones et al., 2000b; Towill, 2005b). The traditional decoupling point was previously used to separate the upstream and downstream players for the supply chains where the order-driven activities and forecast-driven activities meet (Beulens et al., 1999; Mason-Jones & Towill, 1999). In this research, however, the information decoupling point was also added to the concept. Further dimensions were also examined with the information flow, which is a direction for further new research. The information decoupling point is treated as shared information related to demand information, which when moved upstream provides the players with the advantage of not processing defective data. This led to the research theory of moving the information decoupling point upstream to achieve the positive effect on the agility of the supply chain, as little has been done to address this in previous research studies. The current case studies were selected having considered the various customer decoupling points. Another research trend by Olhager et al. (2006) and Wikner and Rudberg (2005a, 2005b) identifies that there is a decoupling zone but the idea was not tested nor its characteristics clarified. Figure 9.1 shows the decoupling point zones that were proposed in this research.

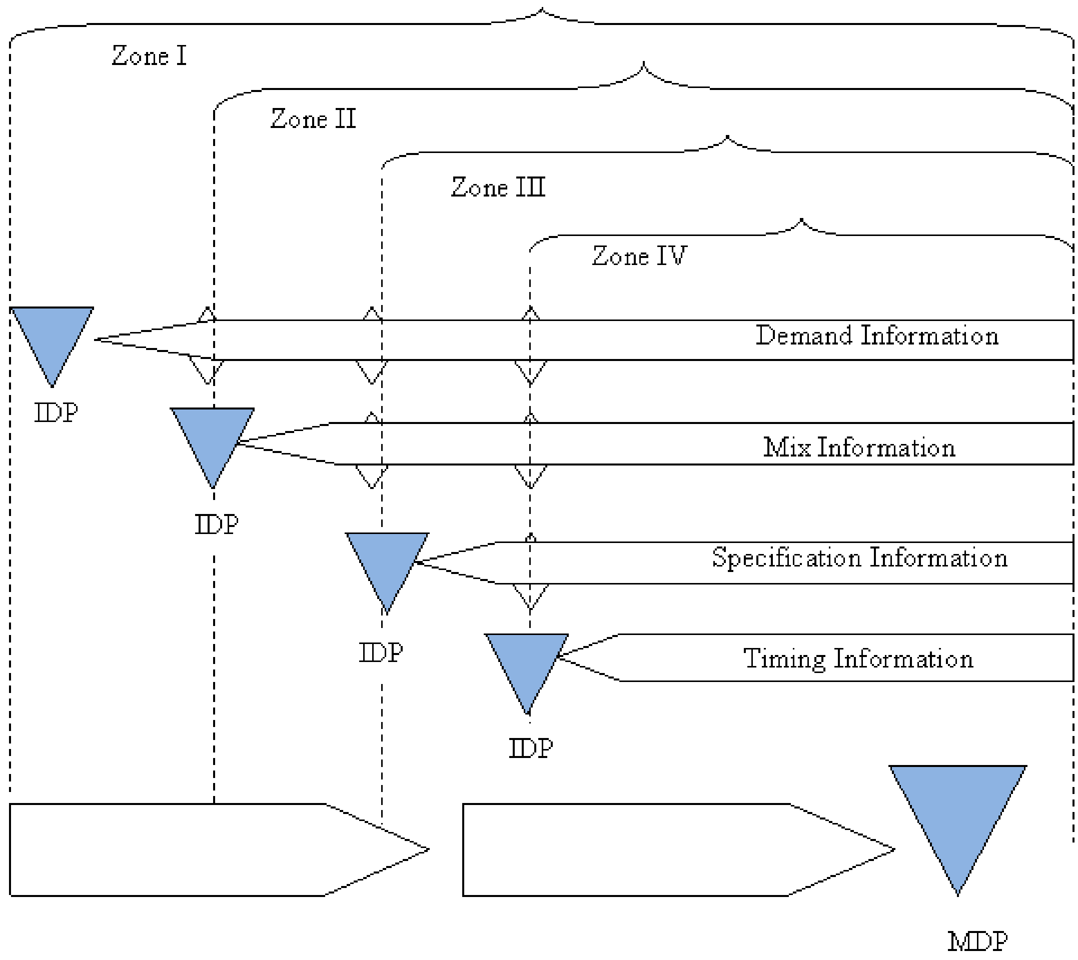

Figure 9.1: The decoupling point zone

The CODP has been examined in the literature as a linear concept by positioning it based on the production and delivery proportion (P/D) approach, and sometimes focusing on one type of manufacturing system with focus on activities of that type upstream and downstream of the order information or from a certain perspective. However, the CODP methodology was extended to two dimensions which are first proposed by Wikner and Rudberg (2005a) who focus on the engineering-related activities to be added to the CODP as a continuum. It has been found that the CODP is so useful a tool for analysing operations, and this has been extended from a different, two-dimensional perspective by Wikner and Rudberg as they focus on adding an engineering dimension to the CODP tool, but this dimension is believed to be part of the ETO type of industry mainly, and therefore it has not been tested in this case study. The next extension idea is by Olhager et al. (2006) whereby the CODP is split into two separate decoupling points, one for the product and the other for the demand mediation, and brings the zonal remarks between the points, which they extend using the Fisher framework concept. In this research, the extended customer decoupling point was based on the material and information dimensions, and the classification considered above was applied in the literature case studies in Chapter 4 and in the in-depth case study to reflect the different kinds of industries and the positioning in each case.

The positioning of the CODP was treated from a strategic point of view (Olhager, 2003) and three factors were identified (market, product, and production) that affect the positioning and shifting of the CODP. Two of Olhager's factors were chosen for this research; volatility was excluded as it is a qualitative factor and the orientation for this research has focused on quantitative factors. However, discussion on CODP positioning is scarce. Sharman (1984) presents the CODP in a logistics position where the product specification is frozen and the last point of inventory is held. The product specification was also added to the research as it is necessary in determining the last point of the inventory held. Olhager and Ostlund (1990) include product structure as a factor with the bottleneck position, which controls the push and pull system integration. However, this leads to the product mix factor as it translates the depth of the product structure and includes a range of associated products that are offered by a firm. Also, Hoekstra and Romme (1992) refer the CODP to the logistics strategy and define it as the point that balances between push and pull systems and is analysed based on the product structure and bottleneck position.

The new knowledge here is that the CODP was extended in two ways to test the theory by applying real cases from the literature. An in-depth case study was also undertaken that increased the scope and acceptance of the CODP and coupled it with agility. This adds to current knowledge by analysing the supply chain based on the decoupling point, and assessing responsiveness based on the CODP analysis.

Four case studies based on the literature were used in an attempt to test the literature review findings. These have included different types of industries to test the positioning of the material and information decoupling points upstream and downstream. The test was designed so that there were four definite possible material decoupling points in four normal situations, but the examination was such that the material decoupling point should be delayed until the latest possible position. This test was done in two stages:

- First, by answering the research questions to identify any existing ideas from the case analysis;

- Second, through the adopted methodology for the simulation modelling.

Research Objective 1 has been proved through the case studies by moving the material decoupling point downstream and involving complexity in terms of possible configurations and issues that have been treated for both the material and information decoupling points. Also, by introducing the two extended decoupling points, it has been tested based on the research questions provided in Chapter 1, which proved that by separating the customer decoupling points, a high level of agility was achieved.

9.2.2 Discussion on the methodology adopted for fulfilling Objective 1

The methodology adopted attempted to capture most of the decoupling point's components used in the supply chain analysis. It was believed that this research needed to consider the information decoupling point to better understand and analyse the supply chain. The CODP was defined as a two-dimensional concept that treats the CODP from material and information flows based on the logistics/material decoupling point, as reported in the literature, and the information decoupling point integrating four types of information. The methodology adopted was to identify the factors related to the CODP that affect agility by focusing mainly on the positioning of the two major factors from the material and information perspectives.

9.2.3 Objective 2: Assess responsiveness from an operational perspective that can be used to analyse and measure the performance of the agile supply chain.

Various definitions of the agility paradigm (cf. Christopher, 2000; Katayama & Bennett, 1999; Kidd, 2000; Power et al., 2001; Sharifi & Zhang, 1999) were vague in the concept, which led to a working definition of agility focusing on the responsiveness measure. Earlier definitions showed agility from an organisational point of view (Goldman et al., 1995; Groover, 2001; Meredith & Francis, 2000; Nagel et al., 1991); debated the concept of leanness; and defined another paradigm combining leanness and agility into the leagile concept (Agarwal et al., 2006; Krishnamurthy & Yauch, 2007; Mason-Jones et al., 2000a, 2000b).

This research therefore adopted responsiveness as a main aspect of agility and identified the components of responsiveness assessment from the literature, in order to achieve agility of the supply chain. It was found that the responsiveness measure is the most suitable component of agility that can link with the decoupling point methodology and adapt to the simulation modelling, as it can be computed quantitatively.

Responsiveness through agility components was captured for the four case studies examined in Chapter 4, and the responsiveness assessment was carried out at the supply chain level. The literature review shows in Chapter 2 that agility has been seen as a business-wide capability, inclusive, and viewed from an organisational perspective. This needs wide-ranging research to actually define and contain the concept, and for this reason it was decided to characterise agility from the responsive perspective, with responsiveness as the quantitative measure, which was introduced and presented in Chapters 5 to 8 inclusive.

9.2.4 Discussion on the methodology adopted for fulfilling Objective 2

Since agility is still in the development stages, evaluation of the literature showed a gap in terms of operational measures; and the research can be extended to enrich the enquiry and help in assessing responsiveness.

The novelty of this approach is to assess the responsiveness of the agile supply chain through the context of the decoupling point changes and supply chain. The contribution is the assessment of responsiveness at the supply chain level and a methodology for conducting this assessment.

The assessment methodology proposed here focused on responsiveness and its potential changes since the focus was on the operational perspective. Responsiveness assessment is to test when and how to respond to changes through the modelling of the supply chain introduced in Chapter 4. The challenge was to obtain sufficient data so as to consider the changes the system may be subjected to.

9.2.5 Objective 3: Investigate whether or not positioning the material decoupling point downstream of the supply chain and the information decoupling point upstream of the supply chain is maximising responsiveness. Relate the decoupling zone as a valid concept.

This objective was articulated as a hypothesis to be tested. To discuss this hypothesis, an investigation was carried out to gather what had been cited about the customer order decoupling points, and the ideas were arranged after the literature review with this objective. The methodology used to investigate Objective 3 was guided to test whether positioning the material decoupling point downstream of the supply chain and the information decoupling point upstream of the supply chain would support the idea of increased agility through responsiveness. The literature showed that there is a relationship between agility and the decoupling point. An attempt was made to link the agility and decoupling point methodology within the case studies and simulated case study. It was found that positioning the material decoupling point downstream of the supply chain and the information decoupling point upstream of the supply chain supports an increase in agility. The agility characteristics that were described in the literature-based case studies proved agility internally and externally in the supply chain cases, in accordance with the research questions in Chapter 1.

Research has been investigating supply chain situations and constructions that can support the efficiency and performance of the supply chain (Bowersox et al., 2007; Fisher, 1997; Ismail & Sharifi, 2006; Towill & Christopher, 2010).

The decision about the positioning of the material decoupling point has been discussed in the literature but the point here is analysis of the positioning. The case studies helped to observe the placement of the information and material decoupling points in the case studies' environments. This led to an analysis of the case studies based on the research questions to find out how the coordination and mechanism of the case studies can be exploited to verify the theory inquiry.

The analysis of the case studies was limited to the availability of information and certain specific elements dependent upon the material and information decoupling point positions for each case, product types, etc. The analysis was directed to the upper supply chain level in relation to methodology constraints. However, the results showed that the material decoupling point is optimally positioned at the latest point possible in the material flow, closer to the customer, depending on the material decoupling point strategy adopted. Regarding the information decoupling point, it was directly related to the available information collected which mainly started with focusing on customer orders going into the information flow, through the ordering process, coordination, and the information is moved upstream until the forecast-based data approaches. The in-depth case study that was based on make-to-stock (MTS) affected the flow and calculation of the information since the forecast information for all the information types was already placed upstream. The information was characterised according to the classification adopted and the orders were controlled by scheduling systems of production, which was carried out using systems logic. The possible material decoupling points for the case studies were included, lead time for both cases was calculated and the information for both cases was included, taking care with the approach of the methodology presented in Chapter 5 which regulated the analysis. Upstream of the information decoupling point, the knowledge of the demand information was used by the make-to-stock case through periodic replenishment of the order-up-to-level. The application of the methodology adopted showed that it was possible to reduce the lead-time cycle while changing the positioning of the decoupling points. The case studies showed the limited value of moving information upstream due to the type of industry and available access. The other case studies from the literature proved the effectiveness of moving information by sharing information between the supply chain players.

In this research, an assumption has been visited and a methodology to address the problem using two approaches: one went over the literature-based case studies and one focused on a simulation-based case study by combining discrete event simulation with the decoupling points' positioning and assessing responsiveness.

The second part of Objective 3:

Mason-Jones and Towill (1999) are the first to extend the decoupling point to two pure flows. Olhager et al. (2006) takes the decoupling point into the decoupling zone, which is the first substantial work towards extending the decoupling point. The research here has taken the decoupling zone into two dimensional approaches: the material flow and the information flow. The information flow consists of four types as shown in Figure 8.3 and Figure 9.1. The proposed types of information extend the information decoupling point to four decoupling zones. The material decoupling point is proposed as the traditional customer order decoupling point to the four strategic types (MTS, ATO, MTO, and ETO). For each material decoupling point based, four types of information decoupling point can be applied. The in-depth case study, Hadeed, which is MTS, has the four types of information flow.

There was evidence of the zonal concept in the information penetration upstream of the supply chain, which conforms to the literature about the idea but differs in the content and information types considered. The discussion presented below shows the methodology adopted. The results obtained from the case studies are promising, but extensive validation is needed for different types of decoupling point strategies to fully explore the link between agility and the decoupling point.

Chapter 9: Discussion, Conclusion and Future work

This research has divided the customer order decoupling point (CODP) into two separate decoupling points: the material decoupling point (MDP) and the information decoupling point (IDP). The analysis performed in Chapter 4 and, as further shown by Figure 8.3 and Figure 9.1, classification of the information types of the information decoupling points, divide the processes of the supply chain into an upstream zone and a downstream zone. The decoupling points can be positioned away from each other through the supply chain, creating four main zones upstream of the MDP.

Figure 9.1 also shows that the IDP is placed within four zones that start from the customer order information, and this is where products manufactured are assigned to specific information types. In Zone I, from the MDP downstream up to the IDP-Demand information, full market demand information is available in the form of actual customer orders. The supply chain has the advantage to organise order fulfilment and its design could absorb demand changes in the market, forming buffer resources upstream. The IDP-Demand information is positioned at the most upstream point in the supply chain, to where information about customers' demands is transferred without modification.

Upstream of the MDP point in Zone II, information about customer orders in terms of products mix and variety can penetrate upstream in the supply chain to the IDP-mix information, which enables the company to satisfy specific customer needs, and to respond to customer orders quickly under some certainty of the orders, and the supply chain has to prioritise replenishment at the IDP-mix buffer where mix information is relatively stable. The supply chain in Zone II should be designed to adapt product mix to provide maximum return in revenues and maximum responsiveness.

Downstream of the IDP-mix and IDP-demand, and upstream of the MDP in Zone III, the function of the supply chain is to replenish based on the customer order specification. The customisation of products based on specification regulates the processes at the IDP-specification to access some order information about specification. The supply chain should therefore be designed to adapt the customisation based on customer order information per specification to balance the efficiency of products flow, based on replenishing the batches of the products, based on the specific information of orders buffer.

In Zone IV, the timing of the customer orders must be maintained in order to fulfil immediately from the physical MDP and not to lose customer demand. This zone covers from MDP up to the IDP-specification to facilitate the company configuring the buffer where the promised due date can take place based on the physical IDP-timing buffer. The main purpose in Zone IV is to maintain a high service level at the MDP physical inventory and ease the replenishment and fulfilment of customers' orders.

9.2.6 Discussion on the methodology adopted for fulfilling Objective 3

Triangulation was used in this thesis, which tried to answer the research questions about the resulting agility while having decoupling points at the latest point upstream and downstream, to enhance confidence in the findings that support the research enquiry. The strategy adopted to fill the gap in the literature was to start with four well-known case studies to answer the research questions as stated in Chapter 1.

The discussion about the case studies from the literature was presented in Chapter 4. Consequently, one in-depth case study was chosen to increase the evidence in the practical environment following a modelling analysis, which is presented in Chapter 5, to perceive the nature of the supply chain systems and consider the tasks adopted to find the results that confirm the hypothesis. The first four literature-based case studies exhibited characteristics information regarding the positioning of the decoupling points. Significant evidence came through about:

1. The triangulation of measuring decoupling points' positions;
2. Investigation into various integration strategies.

This research adopts the traditional CODP as the material decoupling point (MDP), which is classified for the different manufacturing environments such as make-to-stock (MTS), assemble-to-order (ATO), make-to-order (MTO), and engineer-to-order (ETO), all of which relate to the different positions of the MDP. The conceptual model shown in Figure 9.1 is applicable for each CODP strategy.

The information decoupling point has been classified to the different types of information that could be useful in the mediation of information before it is magnified, distorted or not shared completely. Figure 9.1 shows the information decoupling point (IDP) and its positioning upstream.

The results from the case studies, which were between MTO and ATO, showed the influences of the decoupling point from the material and information flow point of view, and also showed that a decoupling zone is valid in terms of the information decoupling point, in accordance with the research questions for the case studies and the proposed classification of information types.

The companies went to some length to improve the utility of the information that is related to the orders:

1. **The demand information**: for the companies' cases spanned through demand fulfilment to control the execution of all the processes before the information decoupling point, subject to the other information types. ATO and MTO types of industries from the case studies focused on assembly orders upstream, raw material and WIP inventories for the assembly, and the downstream tasks are demand information related to demand in terms of delivery of orders from the stock to the customers. The MTS case was similar to the traditional location of the MDP which focuses on the delivery of orders directly to the due date type of information that allocates from stock to the different locations for the customers and warehouses. The transparent sharing of this information resulted in a full agile supply chain.
2. **The mix and specification information**: was used for the case studies as the key part of MRP, ERP, and MPS, which identified the information that relates to the operations for the scheduling activities. The information decoupling for these types resulted in the production orders adjusting the order quantities, and expediting the late orders. The information before the decoupling point for ATO and MTO types focused on the requirements for all assemblies and components. The MTS showed a penetration of this information related to the orders and adjustment of special orders and late orders. The information helped the companies to be more agile through rapid replenishments for the orders.
3. **The timing of orders:** was extended upstream more for the ATO and MTO cases due to the long lead-time. The MTS case focused on the ATP and CTP activities which were limited in the upstream activities related to order promising.

9.2.7 Objective 4: Critically evaluate the effect of the positioning of the decoupling point upon supply chain agility in a real case study within a simulation modelling analysis.

A review of the literature showed how the system dynamics type of simulation has been used for supply chain analysis accompanied with the customer order decoupling point, but showed a limitation in the exploration of the concept of CODP to certain industries and types of manufacturing system. Forrester (1991) mentions that few realise how everything is done in pervasive systems and enclosed systems, and literature deals differently with different kinds of systems. This was the case with the decoupling point and the supply chain. Towill (1996a) evaluated the use of simulation and the effects of various strategies on demand amplification. Evaluation was based on the systems' dynamics perspectives and many from the same group investigated from that perspective. To fulfil this objective, analysing a real case study in-depth and linking it to agility will help in realising the dynamic behaviour. To add to the knowledge, a different tool to observe the supply chain with, and an extension of the research direction from a different perspective, through discrete event simulation, was considered. The evaluation compared the real case of current processes with the designed decoupling point and the new type of system when a new structure would be applied. Most difficulties are due to the internal and external factors that affect agility, alongside the wide-range underground knowledge about agility, which enforced the orientation of the research to rely on the responsiveness measure as a main quantitative measure for the simulation and quantitative analysis.

From the analysis of the in-depth case study in the experimentation, it has been found that positioning the material decoupling point at the latest point close to the customer and positioning the information decoupling points upstream at the farthest point possible was maximising responsiveness. The discussion about how this objective was met is presented in section 9.2.10.

9.2.8 Objective 5: Critically evaluate a new modelling representation that is suitable for the analysis of an agile supply chain.

The literature was examined to identify perspectives and concepts from other modelling techniques and thoughts that could be used to plan characteristics in the supply chain systems. Chan and Chan (2005) identify that there is a lack of a systematic approach to supply chain analysis. Strandhagen et al. (2006) raises the importance of the control dashboard which concurs with the supply chain management aim, but their representation differs in the construction, the actors and thereby the consequences of the decisions made. Most of the modelling for multi-stage supply chain systems has been in the push-pull flow lines, Kanban, and just-in-time concepts. Mathematical analyses of such systems are quite difficult, optimal, and approximate solutions are found for small problems using numeric techniques (Altiok, 1989; Altiok & Melamed, 2007; Gurgur & Altiok, 2004; Karaman & Altiok, 2009). Discrete event simulation is one of the recommended tools for complex systems analysis (Banks et al., 2005; Carson, 1986). Simulation has been used as an analysis tool to predict the performance of an existing system (to assess responsiveness) and to test the new proposed design using the possible material decoupling point. Appendix A presents the simulation modelling in supply chain; definitions, classifications and comparisons between the tools and reasons for choosing discrete event simulation were provided in Chapter 7.

The causal relationships between the decoupling point methodology (material flow, information flow, information types, and decoupling zones) and agility measurement led to creating a structured methodology through DES modelling, to analyse the supply chain with a focus on responsiveness as an agility aspect. The data collected for the case study was discussed in Chapter 7. Then the modelling was validated and experimented with using the case study, which was introduced in Chapter 7 and experimented with in Chapter 8 by applying the decoupling point positioning to examine the effect on responsiveness. The analytical approach to studying the supply chain in relation to the decoupling point was the main contribution linked with agility, which focused on decoupling point positioning and its effect on agility. Also, the model can be exploited by practitioners to find the best effectiveness in various sectors. However, the implementations, descriptions, and stages for any developed simulation differ based on the industry type. Thus, the Hadeed case study was modelled using Arena as a simulation tool to quantify the impact of the decoupling point positioning on agility. The established framework can be generalised for any firm by applying the same principles and considering the decoupling point's positioning. Cardiff Logistics Systems Dynamic Group (LSDG) has served to point out the importance of the material and information principles in general, and focused on the combination of lean and agile into leagile using simulation, but their perspective was on reducing the bullwhip effect, and system dynamics (Christopher & Towill, 2000, 2001; Mason-Jones et al., 2000a; McCullen & Towill, 2001; Naim et al., 2009; Naylor et al., 1999; Towill, 1996b). Simulation and designed experimentation provided added value to the knowledge, which can be used to improve supply chain performance. The simulation coupled with the experimentation provided a useful tool to highlight the analysis of the agile supply chain.

The discussion about how this objective was met is presented in section 9.2.10.

9.2.9 Objective 6: Test the effect of the positioning of the decoupling point upon supply chain responsiveness.

The discrete event simulation model tested the case study using a quantitative assessment of the different configurations of the decoupling point's positioning. The case study supply chain covered two main configurations. It was a MTS type of industry, so rigid scenarios and close effects were computed based on the data collected, the design parameters, and the number of echelons of the supply chain. Chapter 8 presented the experimentation plan for implementing the model, which was the test stage of the modelling. The concept of positioning the decoupling point was further tested and refined using the four literature case studies. The experiments were designed to search between the possible material decoupling point positions and adjusting the logic for each case study simulation problem. It was a simplified representation of a three-tier supply chain including the scheduling system with Hadeed's high-volume manufacturing constraints.

Responsiveness was assessed by comparing the lead times of the supply chain for the case study between changing the material customer decoupling point from MTS to MTO or hybrid MTO/MTS. Placing the CODP closer to the finished product results in lower cycle times. The result was that agility increases as the material decoupling point is delayed closer to the customer or latest point possible. Different types of information and degree of penetration were investigated. The case study type using the simulation showed that the information flow can be shared up the steel plant, which means that beneficial information can be pushed upstream to be the point for positioning within the zones of the information decoupling point, which has been modelled for the information types considered.

The key finding in the Hadeed case study is that the current position for the material decoupling point is not the ideal position from a dynamic perspective in parallel with the responsiveness assessment. This could be seen in the current Hadeed case supply chain, subject to the assumed variables, collected data and generated distributions. The results of the experimental simulation show that the second scenario: has verified the hypothesis of positioning the customer order information decoupling point to the most points upstream and postponing the material flow at the warehouses scenario; and has a reduced lead time cycle, which means the current positioning of the decoupling point is slow to respond to the customer and market changes and therefore incurs a great financial risk of lost sales for the manufacturer if MTS with the current system is maintained.

Chapter 9: Discussion, Conclusion and Future work

Chapter 8 detailed the different scenarios for the in-depth case study of Hadeed, a MTS type of industry, and can be generalised to a certain degree for similar types of industry. The effects of the different types of customer order information when shared upstream showed significant performance results improvement with better production output and more responsiveness.

The limitation of the simulation study was seen when changes could not add significantly because of the type of material decoupling point applied, which constructed the schedule ahead of time based on the annual demand volume, and it was a challenge to not change and intervene with the schedule of the steel. However, production scheduling in the steel industry is known to be one of the most difficult industrial scheduling problems because there many constraints, and several studies have focused mainly on the steel operations in stages. Going into detail in a steel case study is so complex, expensive, and requires such a long and accessible study to be able to enhance the logic, expert system, and methods used to optimise the production strategy. The project modelling was simplified by choosing to simulate the upper level of the steel supply chain and define the major players of the supply chain.

This study adds to the work related to steel-based research since there are few modelling applications and analysis, although the steel industry is a basic industry where very little work has been done in the areas of inventory and manufacturing control of steel plants in terms of supply chain studies.

For the literature case studies, Chapter 4 considered four different well-known companies that have invested in technologies to shorten lead times so the company can be more responsive and closer to market demands. The companies' cases illustrated the importance of the positioning of the customer decoupling point to the agility measurement. The case studies of Benetton, the National Bicycle Company, HP, and Whirlpool, have proven the theory and identified clearly the positioning for the material and information decoupling points. The methodology for conducting the case studies based on the literature is presented in Sections 9.2.6 and 9.2.10.

A discussion about how this objective was achieved is presented in section 9.2.10.

9.2.10 Discussion on the methodology adopted for fulfilling Objectives 4, 5 and 6

The research method used for the in-depth case study to evaluate and test the effect of the decoupling point was quantitative and involved a computer simulation tool. The complexities of the simulation studies are the considered composition and expansion of the stages that can be added to the concepts in the supply chain analysis. The in-depth case study was used in this research to help in evaluating simulation modelling. Some simplifications were made and various variables and characteristics were considered which differ from one simulation study to another based on the variables and characteristic adopted. Chapter 5 regulated the stages and variables considered for the evaluation method for the in-depth case study. Chapter 4 presented the literature-based cases studies.

The modelling of the supply chain considered the inventory level, ordering process, production and delivery lead times, and some of the data, which is explained in Chapter 6. The aim was to assess responsiveness based on quantitative performance measures and according to market changes, response time, fill rate maximisation, and lead-time minimisation. The advantage of this methodology is that it evaluates agility according to the response time for each task, route, and the supply chain in general.

The simulation analysis permitted quantification of the effects of positioning the decoupling points, the inventory, and changes in customer order fulfilment. For future work, evaluating the effects of including more details in the simulation model without complicating the analysis would be useful in expanding supply chain research that relates to the simulation area. Also, including more details about the control levels throughout the supply chain is going to help in modelling and analysing supply chain systems.

Chapter 3 discussed the methodology used in detail.

9.3 Methodology Strengths

The methodology adopted to analyse the agile supply chain showed how it can be tested using the Hadeed case study, presented in Section 9.2.9, and the results of testing the methodology for the in-depth case study. This shows how the agile supply chain can be modelled and experimented using simulation while considering the decoupling point positioning. It tested two alternatives for the material decoupling points and showed which one achieves maximum agility through responsiveness. This work conforms with Mason-Jones and Towill (1999) and Christopher and Towill (2001) in how to achieve agility using an integrated model of an agile supply chain, as well as the design of the decoupling points in optimum zones. The analysis of the information decoupling point with its types added a new dimension to the design and analysis of agile supply chains. These considerations, agility measurement, and material and information decoupling points positioning, formed the core activities and showed a new dimension that enabled improvement in supply chain agility, responsiveness, and efficiency.

Consequently, the case studies in Chapter 4 that were based on the literature confirmed the testing of the material and information decoupling points' positioning through the research questions in Chapter 1 and detailed in Chapter 4, and enabled the testing of various types of material decoupling points. The strength of the methodology adopted is believed to have been achieved through the use of quantitative and qualitative case studies. One relied on the simulation and the other on the literature review.

9.4 Methodology Limitations

Although the Hadeed case study was large, the modelling and approach is simplified using the simple step-by-step guidance of the methodology in Chapter 5. Simulation modelling is always limited by cost and the time available. Collecting, accessing, and verifying the data and results in the Hadeed case study was so complex due to the complexity of the industry adopted and the simulation modelling length. However, the model consisted of a high level of the supply chain, which was of interest. This promoted the need for enough time to understand the case study, model it, write the software, run it, and then analyse it.

One of the limitations of this methodology is related to the fact that industrialists, who will use this methodology to analyse the supply chain and assess responsiveness, are required to have considerable knowledge of the nature of the supply chain, material and information flow and using simulation software. Also, accurate data needs to be collected throughout the sequenced stages of the model.

The model is a stochastic simulation model which produces only estimates that follow the input parameters (Law, 2007). However, it would be more appropriate if the analyst could be present at the project location during the study, so that he can carry out the study in the proper time and access the required information when it is needed.

The second part is the case study that is based on the literature. This was limited due to the limited information about the problem observed and the inflexibility in changing or following the material and information flows. Also, the information collected to conduct the study, satisfy the research questions and achieve the objectives was assumed to be accurate and logical opinions.

The material and information decoupling points and agility have been accepted as concepts already used in the literature whilst being aware of its limitations.

9.5 Achievements and Contribution to Knowledge

This section reviews the contributions this study has made to new knowledge. The greatest impact of this research will be for the practitioners/managers who intend to adopt new manufacturing practices/tools within their organisations. The responsiveness assessment framework in the research would be a valuable aid to help managers/practitioners gain insight into the supply chain/analysis they could adopt or adapt to achieve competitive advantage in their businesses in order to achieve agility. The following contributions were made:

1. This research studied the concept of the decoupling point with agility alongside distinguishing between material and information decoupling points, one upstream and the other downstream. A new analysis of the customer order decoupling point methodology has been explored relative to the information and material flows. Four types of information decoupling points were identified, and characterised the different conditions and types of information flow upstream.
2. While most researchers in the area of operations and production management illustrated the lean, agile, and leagile paradigms using the traditional decoupling point, this research provided an analysis of the supply chain, thus allowing managers to analyse and evaluate the supply chain in their own systems in terms of its responsiveness and agility, and finding the decoupling zones between the information and decoupling points. This analysis incorporated the responsiveness measure, and a set of variables and factors related to the decoupling points (e.g. inventory level, inventory mode), which helps the manager better understand the supply chain system.
3. Very little attention has been given to the decoupling point concept. This study extended the work of Mason-Jones and Towill (1999) by proposing a method of modelling that considers the material and information flows, and introduces a novel

approach for analysing supply chain performance based on the decoupling point positioning while assessing supply chain responsiveness.

4. This research combines DES modelling with the decoupling point concept as most of the literature focuses on the system dynamics (e.g. Towill, 1996a) as standard integration methodology for the leagile supply chain. This study proposed a new supply chain modelling methodology that can enable managers/analysers of supply chains to cope with their supply chain performance and keep it agile and competitive.
5. This research also shows how the modified decoupling point methodology can be applied to the analysis and evaluation of a supply chain's performance and agility. Exploration of the decoupling point positioning with agility achievement was used for multiple case studies from the literature that shows the decoupling point effect from the material and information perspectives.
6. A new positioning conceptual approach has been proposed showing the different zones related to responsiveness and agility. This contributes to the decoupling point concept by extending it to a zonal concept.
7. The research presented the zonal concept from two dimensional approaches, material and information flow (four dimensions: demand, mix, specification, timing per customer order information), and differs from Wikner and Rudberg (2005a) and Olhager et al.'s (2006) research, who think about the zonal concept from engineering and demand mediation perspectives only.

9.6 Conclusions

The conclusions drawn from the research and case study implementation, together with possible further research areas to extend the application of the decoupling point and agility, are shown below:

i. This research has introduced the concept of agility associated with the supply chain and the customer order decoupling point; it has tested a methodology for the evaluation of the supply chain's agility, which involved simulation modelling and, in particular, DES as it is a popular technique to support this step. The research reviewed simulation modelling using DES and the processes involved in a simulation study.
ii. A structured approach was used to develop a responsiveness assessment through the decoupling point's positioning using DES (simulation) modelling. Two factors have been considered for the representation: customer order decoupling point's variations in

behaviour – material and information. The data required to design the model has been collected via a long-term field experiment, processed and then used to create the model. The results of the experiment have demonstrated the different levels of CODPs that exist within a supply chain.

iii. The case studies have shown that separating the decoupling points, the information to the latest point upstream and the material to the most appropriate point downstream, leads to reductions in wastage and, at the same time, enhances the flexibility, responsiveness and agility of the companies' cases that were studied in Chapter 4.

iv. The methodology has been applied to an in-depth case study to understand the different aspects of the organisation's supply chain and, by tracing the material and information flows, to analyse the factors based on the methodology presented in Chapter 5. While it was not possible for the simulation study to cover everything in the supply chain system, it was based upon the objectives addressed and the selected items in the system studied. The different simulation steps have been applied to analyse the decoupling points' positions and to show how to test the hypotheses in a real problem situation.

v. The decoupling point was investigated and the different positions of the material and information decoupling points have been identified, along with their extent, and the factors that maintain agile supply chain performance.

vi. Simulation analysis of the Hadeed supply chain has been presented and shows that sharing information upstream of customer orders provides important insights into the benefit to the material flow and, hence, the responsiveness of the supply chain. More timely information sharing and coordination in the scheduling and planning activities, if a change is required, has been shown to reduce the need for extensive forecasting and decreases slightly the demand amplification within the supply chain. The main information that can flow upstream is shown as the inventory, which manages both the inventory levels and replenishment levels. The research has shown that inventory information flow upstream helps to reduce uncertainties, increase output, and is the main factor in reducing the response time.

vii. Increased knowledge about the customer order is shown to be significant in terms of responsiveness improvement. The inventory information, which keeps the system synchronous, together with planning and scheduling activities were included as delay modules in the in-depth case study and indicated that there is a significant difference between the different types of information decoupling points at the different levels of the Hadeed supply chain, which is shown in the decoupling zones.

9.7 Recommendation for Future Research

The research undertaken has some limitations, partly due to time constraints but also due to the methods chosen for the research, which may reflect on the applicability and generalisation of the results.

The research strategy was four case studies from the literature. There may be some debate about the case studies' validity and the rigour of the results generated. However, this methodology has been used extensively in previous research. McCutcheon and Meredith (1993) identify the difficulty of generalising the results of case study research. Yin (2009) argues that using more than two case studies will strengthen the research findings. The lack of causal and time-dependent relationships between the decoupling points and agility may be considered to have affected the quality of the proof of the theory. In addition, the complexity of case studies involving large organisations and access to the appropriate information was limited.

With any simulation study, the simulation produces only estimates for a stochastic simulation model for the characteristics and input parameters proposed. Simulation modelling was also expensive and time-consuming to develop. The difficulty of communicating with case study management and the department responsible during the simulation study was also a limitation. Moreover, the complexity of the supply chain and the need to include more factors complicated the study.

The accuracy of the real system representation could be affected due to the cooperation from management in this location of the case study, and the level of simplification affected the enhancements of the models, as covered in Chapter 5. Also, as the simulation is based on discrete event simulations, the data collected reflects historical data, which is disadvantageous with regard to agility where current data would be preferable.

It is difficult to classify the information flow and to track it, as it is dependent on the IT used, the industry type, the environment, and the complexity of the supply chain. Identifying the information and following the activities that are related to the required information type was difficult to track due to the combination of activities, separations between departments, and technological barriers. The types of information needed for the simulation modelling were clarified but the type of case study considered was too limited to truly ensure that transparent information flow was captured at the right level.

Further work could also be done to extend the scope and functionality of responsiveness toward agility and the decoupling point strategies. The concepts may be improved in the following areas:

Stage 1: Extending the decoupling point concept under improved conditions

The decoupling point concept could be extended with respect to different priorities upstream and downstream of the supply chain in terms of agility and responsiveness.

Stage 2: Developing an enhanced methodology for analysing the supply chain

Quantitative and qualitative data would help to enable a complete and effective representation of dynamic behaviour. To develop distributions that better reflect true material and information flow, and an enhanced and improved experimental design for the field experiment, would be of benefit. This would allow accounting for more system dynamics effects and, consequently, enable building the desired distributions. More rules could be designed from observations and the collection of qualitative data that describes the supply chain systems.

Stage 3: Develop an improved approach to represent agility from a different perspective

The simulation model was created using a discrete event-driven DES package (Arena). The usage of a multi-agent based simulation (MABS) could be implemented that supports the modelling and implementation of combined methods. The main disadvantage of MABS is that it is usually time driven and is, therefore, a lot slower than an event-driven DES.

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Appendix A

Simulation Modelling in Supply Chain

A.1 Introduction

Computer simulation plays an important role in modelling the dynamic aspects of the supply chain. This appendix reviews simulation modelling concepts, its importance as a modelling method, and its advantages and disadvantages. Different types of simulation languages and simulation manufacturing simulator are discussed. The selection of the most appropriate simulation tool for a manufacturing application is a very difficult decision. The problems associated with the selection of simulation tools for supply chain applications are discussed here.

A.2 Simulation

"Simulation refers to a broad collection of methods and applications to mimic the behaviour of real systems, usually on a computer with appropriate software." (Kelton et al., 2010). Simulation is the process of designing and creating a computerised model of a real or proposed system for the purpose of conducting numerical experiments to give us better understanding of the behaviour of that system for a given set of conditions. Simulation may not be the only tool that could be used to study the model. It is frequently the method of choice. Other models may require stronger simplification assumptions about the system to enable an analysis, which might bring the validity of the model into question.

The field of operations research uses precise mathematical models to make decisions but Management sciences involves using models to make administrative or managerial decisions which show the overlap between these two fields (Seila et al. 2003).

A system is a set of interacting components and entities to accomplish a common goal or objective. Most systems are highly complex and it is useful to be able to divide them into subsystems to perform a specific task that will accomplish the main objective of the whole system. A model is an abstract representation of a system where a stochastic or probabilistic model implies randomness or uncertainty that the variables are random or uncertain in an essential way. The advantage of the simulation is that it allows prediction of how the system will work and respond to various decisions, which will help in making decisions. A parameter is a numerical characteristic of a model or system that describes something about the system. An input parameter will be required as part of the model specification. On the other hand, an output parameter would specify some measures about the system performance based on the system and its input parameters. The relationship is described in Figure A.1 (Seila et al., 2003; Law & Kelton, 1991), which shows the interaction between these.

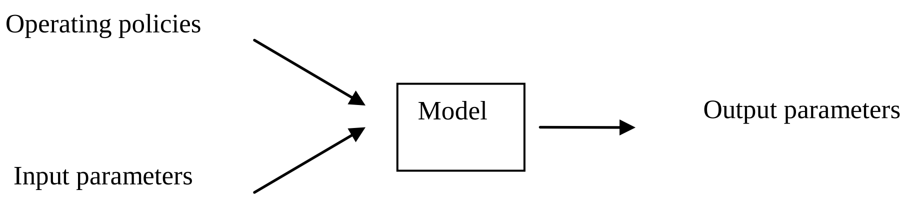


Figure A.1: The model and its parameters

To specify how the model relates the output parameters to the input parameters, there are two ways which use mathematical analysis and simulation. A mathematical analysis produces formulas to give an exact value of the performance measure of the system, while a simulation produces a sample of observations that could be used to compute a confidence interval of the performance measure. The majority of the stochastic models are too complex for analysis using mathematical tools or probability theory, which leaves simulation as the only available method for obtaining information.

Simulation is a set of numerical and programming techniques for representing stochastic models and conducting sampling experiments on those models using digital computers (Seila et al., 2003).

The simulation can be categorised into three general types (Seila et al., 2003): gaming, static systems, and dynamic systems. Gaming simulation includes the interaction of one or more people with the simulation program in an essential way such as video games. Static simulations operate according to formulas or rules, which compose the model by sampling observations and transforming them.

A.3 Why use simulation

There are many reasons for using simulation as opposed to mathematical analysis and here are a few (Seila et al., 2003):

- The model may be too complex to allow output parameters to be computed using mathematical analysis, leaving the simulation as the only method available.
- Most realistic models of actual systems are much too complex to be analysed mathematically.
- The operations of the model can reasonably be represented by a computer program.
- To find the design that maximises one or more performance measures simply study the behaviour of the system.
- Experimenting with the actual system could be impossible, if it does not exist yet, or extremely expensive if it does exist.
- The modelling efforts is frequently useful in itself because it leads to a better understanding of the system.
- The efforts of analysing the system for model specification usually leads to a better understanding of the system and can suggest useful changes even without the remainder of the simulation study.
- As a tool, simulation carries a certain amount of credibility with management.
- It is easier to explain to management the efforts involved with the simulation study than to explain the process of deriving a mathematical solution for the model using the arcane language of mathematics.
- Many modern simulation languages include facilities of animation that present a pictorial image of the system under study.
- The availability of computer hardware and software for simulation; it is one of the most widely used analysis techniques in operations research and management science.

A.4 Advantages and disadvantages of simulation

Among the advantages of using simulation in systems modelling and performance evaluation are:

- "What…if? analysis" – where decision policies can be rapidly tested and compared (Law & Kelton, 1991);

- The development of a simulation model helps the company to separate controllable from no controllable parameters and study the influence of each parameter in the system performance;
- Analysis of long time periods in short execution times;
- Problems that are usually solved by intuitive rules can be solved (and tested) formally;
- Beyond manufacturing (logistics and supply chains), simulation can be applied to many other fields, such as hospitals, supermarkets, airports, banking, and computer networks.

A.5 Process of simulation

The study for modelling the case study would have the following components (Seila et al., 2003; Law & Kelton, 1991):

1. Statement of the decision problem and objectives
2. System analysis
3. Analysis of input distribution and parameters
4. Model building
5. Design and coding of the simulation program
6. Verification of the simulation program
7. Analysis of output data to estimate parameters
8. Validation of the model
9. Experimental design
10. Simulation production runs
11. Statistical analysis and interpretation of data
12. Recommendation for decisions and implementation of the model
13. Final documentation of the model and simulation program.

A.6 Different kinds of simulation

- Static vs. Dynamic: time doesn't play a natural role in static models but does in dynamic models. Most operational models are dynamic.
- Continuous vs. Discrete: in a continuous model, the state of the system can change continuously over time. In a discrete model, change can occur only at separated points in time. Both in the same model are called mixed continuous-discrete models.

- Deterministic vs. Stochastic: models that have no random input are deterministic. Stochastic models, on the other hand, operate with at least some input being random. A model can have both deterministic and random inputs in different components.

A.7 Simulation software

This section is concerned with the selection of the simulation language because this is one of the most important decisions that a model builder must make to perform a simulation stud.

In general, simulation can be classified into three categories:

- **General-purpose languages**

  This type of language, such as FORTRAN, C, Pascal, basic, help to do simulations of more complicated systems. This approach was highly customisable and flexible but also painfully tedious since models had to be coded pretty much from scratch every time.

- **Special-purpose simulation languages**

  This type, like GPSS, Simscript, SLAM, and SIMAN, appeared on the scene some time later and provided a much better framework for the kinds of simulations many people do. Simulation languages became very popular and are still in use.

- **High-level simulators**

  They are easy to use and typically operate by intuitive graphical user interfaces, menus, and dialogs. Select from available simulation–modelling constructs, connect them, and run the model along with a dynamic graphical animation of system components as they move around and change. Some of the packages are SIMAN/ARENA, SIMFACTORY, SLAM II, PC Model, and ProModel.

Table A.1 shows different classifications of model types and techniques.

Appendices

Table A.1: Different classifications of model types and techniques

Simulation Model	Definition	Examples	Generic modelling technique
Static	Operates by sampling observations and transforming them according to formulas as rules that compose the model	A model for profit on a special sale promotion	The spreadsheet model
		A model for sensitivity analysis: financial model for an office building	The spreadsheet model
		Sampling on the computer: a model to estimate π	An experiment to estimate π
		Some techniques for generating random vitiates	Bernoulli Random Vitiates Uniform Random Vitiates Triangular Random Vitiates Normal Random Vitiates Exponential Random Vitiates Discrete Integer-Valued Random Vitiates Other Discrete Random Vitiates The Inverse Transform method Special Considerations
		Evaluating Decisions: a one-period inventory model	The spreadsheet model
		More complex model: Real Estate Model	The spreadsheet model
		An insurance model	Programming Language
Dynamic	The behaviour of a process over time, and dynamic systems simulations observe the behaviour of system models over time. The time advance mechanism used here is the fixed time advance, the models are sufficiently simple that more sophisticated involving worldwide entities, attributes, set, and so on will not be required, and the models can be programmed using a spreadsheet or a general-purpose program main language.	Waiting times in a single-server queuing system: Lindley's formula	The spreadsheet model M/M/1 queuing waiting times
		Discrete-time Marko chains: Inventory model, Queuing model, Reliability model	Analytical: mathematical theory
			Regenerative method for estimating the mean using simulation
		An advanced queuing model	Regenerative method for estimating the mean using simulation
		A marketing model	Special Languages
Discrete-Event Simulation (DES)	The operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system	General-purpose languages	FORTRAN, C/C++, Pascal, basic, Ada, Assembly language, Cobol, Java, Lua, Pascal, PL/I, RPG, Perl, Pike, Python, Ruby, etc.
		Special-purpose simulation languages	GPSS, Simscript, SLAM, and SIMAN
		High-level simulators	SIMAN/ARENA, SIMFACTORY, SLAM II, PC Model, ProModel, Extend, SimProcess, Quest, Witness, GoldSim, AnyLogic, FlexSim, Automod, Simul8, EmPlant, GoldSim, NetSim, Physim, Plant Simulation, PLM, Poses++, Process Model, RENO, Renque, and SimEvents

Systems Dynamic	An approach to understanding the behaviour of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of the entire system. It uses feedback loops, stocks and flows.	Causal loop diagrams Stock and flow diagrams Equations	DYNAMO, IThink/Stella, PowerSim, Vensim, AnyLogic, Berkely Madonna, Exposé, MyStrategy, Simile, and TRUE

A.7.1 Dynamic systems simulation

A computer simulation language describes the operation of a simulation on a computer. It can be classified as being a continuous or discrete-event. Most languages also have a graphical interface. An important part of discrete-event languages is the ability to generate pseudo-random numbers and variates from different probability distributions.

Dynamic systems simulation refers to conducting simulation work and observing its behaviour over time. It is divided into two sub-areas:

1. Continuous simulations (dynamic systems): this is an approach to understanding the behaviour of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of the entire system. Figure A.2 shows a block diagram with feedback. Block could be Integrator, Delay, Gain, etc.

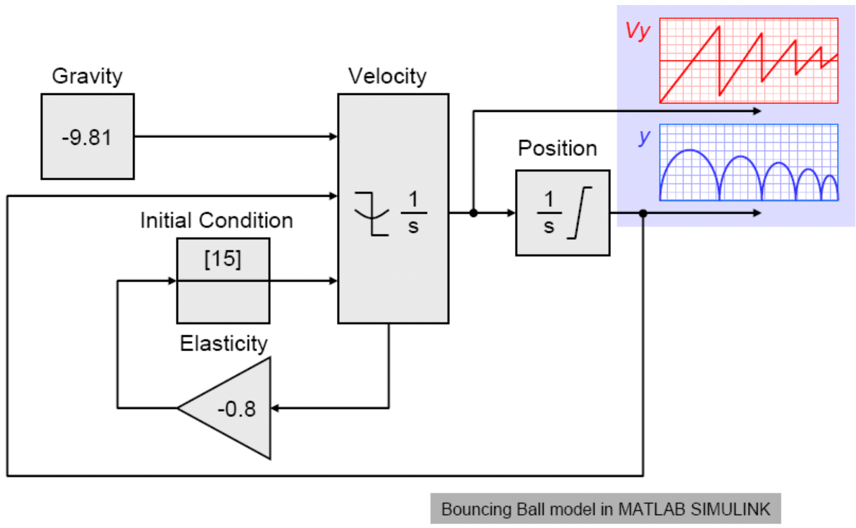


Figure A.2: Block diagram with feedbacks (Borshchev & Filippov, 2004)

System Dynamics uses stocks, flows and their causal relationships. The structure is as interacting feedback loops. This is shown in Figure A.3.

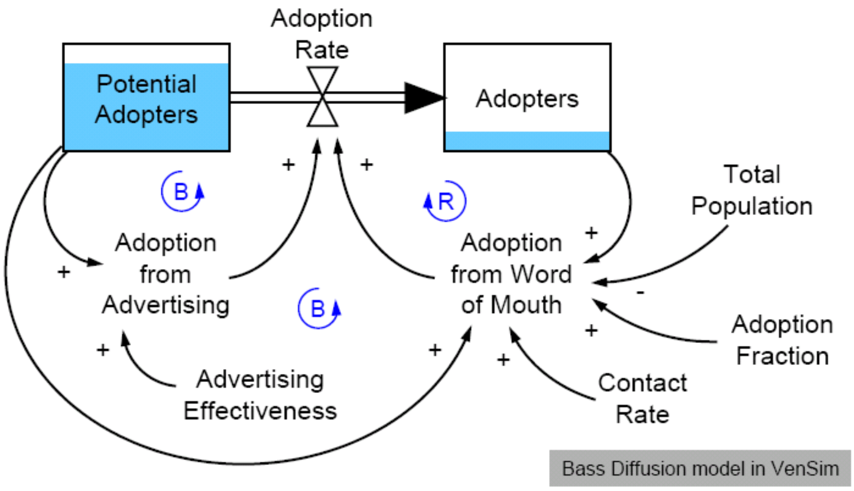


Figure A.3: System Dynamics (Borshchev & Filippov, 2004)

System dynamics are different from other approaches to studying complex systems due to the use of feedback loops, stocks and flows. These elements help describe how even seemingly simple systems display baffling nonlinearity. It involves models whose quantities variables are represented in differential equations that may be influenced by random disturbances. With continuous simulation languages, the model is essentially a set of differential equations such as:

- Advanced Continuous Simulation Language (ACSL), which supports textual or graphical model specification;
- Dynamo;
- Simulation Language for Alternative Modelling (SLAM); (there used to also be a Simulation Language for Analogue Modelling – SLAM);
- VisSim, a visually programmed block diagram language.

2. Discrete simulations (discrete event simulation): this allows for systems variables and attributes to change only at discrete points in time (Figure A.4). Discrete-event simulation languages view the model as a sequence of random events each causing a change in state, such as Rockwell Arena, SIMAN; a language with a very good GUI (Arena) is currently owned by Rockwell Automation Inc.

Discrete event simulations are more applied in management science because most of the models that are modelled by management scientists are discrete-event simulation. Also, it is a more natural to program. Moreover, continuous simulations can be approximated by discrete-event simulations. However, the contrary is not true and continuous simulation cannot be approximated to discrete-event simulation (Seila et al., 2003). Entities and resources (passive objects), and Flowchart blocks (Delay, Q, etc.) drive the model.

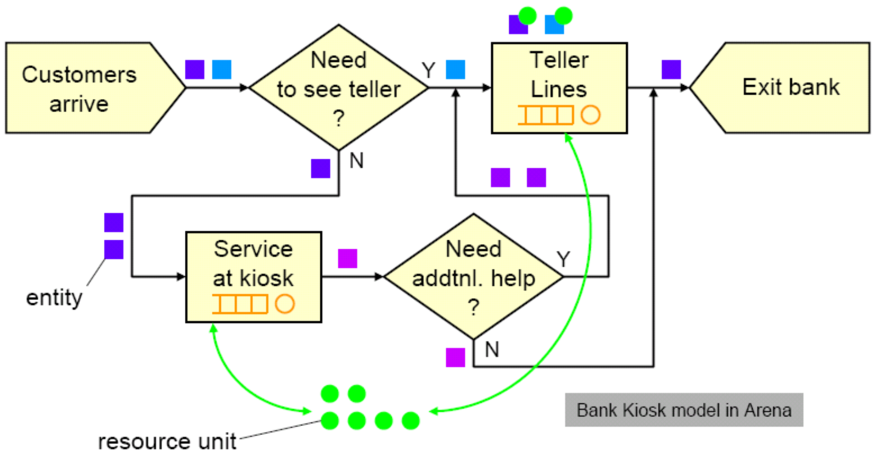


Figure A.4: Discrete events (Borshchev & Filippov, 2004)

3. Hybrid and others, such as:

- EcosimPro Language (EL) – Continuous modelling with discrete events;
- Saber-Simulator – Continuous and discrete-event capability; it simulates physical effects in different engineering domains (hydraulic, electronic, mechanical, thermal, etc.);
- Simulink – Continuous and discrete-event capability;
- SPICE – Analog circuit simulation;
- Z simulation language – Scilab contains a simulation package called Scicos;
- XMLlab – Simulations with XML;
- Flexsim 4.0 – A powerful iterative software for discrete-event and continuous flow simulation.

A.7.2 Comparison between discrete-event simulation and system dynamic modelling

Table A.2: comparison between discrete-event and system dynamic simulations

Discrete-event simulation	System dynamic modelling
Used to model corporate business decisions	
Widely used analytical tool.	SD has some unique terms and concepts.
Can replicate the performance of an existing system very closely and provide insight on how that system might perform if modified, or a new system might perform.	
Requires accurate data on how the system operated in the past or accurate estimates on the operating characteristics of a proposed system.	
Can represent a system in a computer animation that can provide a decision-maker an excellent overview of how a process operates, where backlogs and queues form, and how proposed improvements to the system might alter the system's performance.	
DES models are often built from a process map, or flow chart.	SD models are built based on a causal loop diagram.
	SD more often models abstract, general systems, such as a market for a particular good.
DES models, in contrast, typically have a narrower focus, such as modelling a production line or a call centre. systems under study tend to be easier to define.	Getting a group of experts to agree on a causal loop diagram of such a system is rarely easy.
	Model building is an iterative process involving the model builder and the people who routinely work with the system under study.
Employ computer simulation	
	They begin by identifying the basic structure and relationships within the system (often referred to as "stocks" and "flows"). Assign functions and numerical values to these relationships. Once the group has reached some agreement that the system under study has been adequately described in a causal loop diagram, a computer simulation is run of the model to see if the output reflects the group's intuitive understanding of the system. The model is then iteratively revised and re-run until the group feels comfortable that the important elements of the system are captured and the model's output reflects their view of reality.
Discrete changes in system parameters are easily modelled.	SD models the behaviour of systems using differential equations. Because of the nature of these mathematical functions, SD is well suited to modelling continuous systems.
	SD is less well-suited to providing a detailed representation of a system where there are discrete changes in state variables, or mixed systems of both

	discrete and continuous processes.
DES models use a simulation clock that advances time in fixed increments or advances time to the next scheduled event on a simulation calendar.	An SD model cannot easily model inter-arrival rates of discrete entities in a system.
They have a stronger empirical basis because they usually model concrete, observable processes.	Many writers on system dynamics shy away from holding their models to a strict standard of statistical predictive validity. A possible explanation for this restraint lies in the fact that system dynamics models could be characterised as a collective "best guess" based on a particular group's understanding of a system at a certain point in time.
They usually reflect extensive analysis of historical data.	Since the real systems the models represent are inherently dynamic, changes in the real system could quickly outdate the model.
	Human behaviour often plays an important role in system dynamics models and this is inherently more difficult to quantify.

A.7.3 SIMAN/ARENA

Arena combines the ease of use found in high-level simulators with the flexibility of simulation languages, even all the way down to general-purpose procedural languages such as the Microsoft® Visual Basic® programming system, or C. It does this by providing alternative and interchangeable *templates* of graphical simulation modelling and analysis *modules* that can be combined to build a fairly wide variety of simulation models. For ease of display and organisation, modules are typically grouped into *panels* to compose a template. By switching panels, you gain access to modules from different sets of simulation modelling, constructs, and capabilities. In most cases, modules from different panels can be mixed together in the same model.

Arena maintains its modelling flexibility by being fully hierarchical. At any time low-level modules can be pulled in from the Blocks and Elements panel and access can be gained to simulation-language flexibility if needed to mix in a SIMAN construct together with the higher-level modules from other templates. For specialised needs, such as complex decision algorithms or accessing data from an external application, pieces of a model can be written in a procedural language, for example Visual Basic or C/C++, all regardless of how high or low in the hierarchy, it takes place in the same consistent graphical user interface

In fact, the modules in ARENA are composed of SIMAN components; modules can be created and collected into templates for various classes of systems. For instance, Rockwell Automation has built templates for general modelling, high-speed packaging, contact centres, and other industries.

Further, Arena includes dynamics animation in the same work environment. It also provides integrated support, including graphics, for some of the statistical design and analysis issues that are part and parcel of a good simulation study (Kelton et al., 2010).

A.8 Selection of simulation tools

When deciding which approach is best suited to model a particular problem, the key questions are, which type of model best represents the system under study, what questions does the decision-maker wish to address, and for what purpose will the model be used. System dynamics methodology is best suited to problems associated with continuous processes where feedback significantly affects the behaviour of a system, producing dynamic changes in system behaviour. DES models, in contrast, are better at providing a detailed analysis of systems involving linear processes and modelling discrete changes in system behaviour. DES models are used when the goal is a statistically valid estimate of system performance. SD is more often the tool of choice for a training vehicle. There is certainly a large area of overlap between the two approaches. Many problems could be modelled with both approaches and produce results that would look very similar. Both methods, used appropriately, can help provide increased understanding and serve as an aid to decision making.

A.9 Comparison of discrete-event simulation tools

A detailed comparison was provided by vendors in response to a questionnaire developed by James Swain where OR/MS has listed 48 packages (Swain, 2009). I narrowed down the comparison to the software that supports supply chain modelling that are based on discrete-event simulation.

The factors considered in the survey comparison are as follows and are illustrated in Table A.3:

1. Vendors:

    - Typical applications of the software
    - Primary markets for which the software is applied
    - System requirements: RAM , Operating systems

2. Model building – Graphical model construction:

    - (icon or drag-and-drop),
    - Model building using programming/access to programmed modules
    - Run time debug
    - Input distribution fitting (specify)
    - Output analysis support (specify)
    - Batch run or experimental design (specify)
    - Optimisation (specify)
    - Code reuse (e.g. objects, templates)
    - Model packaging (e.g. can completed model be shared with others who might lack the software to develop their own model?)
    - Tools to support packaging (specify)
    - Does this feature cost extra?
    - Cost allocation/costing
    - Mixed discrete/continuous
    - Modelling (levels, flows, etc.).

3. Animation:

    - Animation
    - Real-time viewing
    - Export animation (e.g. MPEG version that can run independent of simulation for presentation)
    - Compatible animation software
    - 3D Animation
    - Import CAD drawings.

4. Support/Training:

    - User support/hotline
    - User group or discussion area
    - Training courses
    - On-site training

- Consulting available.

5. Price:

    - Standard
    - Student version.

6. Major new features (since 2007)
7. Vendor comments.

Table A.3: Comparison of simulation packages (Swain, 2009)

Software		AnyLogic	Arena	Flexsim	Micro Saint Sharp	Simcad Pro- Patented Dynamic Process Simulator	SIMUL8 Professional	SIMUL8 Standard	SIMUL8 Web	WebGPSS
Vendor		XJ Technologies	Rockwell Automation	Flexsim Software Products Inc.	Alion Science and Technology	CreateASoft, Inc	SIMUL8 Corporation			Beliber AB
Typical applications of the software		Flexible general purpose simulation tool. Discrete Event, Agent Based and System Dynamics modelling	A proven and easy to use general purpose DES software tool. The only boundaries are in the ability to describe the process	Process improvement, process optimisation, capital investment justification, lean implementations	Human performance modelling, manu-facturing, health-care, service industry, military, business process reengineering, supply chains	Continual Process Improvement, Facility Layout/Design, RFID/RTLS, Process Optimis-ation, Lean, CapEx Justification	Optimise throughput, maximise resource utilisation, identify bottlenecks, reduced risk decisions, business process management	Optimise throughput, maximise resource utilisation, identify bottlenecks, reduced risk decisions, business process management	Simulation on the web. Share the benefits and power of simulation with others, no install, no learning curve	General purpose discrete events simulation
Primary markets for which the software is applied		Healthcare, Logistics, Supply Chains, Manufacturing, Defense, IT, Pharmaceuticals, Marketing, Finance, Energy, Education	Manufacturing, Six-Sigma, Packaging, Supply Chain/Logistics, Healthcare, Military/Defense, Service, Contact Centres, etc.	Manufacturing, healthcare, distribution, warehousing, supply chain, transportation, food processing, logistics	Typical markets include human performance, manufacturing, healthcare, supply chain, and command and control modelling	Manufacturing Solutions, Healthcare Solutions, Supply Chain Logistics Solutions, Service/Office Simulation Tools	Business processes: call centre, manufacturing, supply chain, logistics, healthcare, financial, education	Business processes: call centre, manufacturing, supply chain, logistics, healthcare, financial, education	Business processes: call centre, manufacturing, supply chain, logistics, healthcare, financial, education	Education, esp. students of business, OR, logistics, supply chain systems
System Require-ments	RAM	2 GB	1 GB	256 MB	256 MB	256 MB	256 MB	256 MB	Browser requirements only	8 MB
	Operating systems	MS Windows Vista or XP, Apple Mac OS, Linux	Windows Vista (SP1 or later, 32-bit version), Windows Server 2003 Standard Edition R2 (SP2 or later, 32-bit version only), Windows XP Professional (SP2 or later), or Windows XP Home (SP2 or later)	Windows Vista, Windows XP	Microsoft Windows Server 2003, Windows Server 2008, Windows XP, Windows Vista (Operating systems must support the Microsoft .NET Framework 3.5)	Windows 2000 (XP/Vista). Will run on a MAC with a Windows Emulator. If 3D Graphics are needed, a hardware acceleration board will help increase system performance	All Windows editions including Windows 7 & Vista, Linux, Mac OS	All Windows editions including Windows 7 & Vista, Linux, Mac OS	All operating systems	Windows

Model Building: Graphical model construction	(icon or drag-and-drop)	y	y	y	y	y	y	y	y	y
	Programming/access to programmed modules	y	y	y	y	y	y	y		y
	Run-time debug	y	y	y	y	y	y	y		y
	Input Distribution Fitting	y	y	y		y	y	y	y	
	(Specify)	Stat::Fit	Input Analyzer, Chi-square and (for non-integer data) Kolmogorov-Smirnov goodness-of-fit tests	ExpertFit		i.e. database, csv, xls, etc.	Stat::Fit	Stat::Fit	Stat::Fit	
	Output Analysis Support	y	y	y	y	y	y	y	y	y
	(Specify)	Dataset Statistics, Distributions, Regular and 2D Histograms, various Charts, etc.	Output Analyzer tool, Summary Results, Ability to export data to other sources	Flexsim Charts	Micro Saint Sharp automatically collects data needed to understand process. Data on utilisation, queues, resources, and tasks are collected automatically. Users can customise data collection to see whatever results are needed	Value Stream Maps, Gantt Chart, Scenario Analysis, Lean Reports	All features of Standard plus SIMUL8 Results Manager provides: Central-ised results database, Scenario and run compari-son reports, customisable charting and reporting capabilities	Automatic confidence interval calculation, no coding required, results and charts for all simulation objects, dynamic onscreen reporting as simulation executes. Export to external applications Excel, VISA, Minitab and more	Automatic confidence interval calculation, no coding required, results and charts for all simulation objects, dynamic onscreen reporting as simulation executes	Student's t-distribution confidence intervals
	Batch run or experimental design	y	y	y	y	y				

	(Specify)	Simulation, Optimisation, Parameter Variation, Compare Runs, Monte Carlo, Sensitivity Analysis, Calibration, Custom experiment	Scenarios can be defined to experiment on parameters	Flexsim DOE	Users can specify a batch run or can use the Experiment feature to define different experimental conditions and number of replications	Experimental Design: Dynamically interact with the model, or through integrated optimisation. Batch runs: Conduct Monte Carlo runs and publish results to the integrated Simcad Scenario Analysis Tool	Automated batch runs. Design and execute scenarios automatically with Scenario Manager. Execute runs simultan-eously across multiple PCs with parallel processing	Automated batch runs. Design and execute scenarios automatically with Scenario Manager. Execute runs simultaneously across multiple PCs with parallel processing. Automated Warm up and Automated Replication Size	Automated batch runs. Design and execute scenarios automatically with Scenario Manager	
	Optimiza-tion	y	y	y	y	y	y	y		y
	(Specify)	OptQuest	OptQuest	OptQuest	OptQuest optimisation by OpTek Systems Inc.	Built in Dynamic Optimizer Tool, On-the-fly user interaction, Integrated Work-Order/Schedule Optimisation	OptQuest	OptQuest		Grid search
	Code reuse (e.g. objects, templates)	y	y	y	y	y	y		y	
	Model Packaging (e.g. can completed model be shared with others who might lack the software to develop their own model?)	y	y	y	y	y	y		y	

	Tools to support packaging (Specify)	AnyLogic models can be exported as standalone Java applets or Java applications	Runtime Versions available for model distribution	Yes, industry specific and application specific modelling objects and libraries of model-building objects	Users just need to select the Export Model to Runtime option under the Utilities menu and select a folder – Micro Saint Sharp will then create a runtime version of the model that can then be distributed	Simcad Viewer, Simcad Online	SIMUL8 Viewer		Anyone with web access can access model.	
	Does this feature cost extra?	Export as Java applications available in AnyLogic Professional	y	No	Runtime export is included in the Gold version at no extra cost	One viewer included with each Simcad Pro license purchase. Additional Simcad Viewer/ Simcad Online is available for $495	No	No	No	
	Cost Allocation/ Costing	y	y	y	y	y	y	y	y	
	Mixed Discrete/ Continuous Modelling (Levels, Flows, etc.)	y	y	y		y	y	y	y	
Animation	Animation	y	y	y	y	y	y	y	y	
	Real-time viewing	y	y	y	y	y	y	y	y	
	Export animation (e.g. MPEG version that can run independent of simula-tion for present-ation)			y						
	Compatible animation software				y		y	y	y	

	3D Animation	y	y	y	y	y	y			
	Import CAD drawings	y	y	y	y	y	y	y		
Support/ Training	User Support/ Hotline	y	y	y	y	y	y			y
	User group or discus-sion area	y	y	y	y		y			y
	Training Courses	y	y	y	y	y	y			y
	On-site Training	y	y	y	y	y	y			
	Consulting Available	y	y	y	y	y	y			y
Pricing Inform-ation	Standard	Advanced edition: $6,200, Professional edition: $15,800 per seat, discount on volumes	Please contact us for pricing. Versions and functionality available to meet your needs	$15,000–20,000	There are two versions of Micro Saint Sharp available to commercial users: Silver and Gold.	$9,450	$4,995	$1,495	Negotiable, depends on numbers of users	$700
	Student Version	Educational license: from $850, University Researcher license: $3,500	Student version included in Simulation with Arena textbook (other textbooks as well) or request evaluation version	$100	$60 for a student version	Please contact CreateASoft for educational licensing discounts	Free with educational version	Free with educational version	Free with educational version	Ordinary (150 blocks) $40; extended (400 blocks) $90
Major new features (since 2007)		Templates for Agent Based and other methods, Rail Yard library, Pedestrian dynamics modelling, 3D animation (2009)	Ease of use features including bringing data into a model, periodic statistic collection, advanced conceptual example models	Download Flexsim evaluation version, select "Help" from the main menu, then "User Manual" and then "What's New"	3D animation, custom object types, communications module, visio import/export, runtime version export, experiment definition	Multi-core Processor, Dynamic Optimizer, RFID/RTLS, Simcad Online, Excel Import/Export Wizards	Run execution 30% faster, SIMUL8 Results Manager, predictive text, multidimensional arrays, customisable run time charts	Industry first, trial calculator. Numbers of runs you should do for your simulation to get accurate confidence intervals	SIMUL8 first revolutionised the market in 1994, now we're doing it again with the release of SIMUL8 on the web this year	Improved block diagrams; improved matrix handling; new warm up command; extended textbook

Vendor Comments	Very flexible tool, the only one supporting multiple modelling methods including agent-based modelling, open at Java level	Proven, Flexible, Easy to Learn. Flowcharting methodology to construct models without having to write code	Easy to learn and build true 3D models	Micro Saint Sharp has the power, flexibility, speed and interoperability to meet any simulation need!		SIMUL8 Professional, extended ease of use and power to link to any application or data source with SQL & COM	SIMUL8 is easy to use, powerful & fast, faster than any other tool on the market. With free support to help you get started	Host on our website, your website or your corporate network. Option for animation or not. No end client installs	Aims to be the best simulation software for starting courses in simulation, allowing students to do real projects in business

Appendix B

SIMAN/ARENA Modules

As mentioned in previous sections, the simulation software used is SIMAN/ARENA. This section provides a brief summary about the most important modules used.

Create Module

The Create module is intended as the starting point for entities in a simulation model. Entities are created using a schedule or based on a time between arrivals. Entities then leave the module to begin processing through the system. The entity type is specified in this module.

Batch Module

The Batch module is intended as the grouping mechanism within the simulation model. Batches of entities can be permanently or temporarily grouped. Temporary batches must later be split using the Separate module.

Batches may be made with any specified number of entering entities or may be matched together based on an attribute.

Entities arriving at the Batch module are placed in a queue until the required number of entities has accumulated. Once accumulated, a new representative entity is created.

The type of the outgoing entity may be changed by specifying a representative entity type.

Hold Module

The Hold module will hold an entity in a queue to either wait for a signal, wait for a specified condition to become true (scan), or be held infinitely (to later be removed with the Remove module).

If the entity is holding for a signal, the Signal module is used to allow the entity to move on to the next module. If the entity is holding for a given condition to be true, the entity will remain at the module (either in a defined or internal queue) until the condition(s) becomes true. When the entity is in an infinite hold, the Remove module is used to allow the entity to continue processing.

Decide Module

The Decide module allows for decision-making processes in the system. It includes options to make decisions based on one or more conditions (e.g. if entity type is Gold Card) or based on one or more probabilities (e.g. 75% true; 25% false). Conditions can be based on attribute values (e.g. Priority), variable values (e.g. Number Denied), the entity type, or an expression (e.g. NQ (Process A. Queue)).

Assign Module

The Assign module allows the assignment of a value to a user-defined variable, continuous rates or levels, entity attribute or picture, model status variable, or a resource state. Multiple assignments may be made by a single Assign module. When an entity arrives at an Assign module, the assignment value or state is evaluated and is assigned to the variable or resource specified. If an attribute or picture is specified, the arriving entity's attribute or picture is assigned the new value.

Process Module

The Process module is intended as the main processing method in the simulation. Options for seizing and releasing resource constraints are available. Additionally, there is the option to use a "submodel" and specify hierarchical user-defined logic. The process time is allocated to the entity and may be considered to be value added, non-value added, transfer, wait or other. The associated cost will be added to the appropriate category.

Separate Module

The Separate module can be used to either copy an incoming entity into multiple entities or to split a previously batched entity. Rules for allocating costs and times to the duplicate are specified. Rules for attribute assignment to member entities are specified as well.

When splitting existing batches, the temporary representative entity that was formed is disposed of and the original entities that formed the group are recovered. The entities proceed sequentially from the module in the same order in which they were originally added to the batch.

When duplicating entities, the specified number of copies is made and sent from the module. The original incoming entity also leaves the module.

Record Module

The Record module is used to collect statistics in the simulation model. Various types of observational statistics are available, including time between exits through the module, entity statistics (time, costing, etc.), general observations, and interval statistics (from some time stamp to the current simulation time). A count type of statistic is also available. Tally and Counter sets can also be specified.

Dispose Module

The Dispose module is intended as the ending point for entities in a simulation model. Entity statistics may be recorded before the entity is disposed of.

Appendix C
Background, Products, Process, and Rotation at Hadeed

C.1 Introduction

This appendix will start with a glance at Hadeed, its product and the following sections, each corresponding to each plant. Also, it describes the experience during the data collection stage at Hadeed. The second section corresponding to SP will be divided into three subsections relating to the following locations: Furnaces, Castors and Scrap. In addition, the roles of Sales and Marketing will be presented. The Rolling Mill is divided into four main areas: the billet bay, Bar Mill, Rod Mill, and Bar/Section Mill.

C.2 Background on HADEED Company

Background on HADEED Company is detailed in Section 6.3

C.3 HADEED Company Products

HADEED Company Products are detailed in Section 6.4

C.4 HADEED Company Processes

C.4.1 Direct reduction furnace

The shaft furnace is actually a vertical reactor where the iron oxide (Hematite FE_2O_3) and the feed material are fed into a charge bin. The feed material is reduced to metallic iron by introducing hot reducing gases (CO & H_2) into the furnace. Figure C.5 shows the vertical reactor while the feed material is fed into it.

Figure C.5: Vertical reactor

The very basic idea of the plant is to remove the oxygen atom in the Hematite (FE_2O_3), the iron ore, which is imported in large amounts (165,000 tonnes/ship usually) from outside the country, mainly from Brazil, Bahrain and Sweden.

Removing the oxygen atom is done through a complex process involving adding the natural gas (CH_4) to the iron ore. There are three modules, or plants, inside the company's field where this process takes place.

After transferring the iron ore from the port on the longest conveyor of its kind (about 13 km) to the stockyard in the form of beds, it is screened to remove any iron with a diameter less than 6 mm; the maximum allowed diameter is 50 mm. Using another flexural conveyor they are moved directly into the reducing furnace.

The natural gas (CH_4) supplied by Aramco is used to take out the oxygen atom in an interaction starting at 570°C. In the reformer connected to the furnace, there exist the natural reducing agents (CO) and (H_2) which operate effectively at 900°C. The DRI (direct reduced iron) is cooled after the process is completed, producing steam and carbon dioxide to the following equations:

$$Fe_2O_3 + H_2 \Rightarrow Fe + H_2O$$

$$Fe_2O_3 + CO \Rightarrow Fe + CO_2$$

The DRI may gain the oxygen from the air as it is cooled, but if it is cooled to a degree lower than 65°C, then there is no need to repeat the process.

The reformer is used to regenerate the reducing agents and bring it back to the furnace where it is used again in the process, which saves much time and money that would otherwise be spent on ordering more of these gases.

A gas scrubber is used to clean and cool the dust-laden gas in modules (A, B and C). The estimated capacity of each module is:

A and B - 87 tonnes per hour

C - 128 tonnes per hour

- Modules A and B produce around 1,472,000 tonnes/year
- Module C produces around 1,040,000 tonnes/year.

DRI is stored in 4 Silos for Modules A, B, C, and D. Each silo can contain 5,000 tonnes of DRI.

I visited the control room of modules A and B, and observed some main functions handled by the operators on the morning shift.

C.4.2 Supplier

- Samarco: Brazil – Ocean-going Vessel (OGV)
- LKAB: Brazil – OGV
- CVRD: Brazil – OGV
- GIIC: Bahrain – Transfer Vessel (TV)
- IOC: Canada – OGV
- QCM: Canada – OGV.

C.4.3 Steel Plant

The Steel Plant (Long Products) consists of:

- three Electric Arc Furnaces (EAFs) each with 150 tonnes heat size
- two Ladle Furnaces (LF)
- three Casters with seven strands.

C.4.3.1 Furnaces

In this section of SP, I was accompanied by Mr Anayatullah Abdulrahman, who explained briefly the safety procedures inside the plant and in the furnaces area (1, 2 and 3) specifically.

The purpose of this stage of production is to mix the DRI received from the DR plant with scrap (sometimes it is only scrap boiled in the furnace) to deliver to castors for shaping.

DRI is brought to the electrical arc by a conveyor system. The system allows DRI feeding while the furnace is in operation; scrap, DR briquettes and DRI from the DR plant are put into scrap-charging baskets in the scrapyard. When the scrap is required for the furnaces, the overhead crane picks up the basket and places it over the furnace. The crane then opens the basket and scrap falls into the furnace. Figure C.6 shows the Arc furnace.

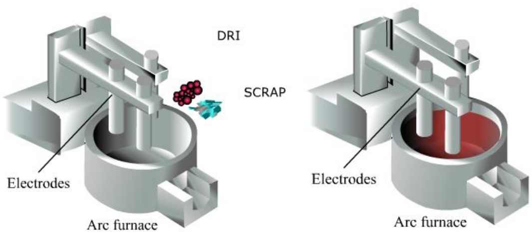


Figure C.6: Arc furnace

Electric Arc Furnaces (EAF) are vessels that turns solid "raw" materials into liquid steel. The furnaces at Hadeed have an input capacity of approximately 185 tonnes of raw materials. Electricity is the main energy supply (average 88.4 megga watt hours/charge, enough to power 737,000 televisions). The electricity is passed down 3 carbon electrodes and form electric arcs. The heat from the arcs melts the raw materials. The melt temperature of the steel is 1500°C+ and the temperatures before tapping are 1590°C to 1700°C. Ladle furnaces are "small" electric arc furnaces. They use electrical energy (average 3 megga watt hours per charge, approximately 25,300 televsions sets) for heating the liquid steel for final adjustment of temperature and chemical analysis. Nitorgen is used to stir the liquid steel in the ladle via the porous plug. This enables the chemical analysis to be controlled within a tight range. The liquid steel temperature can also be controlled to +5°C at 1509°C. Figure C.7 shows where the arc furnace pours the liquid steel into the ladle furnace.

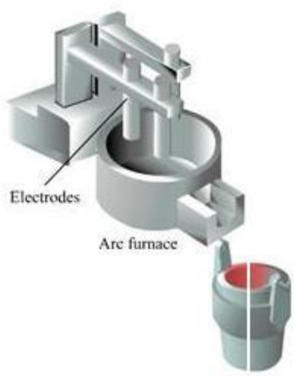


Figure C.7: Ladle furnace

A wire-feeding system can also be used for feeding solid aluminus wire or cored wire (CasI) into the ladle during processing. This allows materials that are normally difficult to add to be added reliably. Lime may also be added at this point.

C.4.3.2 Casting

Afterwards, the ladle is moved to the casting site. Hadeed has 3 x 6 strands of Billet Casters. The ladles are transfered from the ladle furnace to one of the casting machine turrets (Figure C.8). The turret allows the ladle to be sequenced (when one ladle is finished the turret is turned and the next ladle started). A ladle takes approximately 76 minutes to teem.

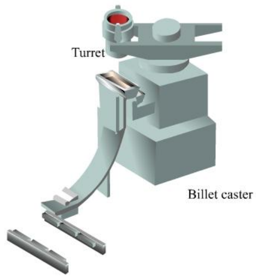


Figure C.8: The turret

The ladle slide gate is opened and steel is teemed into a large rectangular bowl, called the “Tundish”. The tundish is a 15-tonne capacity refractory lined vessel that distributes steel to the six water holes in the bowel, called “atands”, cooled copper moulds ready to shape the steel. (130 mm x 130 mm or 100 mm x 100 mm). Liquid steel enters the mould and starts to solidify. The soldifying “billet” is pulled down through water spray and bent vertically to horizontally round a 5-meter radius curve. The billets are cut by a Gas Cutting “Giga”, a great cutting tool, before they are sent to the cooling area and then the billet area, according to the requirements of the Rolling Mills. But the average length for 130 mm x 130 mm is 14 metres and a small number of 100 mm x 100 mm billets, 12 metres long, are cut for Jeddah Rolling Mills and others.

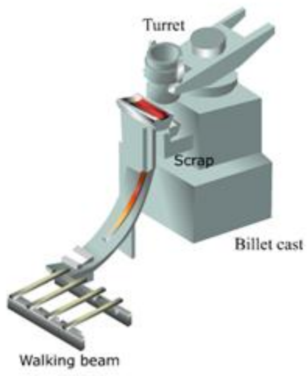


Figure C.9: the casting

The billets travel on a walking beam turnover cooling bed (Figure C.9). This is to ensure even cooling. Moulds are supplied by water, which is the major cause of forming the billet inside the mould, as it cools the outer shell of the billet. The moulds are also seen to be shaking. This is done through hydraulic motors so the steel does not stick to the walls of the mould. This issue is critical, so in case of further concerns, lubricants are added to the walls of the shells in the mould to ease the movement of the steel. This prevents the billets bending. All the billets are made with an identification number. Any scrap generated during the casting process is returned to scrap processing. Scale from the billets are sold to concrete producers. This is used as an additive in concrete.

Apparently, six billets of size 130*130 are formed in about 70-80 minutes. If the size is smaller, 100*100, this would take about 90-100 minutes.

A brief demonstration of how the process takes place was given from inside the control room.

C.4.3.3 Scrapyard and scrap handling

In SP, scrap plays a major role in completing the daily process of producing steel, if the product is not totally made out of scrap. Therefore, this trip to the scrapyard was arranged.

As explained by workers in the scrapyard, if allowed, there will be around 200 trucks full of scrap arriving daily at the plant. Otherwise, it is usually about 100-140 trucks arriving according to a pre-arranged schedule. Furthermore, the usual amount of scrap kept as stock is around 180,000 tonnes of different types.

There are about nine major types of scrap received by the company. The most important are Heavy metal (HM), Furnace size (FS) and mixed or bundle scrap. The more condensed and smaller the scrap pieces, the higher its price. At the scrapyard, scrap is divided into two main categories: prepared and unprepared. Prepared scrap is scrap that is ready to be taken to the furnace without further processing. Unprepared scrap needs to be cut and formed into desired shapes before it is sent to the furnace.

The process begins at the gate when a truck full of scrap arrives to be weighed with the load on. Then, it is inspected to see what kind of scrap it is carrying: prepared or unprepared? HM, FS or mixed scrap? If the load is coming from a frequent customer who has signed a contract with Hadeed, the load must go along with the type of scrap indicated in the slip carried by the driver. If more than 30% of the load is different from the contract, the customer is penalised by either downgrading the load, from HM to FS for example, or by rejecting the whole load and kicking the truck out of the plant.

When the driver is done with the initial stage, he unloads his scrap under the supervision of another inspector to see if the rest of the load, especially the bottom portion, matches the contract slip carried by the driver. Usually, either a grapper or a big magnet is used to move the scrap from one place to another. Cash customers are treated separately according to their load.

Finally, the scrap is divided into prepared and unprepared. The driver then weighs his truck again to see the difference and deals with the purchasing department later to collect his earnings.

Prepared Scrap is any compressed scrap of 100cmx50cmx60cm or smaller, or any 150 cm long or less of loose scrap. It is directed either to the stockyard or to the basket where it is transferred for processing in one of the three furnaces inside the SP.

Unprepared scrap goes to one of three machines:

- the Shredder: processes light scrap and car bodies

- the Shear: processes oversized scrap and any 3 mm+ scrap
- the Burner: processes heavy metal and compresses scrap.

In these machines, unprepared scrap is processed into valid and good prepared scrap for putting in the furnace.

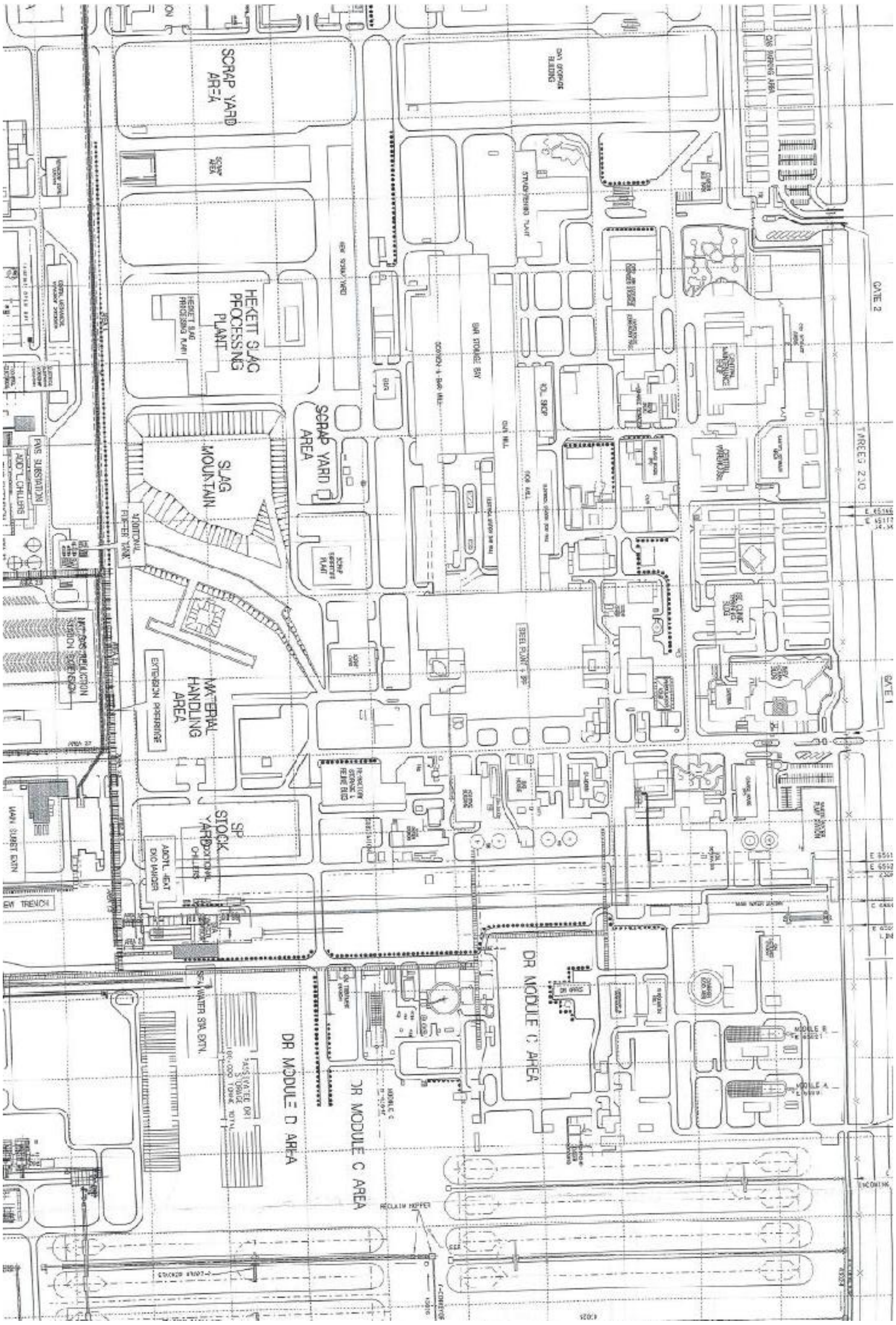


Figure C.10: Hadeed layout

C.4.4 Rolling Mills

Hadeed's long products rolling mills are comprised of four separate units:

1. **Bar Mill**
2. **Rod Mill**
3. **Sections** and **Bar Mill**
4. **Bar** and **Rod Mill (Barod Mill)**

The raw material inputs for the Bar Mill are steel billets, which have 130x130 mm square cross sections and are 14 m in length. These billets are also used in the other two mills.

The billets are reheated to the desired rolling temperature and then rolled into rebars of 12 to 40 mm diameter by 12 m as a standard length. Alternatively, they can be produced according to the customer's preferred length of 12 to 18 m with a standard bundle weight of 2 tonnes.

The annual production capacity of the Bar Mill is around 1.2 million tonnes of rebars.

In the Rod Mill the billets are rolled into wire rod coils and plain and deformed bars, 5.5 to 16 mm in size.

The annual production capacity of the Rod Mill is around 700,000 tonnes, and it is capable of producing various special types, as may be required by customers. These include wire drawing, mesh and electrode fabrication.

The **Section** and **Bar Mills** have an annual production capacity of over 650,000 tonnes of light sections and rebars.

- The sizes of **rebars** range between 10 and 32 mm.
- The light sections include **angles** in sizes of 30x3 to 70x7 mm, **channels** in sizes of 30 x15x4 to 75x40x5 mm, **squares** of 10 to 25 mm and **flat bars** in sizes of 25x5 to 100x6 mm. The total production capability is over 70 profiles.

The wire rod & Bar Mill has a capacity of 700,000 tonnes per year.

C.4.4.1 Bar Mill

This plant receives the readymade billet from the billet bay and inserts it through a sophisticated process to get different sizes of those used mainly in construction work.

This process starts with bringing the billet into an 86-billet-capacity furnace to be heated, using 110 candles or burners, to a degree where its physical properties can be modified. This furnace can process 140 tonnes per hour and only lets the billet out at a temperature of 1170°C.

The billet goes through three main processes to achieve the final desired shape of the bar: Roughing, Intermediate and Finishing. Each process is completed as the billet enters a number of large standing machinery, also called “stands”. In the Bar Mill, there are 18 stands divided between these processes.

The billet is either divided into two bars (slits) or left as one bar. Two slit bars are produced from one billet if the size is smaller than 20 mm. If the size is 20 mm or higher, then a single bar is produced.

The process can be expressed as reducing the size (diameter) of the billet as it goes through this series of stands. Different diameters require a different combination of stands to obtain a particular size. Therefore, any change of size should be accompanied with changes in the settings of the stands for the whole mill or line of production.

Finally, when the rebar is obtained and cut into desired lengths, a sample is taken to make sure the weight matches the predetermined standard weight. Necessary calculations are performed before the cast goes through towards the cooling bed.

In the cooling bed, the bars are aligned, gathered, and wrapped in bundles as well as cooled before they are handed to the dispatch section. Mr Faisal Al-Ruwaili and Mr Majid Al-Shammari were the main source of information in this area of the RM.

The sizes of the rebars are Hadeed Rebar sizes 6, 8, 10, 12, 14, 16, 18, 20, 22, 23, 25, 32, and 40 mm.

C.4.4.2 Bar/Section Mill

The production of sections stopped temporarily two years before my visit and only bars were produced. Although there are more than 70 different sizes of sections, its low demand and the high demand for bars made that change necessary. This mill, consequently, is another Bar Mill except for the fact that it is more automatic and equipped with more advanced machinery.

In this mill, the furnace is also much more advanced and sophisticated. It can accommodate 99 billets at once. These billets stay 90-105 minutes inside the 72-burner furnace before they enter the roughing stage. There are also 18 stands in this mill but the machines here, as stated, are equipped with advanced sensors and automation devices.

Every billet is about 14 m long and is extended to become 1080 m to 1260 m (depending on the size) and then cut into 12 m-long bars.

It takes 6-8 hours to change the size on the production line, including the maintenance check, which usually occupies most of the setup time.

The 18-shear machine is used to cut the desired rebar lengths in both mills.

Unwanted or defective bars are sent to the scrapyard to be reprocessed.

The larger the size, the fewer the number of stands the billet goes through.

C.4.4.3 The Rod Mill

The essential difference between this mill and the Bar Mills is that the product here is a coil instead of a bar. Nevertheless, the furnace in this mill can accommodate 66 billets and there are 25 stands in the production line, roughing (7), intermediate (8) and finishing (10). It would take, for size 5.5 mm for example, about two hours to leave the furnace for the roughing stage.

Sizes start at 5.5 mm diameter up to 16 mm. There are also two types of coils: plain and rebar. The plain type is recognised for the missing lines or marks that are on the rebar type. Furthermore, odd sizes (5.5, 7, etc.) can only be of the plain type where even sizes can be made of any type. The most frequent sizes are 5.5, 8 and 9 mm.

The billet goes through the size-corresponding stands and is changed into a sequence of round and oval shapes before it enters the finishing block to acquire the final shape. The last 10 stands are compressed inside the finishing block and cannot be seen.

After the billet is transformed into its new shape, it is weighed, cooled on the cooling bed, wrapped in a bundle and moved to the dispatch area.

Any change of size should take about 3 hours. Maintenance should take much longer, about 7 hours.

There are two shear machines at the end of the roughing and intermediate stages. They cut the billets when appropriate to acquire the desired size.

Water is used to cool the billet and keep its shape.

On the day of the visit, 9 mm was the size in production. One hour of production would have processed 56 billets.

I received very important and helpful information from Mr Naif Al-Ansari and Mr Naif Al-Ghamdi.

C.4.4.4 Billet Bay

The basic mission of this part of the Rolling Mill plant is to store the hot billets for transfer when appropriate to one of the three mills. Each cast makes 80 billets for transfer to the billet bay. In this large open area, billets are gathered and piled into specific locations according to characteristics. A crane takes the billets to designated locations. It can only lift 6 billets at once.

Later, and according to the schedule from Production Planning, the charging raid is used to deliver these billets to the operating mill. A maximum of 24 billets can be moved to the mill at once. The time needed to deliver them varies between the mills.

The billet bay can accommodate 150,000 tonnes at a time. However, during my visit there were about 200,000 tonnes in the billets bay helped by the extra spaces in dispatch area. The morning shift staff in the bay must prepare a “stock sheet” every day. The sheet shows exactly what is in the bay.

There are 5 cranes; 3 of them for the rolling mill, which lift 6 billets (20 tonnes) maximum to be sent to the mill which contains 24 billets divided into 6 billets together. Another 2 cranes can lift 9 billets (25 tonnes) maximum.

A maximum of 24 billets can be moved to the mill at once. The time needed to deliver them varies between the mills.

Mr Nabeel Al-Hassan and Mr Abdulsalam Al-Anazi were of great help so that I could catch the general idea of how the bay operates.

Figure C.11 is a three-dimensional layout of the plant, in a simplified order.

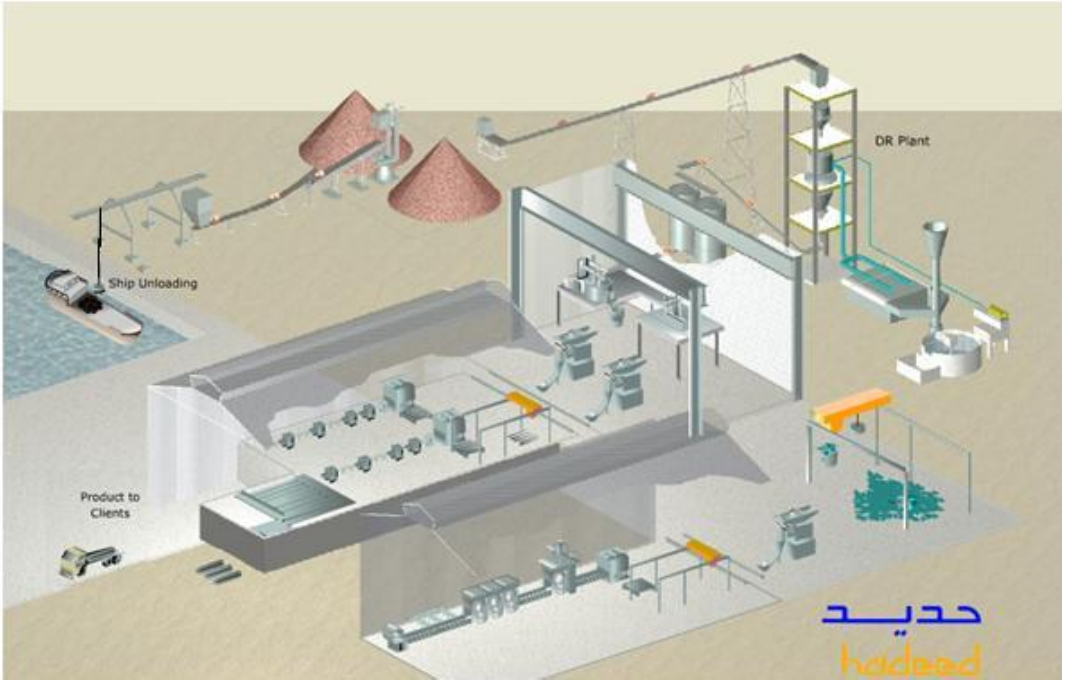


Figure C.11: Three-dimensional layout of Hadeed

C.5 Dispatch

This stage of production is simply lifting the ready products from the production lines over to designated storage locations, or sometimes to the back of trailers if the order is urgent. This is done with a large magnet-supported crane.

Inside the end of the mill, 3 cranes are usually operating; one to lift from the production line to storage, one for loading onto trucks, and one is usually a standby unless it is needed in either one of the other cranes' areas.

Before the wrapped bundles leave the end of the production line, they are tagged with a sticker that shows the weight of the bundle, grade, bundle number, cast number, length, size, name of product and the number of bars, if it is not a coil.

Every day, a dispatching schedule is prepared to ease choosing the locations for loading. The on-duty shift planner is responsible for this job.

The basic procedure of dispatching or loading a truck is explained briefly as follows:

- The driver enters through gate (2) and submits a loading request, which contains all necessary information.

- The driver weighs his truck at the gate.
- The dispatcher receives the order, picks a scheduled loading point and orders the crane to load.
- The load on the back of the truck is checked at the dispatch office by stock controllers before it leaves.
- The truck is weighed again to check it does not exceed the legal limit (44 tonnes including the truck's weight). If the authority at the weighbridge gets suspicious about the weight, he should check the load again himself. (He is usually an expert as he has worked in all three mills and the dispatching office.)
- The truck leaves.

The dispatch section has responsibility to submit the final product to customer in the correct size and quantity. This section is dealt with by QC staff who check the final product and deal with sales inquires. Production planners update data in SAP daily to alert dispatch staff to release the products. Dispatch submits around 10 tonnes daily. They control from 260 to 300 trucks daily, and each truck can carry 30 tonnes. In 2006, dispatch submitted around 3.5 million tonnes of long product alone.

C.5.1 Relevant information about dispatch

- There are some defective bundles, either missing the logo or overweight, etc. They are either fixed or taken to the scrapyard to be reprocessed if they cannot be fixed.
- Some bundles fall as the crane is lifting them. No accidents were reported as a result of this but this is still a near-miss.
- The dispatching and delivery is done through a contractor (Globe Marine).
- Every day, the stock is counted in order to know where to load trucks and to control the stock itself.
- The system becomes very slow if another person occupies the same SAP page the weighbridge dispatcher is using, or wants to use but cannot until the page is free. This is a hassle that need to be solved.
- The average dispatched production of Hadeed is about 10,000 tonnes daily.
- Mr Saad Al-Qahtani and Mr Sayer Al-Shammari were my main sources of information.

C.6 Sales

Sales take the inquiries from customers for the materials needed, which go to production planning. Then, these inquiries are finalised by production planning depending on the capacity of all plants. Sales have a customer services section to resolve complaints from customers. All inquiries are put on the SAP system. I learned in sales how the company receives and processes customers' orders from the minute they are received till they are shipped to their location by Globe Marine, the contractor that Hadeed assigned for that job.

One important note is that, to control the Saudi steel market and ban any unethical actions between the traders, the company specifies a certain amount of steel for each buyer quarterly. It also controls their profit margin by collecting the approximated margin with the price of the order in advance. This agreement which controls this operation is called the "Profit Box".

The sales department is the company's representative to customers. They receive the orders and try to achieve the highest customer satisfaction. The company now receives orders on a quarterly basis (every three months) to avoid the hassle of waiting till the last minute in many cases. The procedure from placing an order to receiving the goods is as follows:

- Order received quarterly by fax usually.
- Order confirmation is issued from sales dept.
- The arranged date of delivery is sent to customer.
- Order received at customer's location using contractor's trucks.
- Delivery order is stamped by customer, acknowledging receipt of the order.
- Sales department, along with Marketing, hold frequent meetings to specify the steel and iron prices according to the world market and consider the port's fees and other transportation.
- A so-called "Profit-box" was established to ensure fairness between customers. According to the regulations and rules of this box, every retailer is entitled to a certain amount of steel every period. A 75-SR profit margin has been determined by the company. The price of any order placed by the customer is automatically increased by 75-SR per tonne. If the customer exceeds and receives more than his arranged share of steel in one period (three months), his profit is decreased and not all 75 riyals are given back.

- There are two ways of paying: Cash and through a Bank guarantee. The bigger the customer the higher his guarantee.
- Thanks to Mr Ahmed Al-Mesned for this information.
- They apply a policy that their sales are either toward traders or manufactures
- They get the order
- Login in to the SAP system
- Email to production planning (SABIC) and scheduling (Hadeed)
- Call within 1-2 days
- Response by email
- Reproducible delivery time
- Send to customer by fax
- Offer validity, conditions, payment terms
- Bank guarantee, cash in advance, LC (letter of credit)
- Purchasing order
- Confirmation
- Finalise the sales order
- They are going to apply Ecommerce
- SABIC is working to open credit
- SAP send orders to level 3 – successfully sent
- There is a technical person to track the orders
- Within 10 days
- Weekly meeting between sales, production planning and scheduling
- Ready for dispatch.

C.7 Marketing

I started my rotation trip in the marketing department. This part of the rotation was the shortest because their staff was too busy. I learned briefly the main functions of the department, which included commercial advertising, performance measurement, financial reporting, product pricing, and forecasting. I noticed that most of their work is done in cooperation with other departments, such as production planning, accounting and finance.

Mr Adel Al-Ghamdi explained the main functions of the company's marketing department. These functions can be identified as follows:

- Commercial advertisements for public audience and big retailers.
- Commercial advertising plans.
- Product specification (along with Sales).
- Forecasting Reports on World and Regional Market.
- Company Performance Measurements.
- Financial Analysis Reports (along with finance and accounting departments).
- Annual study in the 1st quarter to predict the primary and secondary data.
- Process analysis: A lot of variables in the market they analyse and evaluate.
- Annual survey – main survey – first quarter of the year, to know the trend in market-consumption; Objectives basics: new trend added to the study – want to know the consumption.
- Primary data: exists in the system because they supply the customer with all the requirements; no way to get from outside because they have exclusive agreement – mainly local, small portion to GCC 7-8%.
- They go looking for secondary information: other information, new trends, Secondary data, New applications, Distribution of consumption in the sectors, projects, Information about the product from customer.
- Long product: Can do it In-house: very simple.
- Thinking to include researcher contractor.
- At the end of the day, want to know the market behaviour, competitors in the market, Go to adjust production, develop product, Recommendations.
- Do Marketing plan, No need for comprehensive plan mechanism, weekly review from the sales in the market regarding the size and prices.
- Coordinate with finance, production, research and development (R&D).
- They have a book and get back to it, New development, Reference or standard going to be implemented.
- New initiative, Operation planning trying to record market plan to include.
- They get information from Sales volume/price distribution.
- Finance have everything, Planning, Price, Survey competitor, study house.
- Forecast for future: the price is difficult.
- The price increased 300%, raw material iron ore 500%.
- Supply demand so tight.
- Raw material is so limited: Iron ore.

- Plan 2009: Estimate for price based on consumption, already Study for new product, High carbon, New application appropriate plan, Implementation, Input from sales divided confirm, Implementation-sales-Promotion, Exhibition, Advertising, Keep watching implementation, Adjusting price.
- They have to announce it regularly, Change plan, Budget for promotion, Have to spend it, Changes in direction, 10 years budget promotion 10-20%.
- Weekly meeting every two months.
- The demand is calculated based on finding out the total production for all competitors including Hadeed, which is done through coordination between the companies, subtracted from the imported quantities which will give the real consumption.
- The competitors are:
    - Itifaq
    - Rajhi
    - Taiba
    - Wofoor
    - New companies: Yamama.
- The annual net steel consumption in Saudi is 5,700,000 tonnes which is distributed as:
    - 51% Hadeed
    - 24% Itifag
    - 14% Rajhi
    - 3% Qatari
    - 3% Wofoor
    - 1% Taiba
    - 2% imported mainly from Egypt and Turkey.
- Finding the market size:
    - Relationships with the companies through sharing information
    - Quantities through Customs
    - Quantity from the government
    - Quantity from emirate
    - The inventory from SABIC, imported locally
    - Initial market survey.
- Added value price
- Proposal to management

- Technology study – SABIC
- Coordination between SABIC technology centre and Sales
- Visit all the manufacturers who import carbon products
- SABIC collect quality, composition, properties, samples
- It is within SABIC's capabilities and can be produced through the current production line, OK
- If not the project management department, approve it to be applied through a new expansion, otherwise disqualify
    - In the Middle East Hadeed is ranked as the leader of the steel industry which contributed, in all the strategic infrastructure of the main projects around the world, mainly the huge projects, which are:
    - Hong Kong towers
    - Dubai Airport
    - Jumaira beach
    - Burj Alarab tower
- The selection process of Hadeed starts with giving the offers to certain projects and then Hadeed usually wins because of the highly quality products.

C.8 Production Planning

The essential duty of the Production planning section at Hadeed is to produce a periodical (weekly, monthly and yearly) plan that compromises between the demand (certain and forecasted) and the production capacity of the company. This plan mainly assigns certain sizes of finished products to be produced in each of the four mills available in the long products production area.

C.8.1 Production Planning (SBU)

Production planning (SBU) is responsible for the long-term planning such as the annual budget of output and consumption. Also, monthly plan and monthly forecast.

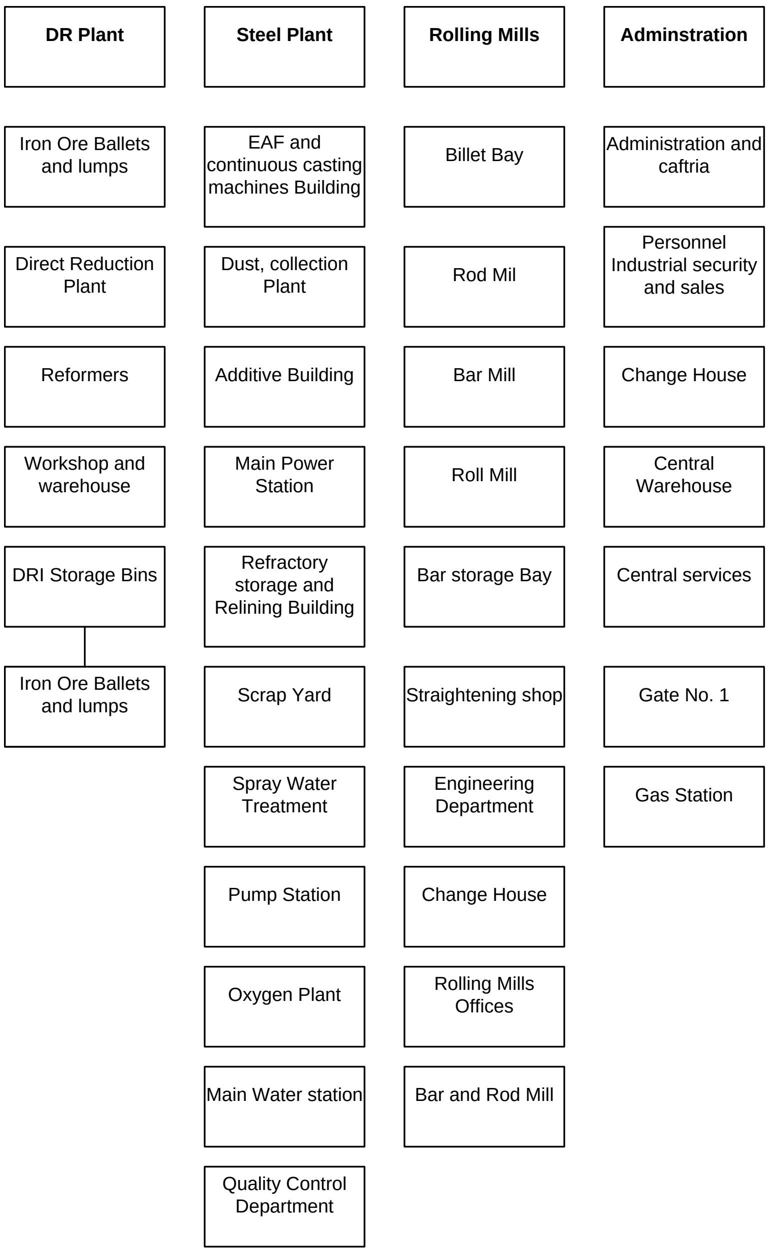
C.9 Quality Assurance Test House (Long Products)

QA carry out many tests of the samples of material in order to release the material to the rolling mills. They check Ultimate Tensile Strength, Yield Strength and elongation. Also, they test band of the material.

C.10 Product Development

Product development have labs to check the metallurgy of material from many sides, such as checking for cracks. They carry out trials in the materials and the plant in order to develop production.

C.11 Organisational chart



C.12 Conclusion

The benefit I acquired from this rotation trip is beyond description. These visits have made my understanding of the many operations and terms faced in the department much easier.

During this valuable rotation trip, I had an opportunity to look closely at the primary functions of the company and how these functions are implemented. This should ease my task of simulating the production line.

Appendix D

Simulation Model

```
;
;
;     Model statements for module:  BasicProcess.Create 3 (iron ore arrives to the
system)
;

58$           CREATE,
1000,HoursToBaseTime(0.0),iron:HoursToBaseTime(2),600000:NEXT(59$);

59$           ASSIGN:        iron ore arrives to the system.NumberOut=iron ore
arrives to the system.NumberOut + 1:NEXT(0$);


;
;
;     Model statements for module:  BasicProcess.Assign 3 (Assign 3)
;
0$            ASSIGN:        ArrTime=tnow:NEXT(1$);


;
;
;     Model statements for module:  BasicProcess.Process 5 (Port)
;
1$            ASSIGN:        Port.NumberIn=Port.NumberIn + 1:
                             Port.WIP=Port.WIP+1;
91$           STACK,         1:Save:NEXT(65$);

65$           QUEUE,         Port.Queue;
64$           SEIZE,         2,VA:
                             Port_R,1:NEXT(63$);

63$           DELAY:         0.027000000000000,,VA:NEXT(106$);

106$          ASSIGN:        Port.WaitTime=Port.WaitTime + Diff.WaitTime;
70$           TALLY:         Port.WaitTimePerEntity,Diff.WaitTime,1;
72$           TALLY:         Port.TotalTimePerEntity,Diff.StartTime,1;
96$           ASSIGN:        Port.VATime=Port.VATime + Diff.VATime;
97$           TALLY:         Port.VATimePerEntity,Diff.VATime,1;
62$           RELEASE:       Port_R,1;
111$          STACK,         1:Destroy:NEXT(110$);

110$          ASSIGN:        Port.NumberOut=Port.NumberOut + 1:
                             Port.WIP=Port.WIP-1:NEXT(23$);


;
;
;     Model statements for module:  BasicProcess.Assign 14 (Assign 14)
;
23$           ASSIGN:        Modules inventory=Modules inventory+1:NEXT(50$);


;
;
;     Model statements for module:  BasicProcess.Record 12 (DR_Counter)
;
```

```
50$           COUNT:         DR_Counter,1:NEXT(24$);


;
;
;     Model statements for module:  AdvancedProcess.Hold 3 (Hold 3)
;
24$           QUEUE,         Hold 3.Queue;
              SCAN:          Modules inventory>=0:NEXT(2$);


;
;
;     Model statements for module:  BasicProcess.Decide 3 (Decide 3)
;
2$            BRANCH,        1:
                             With,(80)/100,113$,Yes:
                             Else,114$,Yes;
113$          ASSIGN:        Decide 3.NumberOut True=Decide 3.NumberOut True +
1:NEXT(49$);

114$          ASSIGN:        Decide 3.NumberOut False=Decide 3.NumberOut False +
1:NEXT(3$);


;
;
;     Model statements for module:  BasicProcess.Record 11 (OxideScreen_Counter)
;
49$           COUNT:         OxideScreen_Counter,1:NEXT(4$);


;
;
;     Model statements for module:  BasicProcess.Process 6 (Module_A)
;
4$            ASSIGN:        Module_A.NumberIn=Module_A.NumberIn + 1:
                             Module_A.WIP=Module_A.WIP+1;
144$          STACK,         1:Save:NEXT(118$);

118$          QUEUE,         Module_A.Queue;
117$          SEIZE,         2,VA:
                             Module_A_R,1:NEXT(116$);

116$          DELAY:         0.342840000000000,,VA:NEXT(159$);

159$          ASSIGN:        Module_A.WaitTime=Module_A.WaitTime + Diff.WaitTime;
123$          TALLY:         Module_A.WaitTimePerEntity,Diff.WaitTime,1;
125$          TALLY:         Module_A.TotalTimePerEntity,Diff.StartTime,1;
149$          ASSIGN:        Module_A.VATime=Module_A.VATime + Diff.VATime;
150$          TALLY:         Module_A.VATimePerEntity,Diff.VATime,1;
115$          RELEASE:       Module_A_R,1;
164$          STACK,         1:Destroy:NEXT(163$);

163$          ASSIGN:        Module_A.NumberOut=Module_A.NumberOut + 1:
                             Module_A.WIP=Module_A.WIP-1:NEXT(17$);


;
;
;     Model statements for module:  BasicProcess.Assign 12 (Assign 12)
;
17$           ASSIGN:        silos inventory=silos inventory+1:NEXT(18$);


;
;
;     Model statements for module:  AdvancedProcess.Hold 1 (Hold 1)
```

```
;
18$            QUEUE,         Hold 1.Queue;
               SCAN:          silos inventory>=0:NEXT(8$);


;
;
;     Model statements for module:  BasicProcess.Process 11 (EAF1)
;
8$             ASSIGN:        EAF1.NumberIn=EAF1.NumberIn + 1:
                              EAF1.WIP=EAF1.WIP+1;
195$           STACK,         1:Save:NEXT(169$);

169$           QUEUE,         EAF1.Queue;
168$           SEIZE,         2,VA:
                              eaf_r,1:NEXT(167$);

167$           DELAY:         UNIF( 0.568 , 0.6736),,VA:NEXT(210$);

210$           ASSIGN:        EAF1.WaitTime=EAF1.WaitTime + Diff.WaitTime;
174$           TALLY:         EAF1.WaitTimePerEntity,Diff.WaitTime,1;
176$           TALLY:         EAF1.TotalTimePerEntity,Diff.StartTime,1;
200$           ASSIGN:        EAF1.VATime=EAF1.VATime + Diff.VATime;
201$           TALLY:         EAF1.VATimePerEntity,Diff.VATime,1;
166$           RELEASE:       eaf_r,1;
215$           STACK,         1:Destroy:NEXT(214$);

214$           ASSIGN:        EAF1.NumberOut=EAF1.NumberOut + 1:
                              EAF1.WIP=EAF1.WIP-1:NEXT(6$);


;
;
;     Model statements for module:  BasicProcess.Process 8 (Ladle Furnace)
;
6$             ASSIGN:        Ladle Furnace.NumberIn=Ladle Furnace.NumberIn + 1:
                              Ladle Furnace.WIP=Ladle Furnace.WIP+1;
246$           STACK,         1:Save:NEXT(220$);

220$           QUEUE,         Ladle Furnace.Queue;
219$           SEIZE,         2,VA:
                              LF2,1:NEXT(218$);

218$           DELAY:         SecondsToBaseTime(Uniform(4,8)),,VA:NEXT(261$);

261$           ASSIGN:        Ladle Furnace.WaitTime=Ladle Furnace.WaitTime +
Diff.WaitTime;
225$           TALLY:         Ladle Furnace.WaitTimePerEntity,Diff.WaitTime,1;
227$           TALLY:         Ladle Furnace.TotalTimePerEntity,Diff.StartTime,1;
251$           ASSIGN:        Ladle Furnace.VATime=Ladle Furnace.VATime + Diff.VATime;
252$           TALLY:         Ladle Furnace.VATimePerEntity,Diff.VATime,1;
217$           RELEASE:       LF2,1;
266$           STACK,         1:Destroy:NEXT(265$);

265$           ASSIGN:        Ladle Furnace.NumberOut=Ladle Furnace.NumberOut + 1:
                              Ladle Furnace.WIP=Ladle Furnace.WIP-1:NEXT(7$);


;
;
;     Model statements for module:  BasicProcess.Process 10 (Turret Process)
;
7$             ASSIGN:        Turret Process.NumberIn=Turret Process.NumberIn + 1:
                              Turret Process.WIP=Turret Process.WIP+1;
297$           STACK,         1:Save:NEXT(271$);

271$           QUEUE,         Turret Process.Queue;
270$           SEIZE,         2,VA:
```

```
                                Turret_R,1:NEXT(269$);

269$           DELAY:           UNIF( 0.016,0.018 ),,VA:NEXT(312$);

312$           ASSIGN:          Turret Process.WaitTime=Turret Process.WaitTime +
Diff.WaitTime;
276$           TALLY:           Turret Process.WaitTimePerEntity,Diff.WaitTime,1;
278$           TALLY:           Turret Process.TotalTimePerEntity,Diff.StartTime,1;
302$           ASSIGN:          Turret Process.VATime=Turret Process.VATime +
Diff.VATime;
303$           TALLY:           Turret Process.VATimePerEntity,Diff.VATime,1;
268$           RELEASE:         Turret_R,1;
317$           STACK,           1:Destroy:NEXT(316$);

316$           ASSIGN:          Turret Process.NumberOut=Turret Process.NumberOut + 1:
                                Turret Process.WIP=Turret Process.WIP-1:NEXT(5$);



;
;
;      Model statements for module:  BasicProcess.Process 7 (Caster1)
;
5$             ASSIGN:          Caster1.NumberIn=Caster1.NumberIn + 1:
                                Caster1.WIP=Caster1.WIP+1;
348$           STACK,           1:Save:NEXT(322$);

322$           QUEUE,           Caster1.Queue;
321$           SEIZE,           2,VA:
                                casterrr,1:NEXT(320$);

320$           DELAY:           0.06,,VA:NEXT(363$);

363$           ASSIGN:          Caster1.WaitTime=Caster1.WaitTime + Diff.WaitTime;
327$           TALLY:           Caster1.WaitTimePerEntity,Diff.WaitTime,1;
329$           TALLY:           Caster1.TotalTimePerEntity,Diff.StartTime,1;
353$           ASSIGN:          Caster1.VATime=Caster1.VATime + Diff.VATime;
354$           TALLY:           Caster1.VATimePerEntity,Diff.VATime,1;
319$           RELEASE:         casterrr,1;
368$           STACK,           1:Destroy:NEXT(367$);

367$           ASSIGN:          Caster1.NumberOut=Caster1.NumberOut + 1:
                                Caster1.WIP=Caster1.WIP-1:NEXT(22$);



;
;
;      Model statements for module:  BasicProcess.Assign 13 (Assign 13)
;
22$            ASSIGN:          BB Inventory=BB Inventory+1:NEXT(20$);



;
;
;      Model statements for module:  AdvancedProcess.Hold 2 (Hold 2)
;
20$            QUEUE,           Hold 2.Queue;
               SCAN:            BB Inventory>=0:NEXT(9$);



;
;
;      Model statements for module:  BasicProcess.Decide 5 (Decide 5)
;
9$             BRANCH,          1:
                                With,(33.33)/100,10$,Yes:
                                With,(33.33)/100,12$,Yes:
                                With,(33.34)/100,11$,Yes:
                                Else,14$,Yes;
```

```
;
;
;     Model statements for module:  BasicProcess.Dispose 6 (Dispose 6)
;
14$           ASSIGN:        Dispose 6.NumberOut=Dispose 6.NumberOut + 1;
372$          DISPOSE:       Yes;


;
;
;     Model statements for module:  BasicProcess.Process 12 (bar mill1)
;
10$           ASSIGN:        bar mill1.NumberIn=bar mill1.NumberIn + 1:
                             bar mill1.WIP=bar mill1.WIP+1;
402$          STACK,         1:Save:NEXT(376$);

376$          QUEUE,         bar mill1.Queue;
375$          SEIZE,         2,VA:
                             bar mill1_R,1:NEXT(374$);

374$          DELAY:         0.396,,VA:NEXT(417$);

417$          ASSIGN:        bar mill1.WaitTime=bar mill1.WaitTime + Diff.WaitTime;
381$          TALLY:         bar mill1.WaitTimePerEntity,Diff.WaitTime,1;
383$          TALLY:         bar mill1.TotalTimePerEntity,Diff.StartTime,1;
407$          ASSIGN:        bar mill1.VATime=bar mill1.VATime + Diff.VATime;
408$          TALLY:         bar mill1.VATimePerEntity,Diff.VATime,1;
373$          RELEASE:       bar mill1_R,1;
422$          STACK,         1:Destroy:NEXT(421$);

421$          ASSIGN:        bar mill1.NumberOut=bar mill1.NumberOut + 1:
                             bar mill1.WIP=bar mill1.WIP-1:NEXT(26$);


;
;
;     Model statements for module:  BasicProcess.Assign 15 (Update bar inventory)
;
26$           ASSIGN:        InventoryPosition_Bar=InventoryPosition_Bar+1:
                             Bar Inventory=Bar Inventory+1:NEXT(16$);


;
;
;     Model statements for module:  BasicProcess.Record 6 (Record 6)
;
16$           TALLY:         Record 6,INT(ArrTime),1:NEXT(57$);


;
;
;     Model statements for module:  BasicProcess.Assign 29 (Finishing time)
;
57$           ASSIGN:        Finishedtime=TNOW:NEXT(15$);


;
;
;     Model statements for module:  BasicProcess.Record 5 (Record 5)
;
15$           COUNT:         Record 5,1:NEXT(13$);


;
;
;     Model statements for module:  BasicProcess.Dispose 5 (Dispose 5)
;
```

```
13$          ASSIGN:       Dispose 5.NumberOut=Dispose 5.NumberOut + 1;
424$         DISPOSE:      Yes;


;
;
;     Model statements for module:  BasicProcess.Process 14 (bar mill3)
;
12$          ASSIGN:       bar mill3.NumberIn=bar mill3.NumberIn + 1:
                           bar mill3.WIP=bar mill3.WIP+1;
454$         STACK,        1:Save:NEXT(428$);

428$         QUEUE,        bar mill3.Queue;
427$         SEIZE,        2,VA:
                           Bar mill3_R,1:NEXT(426$);

426$         DELAY:        0.396,,VA:NEXT(469$);

469$         ASSIGN:       bar mill3.WaitTime=bar mill3.WaitTime + Diff.WaitTime;
433$         TALLY:        bar mill3.WaitTimePerEntity,Diff.WaitTime,1;
435$         TALLY:        bar mill3.TotalTimePerEntity,Diff.StartTime,1;
459$         ASSIGN:       bar mill3.VATime=bar mill3.VATime + Diff.VATime;
460$         TALLY:        bar mill3.VATimePerEntity,Diff.VATime,1;
425$         RELEASE:      Bar mill3_R,1;
474$         STACK,        1:Destroy:NEXT(473$);

473$         ASSIGN:       bar mill3.NumberOut=bar mill3.NumberOut + 1:
                           bar mill3.WIP=bar mill3.WIP-1:NEXT(27$);


;
;
;     Model statements for module:  BasicProcess.Assign 16 (Update rod inventory)
;
27$          ASSIGN:       InventoryPosition_Rod=InventoryPosition_Rod+1:
                           rod Inventory=rod Inventory+1:NEXT(16$);


;
;
;     Model statements for module:  BasicProcess.Process 13 (bar mill2)
;
11$          ASSIGN:       bar mill2.NumberIn=bar mill2.NumberIn + 1:
                           bar mill2.WIP=bar mill2.WIP+1;
505$         STACK,        1:Save:NEXT(479$);

479$         QUEUE,        bar mill2.Queue;
478$         SEIZE,        2,VA:
                           Bar mill2_R,1:NEXT(477$);

477$         DELAY:        0.396,,VA:NEXT(520$);

520$         ASSIGN:       bar mill2.WaitTime=bar mill2.WaitTime + Diff.WaitTime;
484$         TALLY:        bar mill2.WaitTimePerEntity,Diff.WaitTime,1;
486$         TALLY:        bar mill2.TotalTimePerEntity,Diff.StartTime,1;
510$         ASSIGN:       bar mill2.VATime=bar mill2.VATime + Diff.VATime;
511$         TALLY:        bar mill2.VATimePerEntity,Diff.VATime,1;
476$         RELEASE:      Bar mill2_R,1;
525$         STACK,        1:Destroy:NEXT(524$);

524$         ASSIGN:       bar mill2.NumberOut=bar mill2.NumberOut + 1:
                           bar mill2.WIP=bar mill2.WIP-1:NEXT(26$);


;
;
;     Model statements for module:  BasicProcess.Dispose 4 (Lessthan3mmDepart)
;
```

```
3$            ASSIGN:       Lessthan3mmDepart.NumberOut=Lessthan3mmDepart.NumberOut
+ 1;
527$          DISPOSE:      Yes;


;
;
;     Model statements for module:  BasicProcess.Create 4 (Create Customer demand
arrival at sales)
;

528$          CREATE,       1,DaysToBaseTime(0.0),bar
customer:DaysToBaseTime(1):NEXT(529$);

529$          ASSIGN:       Create Customer demand arrival at sales.NumberOut=
                            Create Customer demand arrival at sales.NumberOut +
1:NEXT(47$);


;
;
;     Model statements for module:  BasicProcess.Assign 27 (Assign 27)
;
47$           ASSIGN:       bar Demand arr time=TNOW:NEXT(51$);


;
;
;     Model statements for module:  AdvancedProcess.Delay 1 (Delay 1)
;
51$           DELAY:        4320.000000000000000,,Other:NEXT(42$);


;
;
;     Model statements for module:  BasicProcess.Record 9 (Tally bar Demand)
;
42$           COUNT:        Tally bar Demand,1:NEXT(28$);


;
;
;     Model statements for module:  BasicProcess.Assign 17 (Customer Demand1)
;
28$           ASSIGN:       Bar Demand=Unif(6667,7300):
                            total bar customers=total bar customers+1:NEXT(29$);


;
;
;     Model statements for module:  BasicProcess.Decide 6 (check Bar inventory)
;
29$           BRANCH,       1:
                            If,Bar Demand<=Bar Inventory,532$,Yes:
                            Else,533$,Yes;
532$          ASSIGN:       check Bar inventory.NumberOut True=check Bar
inventory.NumberOut True + 1:NEXT(30$);

533$          ASSIGN:       check Bar inventory.NumberOut False=check Bar
inventory.NumberOut False + 1:NEXT(34$);


;
;
;     Model statements for module:  BasicProcess.Assign 18 (Take away from bar
inventory)
;
30$           ASSIGN:       Bar Inventory=Bar Inventory-bar demand:NEXT(44$);
```

```
;
;
;     Model statements for module:  BasicProcess.Assign 25 (Take away from bar
inventory position)
;
44$           ASSIGN:        InventoryPosition_Bar=InventoryPosition_Bar-bar
demand:NEXT(35$);


;
;
;     Model statements for module:  BasicProcess.Decide 8 (order bar from bar DC?)
;
35$           BRANCH,        1:
                             If,InventoryPosition_Bar<=Bar_Reorder_Point,534$,Yes:
                             Else,535$,Yes;
534$          ASSIGN:        order bar from bar DC?.NumberOut True=order bar from bar
DC?.NumberOut True + 1:NEXT(36$);

535$          ASSIGN:        order bar from bar DC?.NumberOut False=order bar from
bar DC?.NumberOut False + 1:NEXT(46$);


;
;
;     Model statements for module:  BasicProcess.Assign 22 (order from DC and update
bar inventory position)
;
36$           ASSIGN:
InventoryPosition_Bar=InventoryPosition_Bar+bar_order_qty:
                             order_bar_DC=1:NEXT(46$);


;
;
;     Model statements for module:  BasicProcess.Dispose 7 (Dispose 7)
;
46$           ASSIGN:        Dispose 7.NumberOut=Dispose 7.NumberOut + 1;
536$          DISPOSE:       Yes;


;
;
;     Model statements for module:  BasicProcess.Assign 21 (Lost Customer)
;
34$           ASSIGN:        Lost bar customers=Lost bar customers+1:NEXT(53$);


;
;
;     Model statements for module:  AdvancedProcess.Delay 3 (Delay 3)
;
53$           DELAY:         43200.000000000000000,,Other:NEXT(37$);


;
;
;     Model statements for module:  BasicProcess.Record 7 (Tally bar lost customer)
;
37$           COUNT:         Tally bar lost customer,1:NEXT(54$);


;
;
;     Model statements for module:  BasicProcess.Record 13 (delay for schedule
change)
```

```
;
54$            TALLY:          delay for schedule change,INT(bar Demand arr
time),1:NEXT(35$);


;
;
;     Model statements for module:  BasicProcess.Create 5 (Create rod Customer demand
arrival at sales)
;

537$           CREATE,         1,DaysToBaseTime(0.0),rod
customer:DaysToBaseTime(1):NEXT(538$);

538$           ASSIGN:         Create rod Customer demand arrival at sales.NumberOut=
                               Create rod Customer demand arrival at sales.NumberOut +
1:NEXT(48$);


;
;
;     Model statements for module:  BasicProcess.Assign 28 (Assign 28)
;
48$            ASSIGN:         Rod Demand arr time=TNOW:NEXT(52$);


;
;
;     Model statements for module:  AdvancedProcess.Delay 2 (Delay 2)
;
52$            DELAY:          4320.000000000000000,,Other:NEXT(43$);


;
;
;     Model statements for module:  BasicProcess.Record 10 (Tally Rod Demand)
;
43$            COUNT:          Tally Rod Demand,1:NEXT(31$);


;
;
;     Model statements for module:  BasicProcess.Assign 19 (Customer Demand2)
;
31$            ASSIGN:         rod Demand=unif(818,1043):
                               total rod customers=total rod customers+1:NEXT(32$);


;
;
;     Model statements for module:  BasicProcess.Decide 7 (check rod inventory)
;
32$            BRANCH,         1:
                               If,rod Demand<=rod Inventory,541$,Yes:
                               Else,542$,Yes;
541$           ASSIGN:         check rod inventory.NumberOut True=check rod
inventory.NumberOut True + 1:NEXT(33$);

542$           ASSIGN:         check rod inventory.NumberOut False=check rod
inventory.NumberOut False + 1:NEXT(38$);


;
;
;     Model statements for module:  BasicProcess.Assign 20 (Take away from rod
inventory)
;
33$            ASSIGN:         rod Inventory=Rod Inventory-Rod demand:NEXT(45$);
```

```
;
;
;     Model statements for module:  BasicProcess.Assign 26 (Take away from rod
inventory position)
;
45$           ASSIGN:        InventoryPosition_Rod=InventoryPosition_Rod-rod
demand:NEXT(39$);


;
;
;     Model statements for module:  BasicProcess.Decide 9 (order Rod from DC?)
;
39$           BRANCH,        1:
                             If,InventoryPosition_Rod<=Rod_Reorder_Point,543$,Yes:
                             Else,544$,Yes;
543$          ASSIGN:        order Rod from DC?.NumberOut True=order Rod from
DC?.NumberOut True + 1:NEXT(41$);

544$          ASSIGN:        order Rod from DC?.NumberOut False=order Rod from
DC?.NumberOut False + 1:NEXT(46$);


;
;
;     Model statements for module:  BasicProcess.Assign 24 (order from DC and update
rod inventory position)
;
41$           ASSIGN:
InventoryPosition_Rod=InventoryPosition_Rod+Rod_order_qty:
                             order_rod_DC=1:NEXT(46$);


;
;
;     Model statements for module:  BasicProcess.Assign 23 (Lost Customer1)
;
38$           ASSIGN:        Lost customers1=Lost customers1+1:NEXT(55$);


;
;
;     Model statements for module:  AdvancedProcess.Delay 4 (Delay 4)
;
55$           DELAY:         43200.000000000000000,,Other:NEXT(40$);


;
;
;     Model statements for module:  BasicProcess.Record 8 (Tally rod lost customer)
;
40$           COUNT:         Tally rod lost customer,1:NEXT(56$);


;
;
;     Model statements for module:  BasicProcess.Record 15 (delay for rod schedule
change)
;
56$           TALLY:         delay for rod schedule change,INT(Rod Demand arr
time),1:NEXT(39$);
```

Glossary

Advanced Planning and Scheduling (APS)

"A manufacturing management process by which raw materials and production capacity are optimally allocated to meet demand. APS is especially well-suited to environments where simpler planning methods cannot adequately address complex trade-offs between competing priorities." (Vitasek, 2010)

Agile Enterprise

"An agile enterprise is a fast moving, adaptable and robust business. It is capable of rapid adaptation in response to unexpected and unpredicted changes and events, market opportunities, and customer requirements. Such a business is founded on processes and structures that facilitate speed, adaptation and robustness and that deliver a coordinated enterprise that is capable of achieving competitive performance in a highly dynamic and unpredictable business environment that is unsuited to current enterprise practices." (Kidd, 2000)

Agile Manufacturing

"Assumes the business environment is subject to conditions of continuous change, uncertainty and unpredictability. An Agile approach requires an ability to easily reconfigure strategies, structures and processes and to continuously review company market positioning and the business environment." (Kidd, 2000)

Agility

"The ability to change and reconfigure the internal and external parts of the enterprise – strategies, organisation, technologies, people, partners, suppliers, distributors, and even customers in response to change, unpredictable events and uncertainty in the business environment." (Kidd, 2000)

Assemble-to-Order

"A strategy employed in production and light manufacturing environments where complete subassemblies and components are assembled into a finished product just prior to customer shipment." (Vitasek, 2010) Synonym: Finish to Order.

Assembly

"A collection of components which have been put together into a unit, or the activity involved with putting components together to form a unit." (Vitasek, 2010)

Glossary

Assembly Line

"A manufacturing process where products are completed from components as a result of a series of continuous activities. Henry Ford is widely recognized as the father of the assembly line." (Vitasek, 2010)

Automated Storage/Retrieval System (AS/RS)

"An inventory storage system which uses un-manned vehicles to automatically perform stock put-away and picking actions." (Vitasek, 2010)

Available to Promise (ATP)

"The quantity of a product which is or will be available to promise to a customer based on their required shipment date. ATP is typically 'time phased' to allow for promising delivery at a future date based on anticipated purchase or production receipts." (Vitasek, 2010)

Backorder

"The act of retaining a quantity to ship against an order when other order lines have already been shipped. Backorders are usually caused by stock shortages, or the quantity remaining to be shipped if an initial shipment(s) has been processed. Note: In some cases backorders are not allowed, this results in a lost sale when sufficient quantities are not available to completely ship an order or order line." (Vitasek, 2010)

Bill of Material (BOM)

"A structured list of all the materials or parts and quantities needed to produce a particular finished product, assembly, subassembly, or manufactured part, whether purchased or not." (Vitasek, 2010)

Bullwhip Effect

"Also known as 'Whiplash Effect' it is an observed phenomenon in forecast-driven distribution channels. The oscillating demand magnification upstream a supply chain is reminiscent of a cracking whip. The concept has its roots in J Forrester's Industrial Dynamics (1961) and thus it is also known as the Forrester Effect." (Vitasek, 2010)

Capable to Promise (CTP)

"A technique similar to Available-to-Promise, it uses the availability of individual components to determine if an end item can be configured and assembled by a customer-given request date and provides the ability of adjusting plans due to inaccurate delivery date promises. Capable to promise looks at both materials and labour/machine requirements." (Vitasek, 2010)

Change Competency

"The key meaning of agility – a core competency, being the ability to change and cope with massive uncertainties. Change competency is measured in terms of five performance metrics – time, cost, scope, stability and frequency." (Kidd, 2000)

Glossary

Clock Speeds

"The life cycle from concept to death for products, concepts, technologies etc. which varies not only across industries but within industries for different product components, services and enterprise techniques." (Kidd, 2000)

Collaborative planning, forecasting, and replenishment (CPFR)

"Process or is a cooperative process that coordinates the requirements planning process between supplier partners for demand creation and demand fulfilment." (Bowersox et al., 2007)

Core Competencies

"Technologies and skills that (i) provide the potential to gain access to a wide variety of markets; (ii) offer significant enhancement of the perceived benefits of goods and services; (iii) are difficult to copy; and (iv) are not necessarily obvious to outsiders." (Kidd, 2000)

Decoupling point (DP)

"The point in the material flow streams to which the customer's order penetrates. It is here where order-driven and the forecast driven activities meet. As a rule, the decoupling point coincides with an important stock point – in control terms a main stock point – from which the customer has to be supplied." (Hoekstra & Romme, 1992)

"It separates the part of the organisation [supply chain] oriented towards customer orders from the part of the organisation [supply chain] based on planning. The decoupling point is also the point at which strategic stock is often held as a buffer between fluctuating customer orders and/or product variety and smooth production output." (Naylor et al., 1999)

Demand Planning

"The process of identifying, aggregating, and prioritizing, all sources of demand for the integrated supply chain of a product or service at the appropriate level, horizon and interval. The sales forecast is comprised of the following concepts:

1. The sales forecasting level is the focal point in the corporate hierarchy where the forecast is needed at the most generic level, i.e. Corporate forecast, Divisional forecast, Product Line forecast, SKU, SKU by Location.

2. The sales forecasting time horizon generally coincides with the time frame of the plan for which it was developed, i.e. Annual, 1-5 years, 1- 6 months, Daily, Weekly, Monthly.

3. The sales forecasting time interval generally coincides with how often the plan is updated, i.e. Daily, Weekly, Monthly, and Quarterly." (Vitasek, 2010)

Distribution Requirements Planning (DRP)

"A system of determining demands for inventory at distribution centers and consolidating demand information in reverse as input to the production and materials system." (Vitasek, 2010)

Efficient Consumer Response (ECR)

"The objective of ECR is to 'develop a trust-based relationship between manufacturers and retailers with the sharing of strategic information in order to optimise overall supply chain results." (Barratt & Oliveira, 2001)

"The four basic strategies are efficient product introduction, promotion, store assortment, replenishment." (Tajima, 2005)

Electronic Data Interchange (EDI)

"Intercompany, computer-to-computer transmission of business information in a standard format. For EDI purists, 'computer-to-computer' means direct transmission from the originating application program to the receiving, or processing, application program. An EDI transmission consists only of business data, not any accompanying verbiage or free-form messages. Purists might also contend that a standard format is one that is approved by a national or international standards organization, as opposed to formats developed by industry groups or companies." (Vitasek, 2010)

Engineer-to-Order

"A process in which the manufacturing organization must first prepare (engineer) significant product or process documentation before manufacture may begin." (Vitasek, 2010) Synonym: Buy-to-order (BTO)

Enterprise Design

"An approach to change which seeks to design individual enterprises to meet specified and changing requirements. Stands in contrast to the prescriptive 'copy cat' best practice approaches." (Kidd, 2000)

External Agility

"The ability to change and reconfigure the external parts of the enterprise – partners, suppliers, distributors, and even customers in response to change, unpredictable events and uncertainty in the business environment. See also Agility and Internal Agility." (Kidd. 2000)

Fill Rate

"The percentage of order items that the picking operation actually fills within a given period of time." (Vitasek, 2010)

Information Decoupling Point

The customer order decoupling point (information pipeline): "The point in the information pipeline to which the marketplace order penetrates without modification. It is where market-driven information flow meets." (Mason-Jones & Towill, 1999)

Internal Agility

“The ability to change and reconfigure the internal parts of the enterprise – strategies, organisation, technologies, and even people in response to change, unpredictable events and uncertainty in the business environment. See also Agility and External Agility.” (Kidd, 2000)

Just-in-Time (JIT)

“A broad philosophy of management that seeks to eliminate waste and improve quality in all business processes. Throughout the supply network the trigger to start work is dictated by demand from the end customer who is characterised as pull system.” (Harrison & Van Hoek, 2005).

Kanban

“Japanese word for ‘visible record’, loosely translated means card, billboard or sign. Popularized by Toyota Corporation, it uses standard containers or lot sizes to deliver needed parts to assembly line ‘just in time’ for use. Empty containers are then returned to the source as a signal to resupply the associated parts in the specified quantity.” (Vitasek, 2010)

Knowledge-based Systems

“A computer programming paradigm where knowledge is separated from program control. This technique enables applications that involve developing systems that can mimic expert knowledge in well defined areas, or which can be used for more complex and less well defined areas to give advice about consequences of decisions, or add to knowledge, or provide expert advice from one domain to experts in other domains.” (Kidd, 2000)

Leagile

“The combination of the lean and agile paradigms within a total supply chain strategy by positioning the decoupling point so as to best suit the need for responding to a volatile demand downstream yet providing level scheduling upstream from the marketplace.” (Naylor et al. 1999)

Leanness

“means developing a value stream to eliminate all waste, including time, and to ensure a level schedule” (Naylor et al., 1999).

Lean Production

“An enterprise paradigm concerned with doing more with less. Involves continuous efforts to eliminate waste of all kinds, such as inventory, stocks, time spent waiting, etc. Often confused with agility, lean enterprises are however fragile in that they only have limited capabilities to handle change, uncertainty and unpredictability, while agile enterprises are designed to thrive under such conditions.” (Kidd, 2000)

Logistics

"The process of strategically managing the procurement, movement and storage of materials, parts and finished inventory (and the related information flows) through the organization and its marketing channels in such a way that current and future profitability are maximized through the cost-effective fulfilment of orders." (Christopher, 2005)

Lot-for-Lot

"A method used in lot-sizing where production orders are created in quantities which match the net requirements for the manufacturing cycle." (Vitasek, 2010)

Make-to-Order (Manufacture-to-order)

"A manufacturing process strategy where the trigger to begin manufacture of a product is an actual customer order or release, rather than a market forecast. For Make-to-Order products, more than 20% of the value-added takes place after the receipt of the order or release, and all necessary design and process documentation is available at time of order receipt." (Vitasek, 2010)

Make-to-Stock (Manufacture-to-stock)

"A manufacturing process strategy where the finished product is continually held in plant or warehouse inventory to fulfill expected incoming orders or releases based on a forecast." (Vitasek, 2010)

Mass Customization

"Production of individually personalised goods and service at mass production prices. Enabled by concepts such as lean production, IT systems, late configuration, product modularisation." (Kidd, 2000)

"A phrase used in marketing, manufacturing, call centers and management referring to the use of flexible computer-aided manufacturing systems to produce custom output. Those systems combine the low unit costs of mass production processes with the flexibility of individual customization. At its core is a tremendous increase in variety and customization without a corresponding increase in costs." (Vitasek, 2010)

Master Production Schedule (MPS)

"The master level or top level schedule used to set the production plan in a manufacturing facility." (Vitasek, 2010)

Materials Requirements Planning (MRP)

"A decision-making methodology used to determine the timing and quantities of materials to purchase." (Vitasek, 2010)

Next Generation Manufacturing Enterprise

"Post mass/lean production enterprise operating is a post mass consumption society. The next generation enterprise is founded on the supporting strategies of agility, niche operations, knowledge based wealth creation." (Kidd, 2000)

Nimble Manufacturing

"A term used by Ford as part of its Ford 2000 Program. As a term internal to Ford it could mean the same as agile, or lean or flexible manufacturing or mass customisation. Ford 2000 itself however is a major reorganisation program which has involved the creation of a single global company from all of Ford's Automotive operations in North America and Europe, the reorganisation of product development into platform teams based upon a matrix structure, and the pursuit of a strategy of building more product variety off fewer vehicle platforms and exploiting niche markets for vehicles as well as volume vehicle production." (Kidd, 2000).

Planned Order

"An order proposed by an MRP system to cover forecast demand in a future period. Planned orders will changes dynamically over time to accommodate changes in forecasts and actual usage until they become 'firm planned orders' either through manual intervention or by virtue of the associated period moving within a planning horizon. The next step in the process would be to create an actual purchase or production order." (Vitasek, 2010)

Planned Receipt

"Any line item on an open purchase or production order which has been scheduled but not yet received into stock." (Vitasek, 2010)

Planning Horizon

"In an MRP system this is the length of time into the future (number of periods or days) for which the planning system will generate requirements. The horizon should be set long enough out to accommodate the longest cumulative lead time for any item in the population." (Vitasek, 2010)

Postponement

"The delay of final activities (i.e., assembly, production, packaging, etc.) until the latest possible time. A strategy used to eliminate excess inventory in the form of finished goods which may be packaged in a variety of configurations and to maximize the opportunity to provide a customized end product to the customer." (Vitasek, 2010)

Pull system

"A system of controlling materials whereby the user signals to the maker or provider that more material is needed. Material is sent only in response to such a signal." (Harrison & Van Hoek, 2005)

Push System

"A system of controlling materials whereby makers and providers make or send material in response to a pre-set schedule, regardless of whether the next process needs them at the time." (Harrison & Van Hoek, 2005)

Quick Response (QR)

"A strategy widely adopted by general merchandise and soft lines retailers and manufacturers to reduce retail out-of-stocks, forced markdowns and operating expenses. These goals are accomplished through shipping accuracy and reduced response time. QR is a partnership strategy in which suppliers and retailers work together to respond more rapidly to the consumer by sharing point-of-sale scan data, enabling both to forecast replenishment needs." (Vitasek, 2010)

Re-configurability

"Ability to reconfigure enterprises, technologies, organisations, virtual corporations etc. in response to rapidly changing circumstances." (Kidd, 2000)

Sales and Operations Planning (S&OP)

"A strategic planning process that reconciles conflicting business objectives and plans future supply chain actions. S&OP Planning usually involves various business functions such as sales, operations and finance to agree on a single plan/forecast that can be used to drive the entire business. Some organizations include suppliers and customers in their S&OP processes." (Vitasek, 2010)

Supply Chain

"A system whose constituent parts include material suppliers, production facilities, distribution services and customers linked together via a feed-forward flow of materials and feedback flow of information. This should be expanded to include the flow of resources and cash through the supply chain." (Naylor et al., 1999)

Supply Chain Management

"The management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole." (Christopher, 2005)

Supply Chain Operations Reference Model (SCOR)

"This is the model developed by the Supply-Chain Council (SCC) and is built around six major processes: plan, source, make, deliver, return and enable. The aim of the SCOR is to provide a standardized method of measuring supply chain performance and to use a common set of metrics to benchmark against other organizations." (Vitasek, 2010)

Takt Time (Taktzeit)/Cycle Time

"It is derived from the German word 'Taktzeit' (cycle time). Takt time sets the pace for industrial manufacturing lines. For example, in automobile manufacturing, cars are assembled on a line and are moved on to the next station after a certain time. Therefore, the time needed to complete work on each station has to be less than the takt time in order for the product to be completed within the allotted time." (Vitasek, 2010)

Vendor Managed Inventory (VMI)

"It is an arrangement under which the supplier, not the customer, decides how and when to replenish the customer's inventory." (Cooke, 1998)

Value Chain

"A chain of activities. Products pass all activities of the chain in order and at each activity the product gains some value. The chain of activities gives the products more added value than the sum of added values of all activities." (Vitasek, 2010)