COLLABORATIVE SUPPLY CHAIN MODELLING AND PERFORMANCE MEASUREMENT

A thesis submitted for the degree of Doctor of Philosophy

by

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ABSTRACT

For many years, supply chain research focused on operational aspects and therefore mainly on the optimisation of parts of the production and distribution processes. Recently, there has been an increasing interest in supply chain management and collaboration between supply chain partners. However, there is no model that takes into consideration all aspects required to adequately represent and measure the performance of a collaborative supply chain.

This thesis proposes a model of a collaborative supply chain, consisting of six constituents, all of which are required in order to provide a complete picture of such a collaborative supply chain. In conjunction with that, a collaborative supply chain performance indicator is developed. It is based on three types of measures to allow the adequate measurement of collaborative supply chain performance.

The proposed model of a collaborative supply chain and the collaborative supply chain performance indicator are implemented as a computer simulation. This is done in the form of a decision support environment, whose purpose is to show how changes in any of the six constituents affect collaborative supply chain performance.

The decision support environment is configured and populated with information and data obtained in a case study. Verification and validation testing in three different scenarios demonstrate that the decision support environment adequately fulfils it purpose.

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ABBREVIATIONS

Abbreviation	Full Name
3PL	Third Party Logistics
C	Cost
CD	Customer Demand
CS	Customer Satisfaction
CSCO	Chief Supply Chain Officer
CSCPI	Collaborative Supply Chain Performance Indicator
CU	Capacity Utilisation
DMI	Desired Manufacturer Inventory
DSE	Decision Support Environment
ED	Expected Demand
EDI	Electronic Data Interchange
EDM	Expected Demand Manufacturer
EIS	Executive Information System
ERP	Enterprise Resource Planning
ET	Enabling Technology
FA	Forecast Accuracy
FC	Fixed cost
FM	Flexibility Measure = Supply Chain Flexibility
GDS	Group Decision Support
IC	Inventory Coverage
ID	Information Delay
IG	Inventory Gap
ISCM	International Supply Chain Management
LA	Level of Alignment
MAPE	Mean Absolute Percent Error
MI	Manufacturer Inventory
MIS	Management Information System
MRP	Manufacturing Resource Planning
NE	North East
NW	North West

OM .... Output Measure
P .... Profit
PBM .... Participative Business Modelling
PC .... Production Capacity
PQ .... Product Quality
PS .... Production Starts
PTMT .... Production To Market Time
R .... Revenue
RC .... Repair Cost
RI .... Retailer Inventory
RM .... Resource Measure
RMat .... Raw Material
RSP .... Retailer Supplier Partnership
SCF .... Supply Chain Flexibility = Flexibility Measure
SCOR .... Supply Chain Operations Reference Model
SD .... System Dynamics
SE .... South East
SI .... Système International d'unités
SO .... Stock Out
SQ .... Sales Quantity
SW .... South West
TP .... Total Production
TPS .... *Transaction Processing System*
TTM .... Time to Market
USP .... Unit selling price
UVC .... Unit variable cost
VC .... Variable cost
VVT .... Verification and Validation Testing
WI .... Wholesaler Inventory
ρ .... Correlation Coefficient

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CHAPTER 1: SUPPLY CHAIN MODELLING

This thesis is concerned with the modelling of supply chains and in particular decisions made about improving supply chain performance.

1.1 RESEARCH REVIEW

Recent research in supply chain modelling is grouped into 3 major research areas: (1) Research concerned with demand amplification in supply chains, also referred to as the 'bullwhip effect'; (2) research applying modelling techniques within a framework for supply chain analysis and design; and (3) research contributing to international supply chain management.

1.1.1 Demand Amplification

Typical of research on demand amplification is the work of Anderson *et al.* (2000) and Dejonckheere *et al.* (2002). In addition, Sterman (1989a, b) presents a generic model of a stock management system, pointing out the decision-making involved in managing inventories.

Although cyclic demand fluctuation in market driven economies is a widely researched issue and well understood, upstream demand amplification in an industrial supply chain is less tacit. Using the machine tool industry as a case study, Anderson *et al.* (2000) explore the implication of demand amplification on lead-time, inventory, production, productivity, and workforce. Capital equipment firms are exposed to particularly large variances in demand, because a small change in end-product demand creates dramatic changes in the demand for the capital equipment required to manufacture those products. Anderson *et al.* (2000) use a system dynamics model to explain demand amplification along capital equipment supply chains, and test various strategies that could improve the functioning of the industry.

The system dynamics modelling methodology allows them to incorporate typical features of the capital equipment industries, such as feedback loops, delays and non-linearity. Although a discrete representation is more realistic for some parts of the model, continuous formulations are chosen for time and stocks, and found to be not too distorting; the essential dynamics of the industry are well demonstrated. Anderson *et al.* (2000) develop a model of the machine tool industry, consisting of three firms: a product maker, a machine maker, and a product parts supplier. Each firm in the model is represented by a simplified version of the 'standard system dynamics firm model' (Lyneis 1980). Some factors, including order cancellations, pricing policies, and national vs. international market share, are not incorporated in the model, but this does not have a negative impact on model accuracy in relation to the problems investigated. Next, they compare simulated with actual data, using statistical data as the input order rate to the model. Size and timing of the simulated time-series is shown to reflect the aggregate industry behaviour relatively accurately, as shown with goodness-of-fit tests based on the R2 and the Theil inequality statistics. Policy development then is conducted based on four hypotheses, which are derived from interviews at manufacturing and machine tool companies. Anderson *et al.* (2000) demonstrate that: (1) the (observed and simulated) extreme amplification is primarily due to the machine tool industry production capacity in conjunction with the 'investment accelerator' effect; (2) the machine-maker's employee productivity decreases with increasing volatility; (3) shorter production lead-time reduces supplier backlogs; and (4) smoothing machine-maker employment policies and product-maker order policies can improve machine-maker operations. They also identify the machine tool customers' order forecast rules as an important leverage point for reducing volatility, which could be improved through closer collaboration between customers and suppliers in the machine tool industry.

Dejonckheere *et al.* (2002) analyse how the bullwhip effect is generated by exponential smoothing algorithms. The bullwhip effect occurs when individual players in the chain order more products from their suppliers than their customers demand, which is especially likely to occur when orders throughout the chain are fluctuating. They note that the bullwhip effect in supply chains can be effectively controlled through design and re-engineering of supply chains. Transfer function models, in the form of the ratio of two polynomials in the Laplace Operator, are used to predict results from ordering policies within an inventory controlled feedback system. Those results are then confirmed by simulation. By introducing a matched filter, which adjusts the value of the smoothing constant, Dejonckheere *et al.* (2002) show that they are able to equalise the output variance when there is random demand. They conclude that the use of sophisticated forecasting methods in inventory controlled feedback systems bring only little advantage, unless at the same time the matched filter concept is used as well.

Sterman (1989b) argues that misperceptions of feedback account for poor performance in dynamic decision-making, as the decision processes are based on an anchoring and adjustment heuristic. Feedback is defined as not only outcome feedback, but also changes in the environment or condition of choice, which are caused by past action. Such multiple feedbacks are the norm in real problems of choice. Sterman (1989b) presents a generic model of a stock management system as shown in Figure 1.1, which forms the basic structure in an environment for a decision-making experiment. This generic stock management structure is applicable to many different scenarios, including raw material ordering, production control, or at a macroeconomic level, the control of the stock of money. The model consists of two parts, the physical stock and flow structure of the system, and the decision rules used to control the system. Sterman (1989b) states that "in most realistic stock management situations the complexity of the feedbacks among the variables precludes the determination of the optimal strategy", and proposes an order decision model based on a locally rational heuristics. An anchoring and adjustment policy is characterised by a mental simulation process, where an unknown quantity is estimated through recalling a known reference point (called the anchor), and then adjusting it according to other factors.

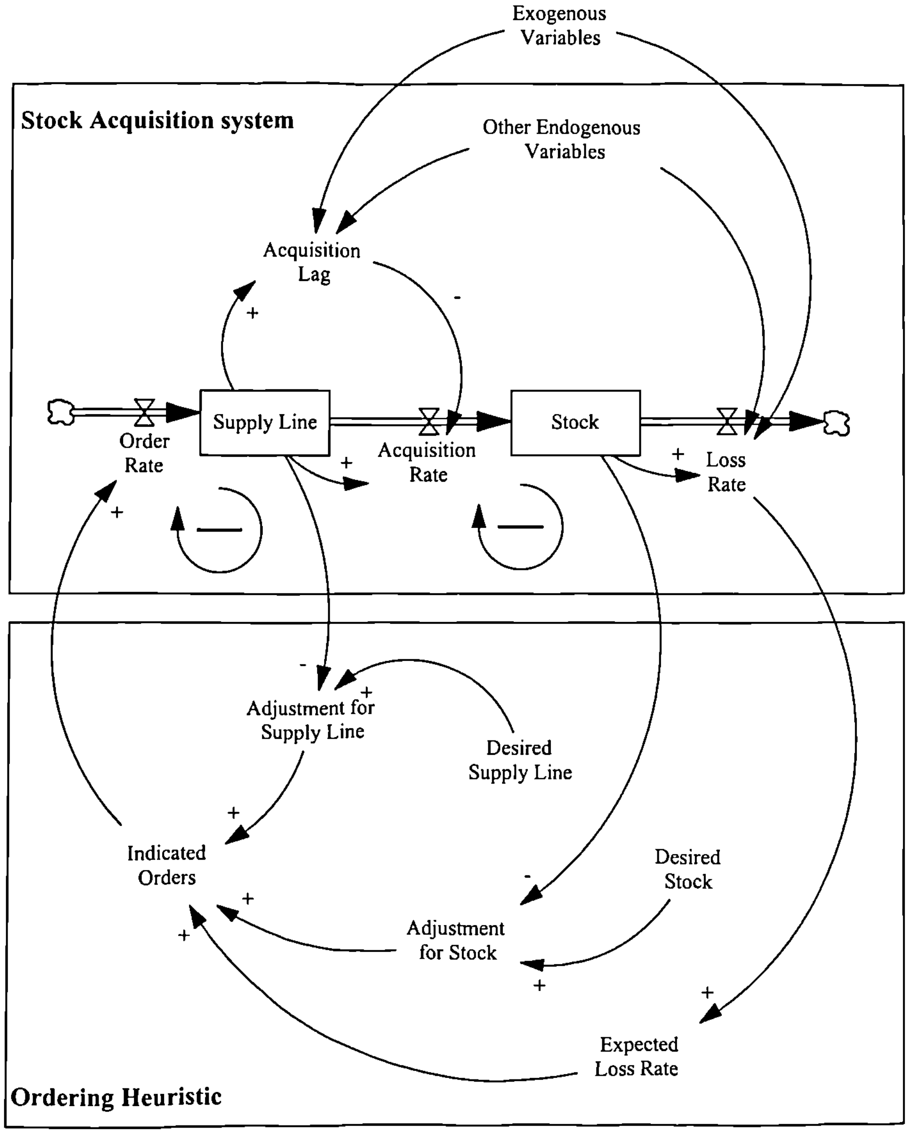


Figure 1.1: Generic Stock Management System

Sterman (1989b) then uses the 'Beer Game' (Sterman 1984) to conduct an experiment on managing a simulated industrial production and distribution system. The Beer Game presents a multi-echelon production distribution system, containing multiple actors, non-linearities, feedbacks and time delays throughout the supply line. The players are advised to minimise costs by managing their inventories under uncertain demand and unknown delivery lags. During the course of a simulation run, the system exhibits oscillations – the decision rules applied do not take account of long time lags between placing an order and receiving the goods. Sterman (1989b) suggests that the decision-making process is dominated by locally rational heuristics, in the form of an anchoring and adjustment policy. This is due to the complexity of the system and time pressure, under which decisions are taken. Further factors to include in this hypothesis of decision-making are the availability, timeliness and perceived accuracy of information regarding the supply line.

1.1.2 Supply Chain Analysis and Design

The work of Childerhouse *et al.* (2002) presents typical research on supply chain analysis and design. They propose focused demand chains as a solution to the need of retaining competitive advantage in a fast changing international business environment. The theory of focused demand chains assumes that in modern markets there are diverse requirements for alternative products and services. Although the concept of focused demand chains dates back to 1974, so far there is no comprehensive framework for the development of a focused supply chain strategy. A structured methodological framework is then presented, consisting of six steps:

1. Development of a holistic demand chain strategy
2. Identification of specific product or service offerings
3. Categorisation of demand chain types using DWV^3 variables
4. Identification of facility requirements
5. Development of individual echelon production layouts and control mechanisms
6. Implementation of focused demand chains

A central role in this integrated framework plays the DWV^3 classification scheme, consisting of five parameters:

- Duration of life cycle
- Time window for delivery,
- Volume
- Variety
- Variability

This classification scheme is used to provide operational benchmarks. The authors apply the methodological framework in a two-phased case study in a UK lighting manufacturer, which is carried out during a four year period. This results in four focused demand chain strategies, which greatly enhance the competitiveness of the company and their partners. They achieve a 75% reduction in product development time, 27% reduction of manufacturing costs, whilst the delivery lead times are reduced up to 95%.

Towill (1996b) proposes that rapid, effective and efficient response to changes in the market is one of the main challenges in modern supply chains. Time compression, therefore, is an answer to these challenges. Towill (1996b) proposes that time compression strategies based on simulation allow to predict supply chain performance improvements. By means of using the Forrester Model (Forrester 1961) as a framework for improving systems performance, he provides a ranking of supply chain re-engineering strategies. A performance metric as proposed by Johansson *et al.* (1993) is used for supply chain benchmarking.

$$PI = \frac{quality * customer\ service\ level}{total\ cost * leadtime} \tag{1.1}$$

Equation (1.1) shows this performance metric, consisting of four components. Each of these components may be adjusted by adding a relative weighting, allowing for adaptation to different preferences. According to Towill (1996b), the cycle time compression paradigm suggests that reduced lead-times will also positively influence the other three components. While lead-time has a critical effect on the stability of a supply chain, the key benefits of time compressing are improved demand forecasting, quicker defect detection, quicker time to market and also a forward shift of decoupling points towards the customer. Based on the simulation results, Towill (1996b) then proposes the use of re-engineering strategies as follows: (1) reduction in all lead-times (material-, information- and cash-flows); (2) elimination of time delays in decision points; (3) provision of marked information to all upstream decision makers.

Based on the case of a two-echelon steel industry supply chain, Hafeez *et al.* (1996) demonstrate the application of 'systems engineering' to supply chains and describe an integrated system dynamics framework, with the aim of giving an example to 'good total systems design'. The modelling exercise deals with the design of a supply chain with respect to moving more rapidly towards a minimum reasonable inventory, whereby the chain exhibits capacity constraints, breakdowns and material supply lead-time bottlenecks. Hafeez *et al.* (1996) describe the complex combination of 'man' and 'machine' as one of the major problems in modelling supply chains. By using an integrated system dynamics framework (Naim and Towill 1994), they make an effort to take into consideration the complex details associated with modelling attitudinal, organisational and technological issues. Having simulated and analysed several different scenarios based on a real-world steel supply chain case, Hafeez *et al.* (1996) propose that the developed model may be viewed as a 'Management Information System' and suggest that the generalised integrated system dynamics framework should be tested for its effectiveness in various (other) market sectors. Figure 1.2 shows a flowchart representation of the 'Cardiff Framework for Supply Chain Design' by Naim and Towill (1994). The framework is specifically designed to allow a holistic approach to modelling supply chains, through decomposition of the supply chain into distinct autonomous business units. After going through overlapping phases of qualitative and quantitative analysis, the partial models then are combined to represent the complete supply chain. The qualitative phase is concerned with the acquisition of intuitive and conceptual knowledge sufficiently comprehensive to understand the structure and operation of the supply chain. Input-output analysis, conceptual modelling and block diagramming form part of this phase, which is aiming to deal with the conceptual problem. When dealing with more technical problems during the quantitative phase, the development and analysis of mathematical and simulation models become the focus of the approach. Naim and Towill (1994) conclude that the combination of a 'hard' systems approach with a 'soft' systems analysis allows for a structured approach to supply chain design.

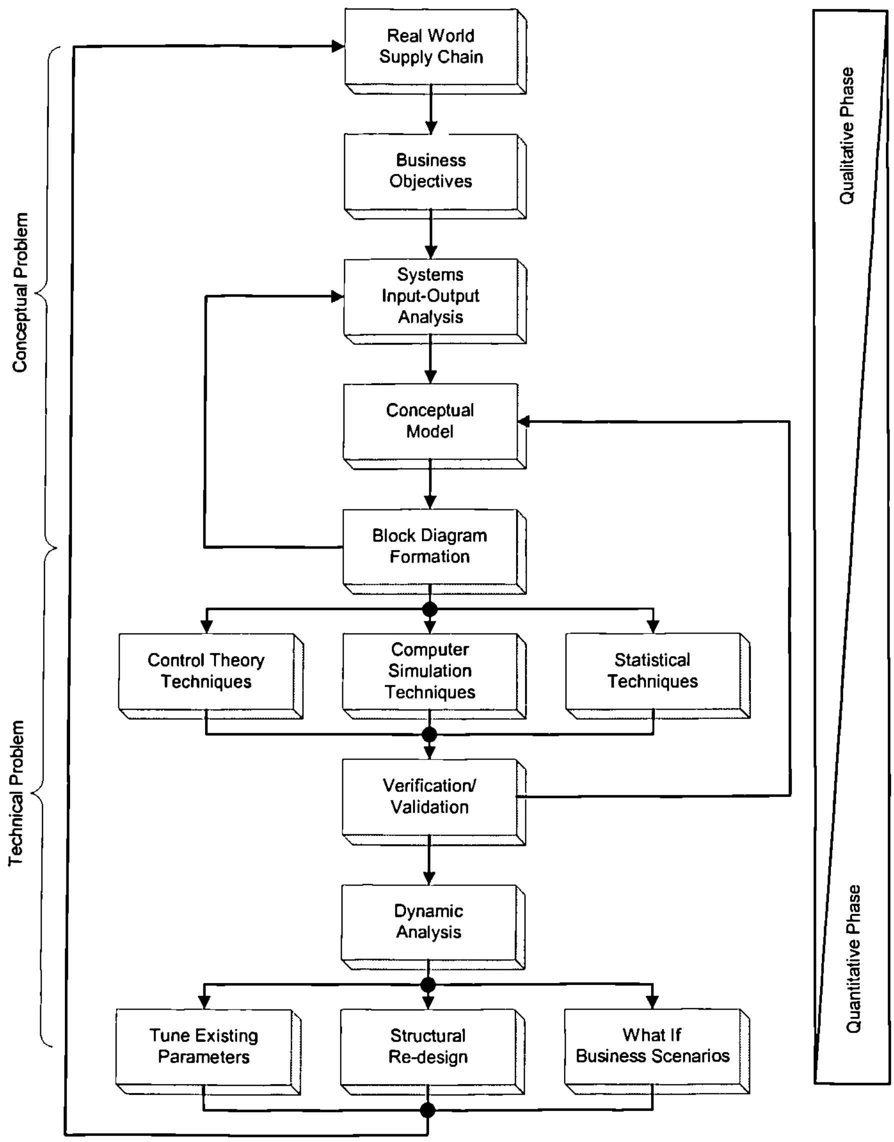


Figure 1.2: The Cardiff Framework for Supply Chain Design

An integrated approach to re-engineering the supply chain interface is presented in the research of Lewis *et al.* (1997). Based on a case study with a manufacturer of mechanical/electrical equipment for the construction industry, they discuss the re-engineering approach adopted to improve the company's material flows via integration of the supply chain. With customer demand suffering from extreme irregularities in terms of variation, the company is forced to hold high stocks in finished goods as well as high component stocks. Due to a quest for improved customer satisfaction throughout this industry, the company aims to maximise the efficiency of all internal and external operations through integrating its supply chain. Lewis *et al.* (1997) adopt the 'supply chain integration model' (Stevens 1989) to identify the steps necessary to accomplish totally integrated material-flow. Starting with internal re-engineering, they suggest changes to the shop-floor operations and the inventory control system. As a next step, they tackle the re-engineering of the supplier inteıface. By setting up collaboration between the company and the suppliers, the information exchange between the parties is improved. An integrated approach to re-engineering materials and logistics control, according to Lewis *et al.* (1997), therefore, consists of three levels, allowing for the strategic, tactical and operational policies to be defined. Figure 1.3 provides a diagrammatic representation of this approach.

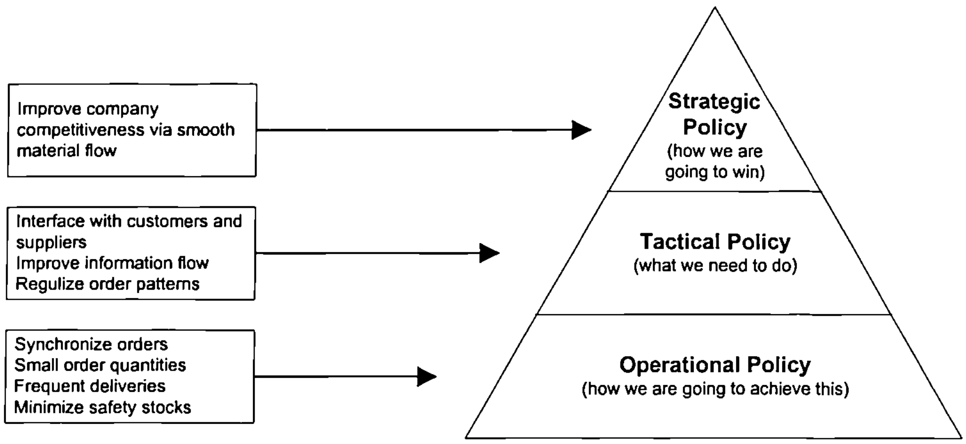


Figure 1.3: An Integrated Approach to Re-engineering the Supply Chain Interface

At the first level, the strategic policy deals with the identification of the top priorities (within the company). In contrast, at the second level, the tactical policy involves setting up better supplier relationships through collaboration. At the third level, operational policy helps to define how to achieve the above goals. At this bottom level, simulations are used to assess the impact of changes prior to actual implementation.

Berry's (1994) research focuses on the behaviour of material and information flows and the associated decision processes in supply chain dynamics. He presents a methodology for analysing, modelling, simulating and re-engineering supply chains. Based on work undertaken on electronic, steel, and automotive industry supply chains, Berry shows the application of his methodology to be suitable for a quantifiable cost-benefit evaluation of supply chain re-engineering strategies. Concluding from various case studies carried out, he proposes that supply chains need to be designed and optimised with respect to operating constraints and suggests collaboration in supply chains as an area for further research. Berry *et al.* (1994) expand on these initial ideas on collaboration and describe approaches to improved supply chain management, drawing on the 'organisational behaviour approach' (Ellram 1991) and 'systems engineering approach' (Towill *et al.* 1992). They highlight the most common problem in an electronics products supply chain to be demand amplification. This problem had been identified by Forrester (1961) and Burbidge (1961), whilst Wikner *et al.* (1991) suggest several ways to dampen demand amplification. Based on the premises that good supply chains relate materials flow, information flow, and cash flow (Towill 1994), they contemplate customer/supplier relationships as an important factor for improved supply chain performance. As a first step Berry *et al.* (1994) assess opportunities for using supply chain management. Therefore, they review different forms of supply chain relationships as suggested by Ellram (1991), and then create a profile of companies within the electronics industry based on five profiling criteria provided by Hill (1993):

- Power
- Product Range
- Technical Emphasis of Products
- Position in the Supply Chain in Relation to End Customers
- Reputation

Those criteria allow quantifying the 'supply chain strength' of the individual companies. Berry *et al.* (1994) distinguish four distinct phases of re-engineering: Phase 1, 'Just-in-Time', identifies the progression from the baseline scenario to just-in-time techniques, while phase 2, 'interplant planning and logistics integration', goes a step further to linking all material requirements planning systems via electronic data exchange. Phase 3, 'vendor integration', represents a closer form of collaboration, which links suppliers to a manufacturing database. Finally, phase 4, 'time-based management', promotes even closer collaboration through integration of development and manufacturing personnel. From phase to phase the level of collaboration between companies increases. Using a set of dynamic simulation models, Berry *et al.* (1994) are able to prove that demand amplification is reduced at each of the four successive phases of supply chain re-engineering, which means that collaboration dampens demand amplification.

1.1.3 International Supply Chain Management

Reflecting a shift in emphasis in supply chain management in recent years, Akkermans *et al.* (1999) address the complex issue of international supply chain management (ISCM). They propose a new theory of 'virtuous and vicious cycles' in international supply chain management, by establishing an exploratory causal model of goals, barriers, and enablers on the road towards effective international supply chain management. They define supply chain management as: (1) involving multiple echelons, processes, and organisational functions, (2) displaying a clear focus on co-ordination and/or integration, and (3) aiming for a simultaneous increase in customer service and profitability. Current success factors include top management commitment, cross-functional teams with feedback between management and staff, and the use of new information systems. However, until to date no causal model exists, which explains the interrelationship between these factors and performance improvement in the supply chain. In order to develop such a causal model, a Delphi-study (Vennix 1996) was carried out, involving about 30 ISCM experts from various industries. Addressing 'Participative Business Modelling' (Akkermans 1995), Akkermans *et al.* (1999) question (a) the main goals for implementing ISCM, (b) the obstacles and enablers, and (c) the interrelationship between these factors. Several obstacles (roadblocks) are identified, including local optimisation and functional silos, insufficient communication throughout the supply chain, and lack of top management support. On the other hand, the implementation of sophisticated information technology systems, the promoting of cross functional careers, the pressure from customers demanding ISCM services, and the use of best practices established by innovative companies are seen as enablers 'on the road towards ISCM'. Akkermans *et al.* (1999) propose a causal model describing their theory of the interrelations of key success factors in international supply chain management.

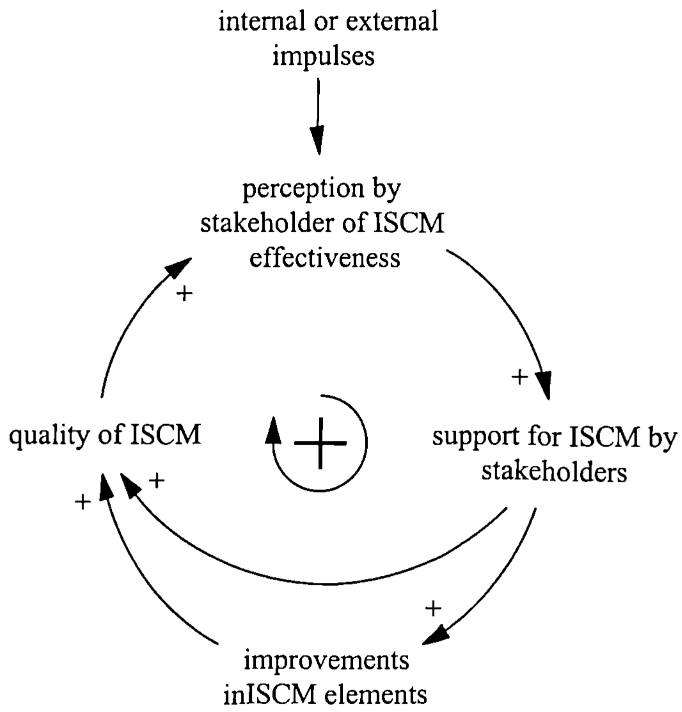


Figure 1.4: Virtuous and Vicious Cycles in ISCM

Figure 1.4 shows that the core dynamics are straightforward and all participating companies seem to be caught in a reinforcing loop of either success or failure. Furthermore, Akkermans *et al.* (1999) point out that the same mechanisms form either a virtuous or vicious cycle, and are fairly generic across industries.

Another perspective on international supply chain management is presented by the work of Vos and Akkermans (1996). Globalisation presents a new challenge in the allocation of facilities in multi-national companies. Location-specific variables may change frequently and thus make allocation decisions more complex. Besides profitability, other aspects such as quality and lead-time have to be taken into consideration. Most traditional methods fail to address dynamic issues, creating a need for new approaches. Vos and Akkermans (1996) use a combination of Vos' method and system dynamics modelling to develop 'ex ante' models to support managerial decision-making, as shown in Figure 1.5.

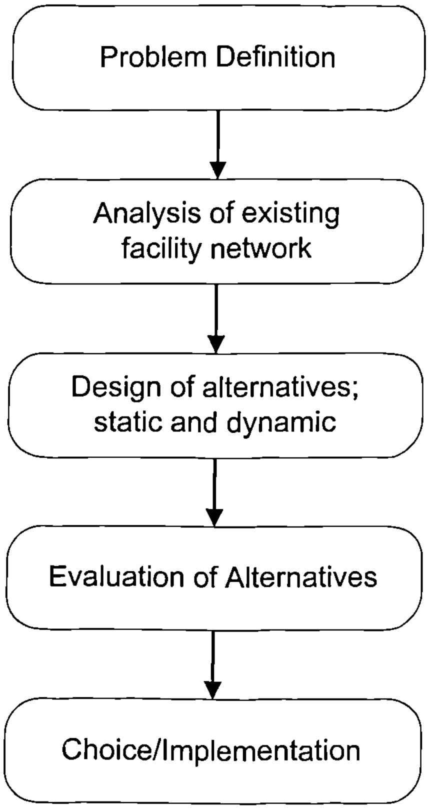


Figure 1.5: Vos' extended Design Method

Vos' original method is based on three principles: (1) the identification and design phase of strategic decision-making; (2) the active participation of decision-makers; and (3) an integral chain approach as the underlying conceptual model. It is enhanced by the use of system dynamics modelling to overcome the restrictions imposed by the static nature of the original method. Vos and Akkermans (1996) apply this framework in the case of a European company considering expansion to Asia. Starting with a static analysis in the form of a production function comparison, they assess the cost benefit of an Asian plant. As a next step, a system dynamics model is developed and a sensitivity analysis is carried out. Results show low sensitivity regarding changes in personnel and fixed costs, however, demand fluctuations have a great impact on financial performance. Vos and Akkermans (1996) state that this 'dynamic allocation method' provides valuable insights to participating managers. Facilitation-oriented approaches combined with system dynamics modelling allow for the incorporation of 'soft' variables, such as employee skills or motivation, and at the same time overcome the restrictions of traditional static approaches.

Akkermans (1995) demonstrates the design of a logistics strategy. He proposes an approach labelled 'Participative Business Modelling' (PBM) to address not only the technical, but also the organisational complexities inherent in the development of logistics strategies, by combining group decision support (GDS) with system dynamics modelling. Existing methods mainly focus on technical complexity, and although they excel in tackling these issues, often the implementation success does not live up to the expectations. This is due to low management participation and the resulting lack of commitment towards the proposed strategies. Participative business modelling combines intensive management participation with rigorous analysis and extensive modelling, aiming to facilitate learning about strategic issues and, therefore, the gaining of insights. Starting with qualitative analysis, the method gradually leads to more formal, quantitative modelling. PBM draws from several different methods, including system dynamics modelling, operational research, social sciences and process consultation, and aims to combine them for a greater benefit. It contains an implicit conceptual model (or theory) on effective strategic decision-making. Figure 1.6 shows the conceptual research model for the PBM.

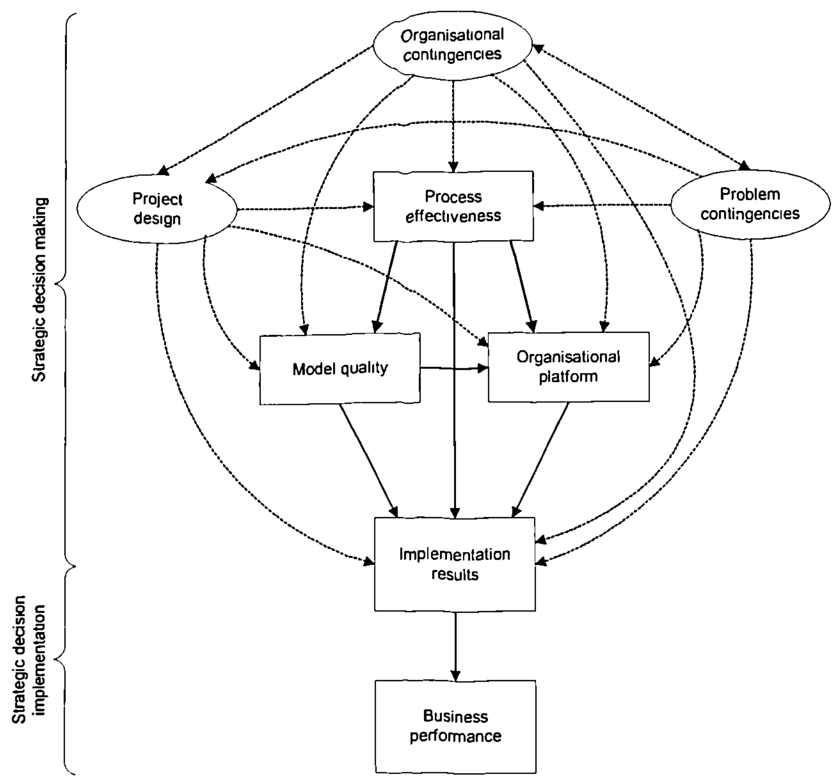


Figure 1.6: PBM: A Conceptual Model of Strategic Decision-Making

Participative business modelling comprises of four project phases: (1) the project definition phase, using cognitive mapping; (2) the model conceptualisation phase, employing brainstorming, causal loop diagramming, and stock and flow diagramming; (3) the modelling formalisation phase, applying system dynamics modelling as well as discrete event simulation; and (4) the knowledge dissemination phase, where the models are used for sensitivity and scenario analysis. Akkermans (1995) demonstrates the application of PBM to facilitate the design of a logistics strategy through a case study, were an international company sets out to establish logistic operations in Europe. Two types of constrains are identified: Firstly, technical complexities, such as requirements for time-critical operation, marketing, financial and legal constraints, and the lack of an existing logistics structure; and secondly, organisational complexities, including low management support and geographically separated decision-makers. In applying the PBM method, Akkermans and the management involved go through four phases, starting with structured interviews, followed by quantitative modelling, before these models are finally used to understand and improve the logistics performance of the proposed system. Finally, a review is undertaken of both the approach and the model.

The next section summarises the current research opportunities arising from existing research work in supply chain modelling.

1.2 Current Research Opportunities

A review of recent models and techniques in supply chain modelling led to the identification of collaborative supply chain modelling and collaborative supply chain performance measurement as specific domains that warrant further research (Angerhofer and Angelides 2000). Ackoff (1979) propounds that "the future depends at least as much on what we and others do between now and then, as it does on what has already happened. Therefore, we can affect it, and by collaboration with others – expanding the system to be controlled – we can increase our chances of 'making it happen'." However, until now most research in supply chain modelling, both empirical and formal modelling-based, has been focused on a perspective of the individual firm (Pol and Akkermans 2000). A shift in focus in supply chain research, as it is becoming apparent in recent years, is manifested in: "Properly viewed, the company and its supply chain are joined at the hip, a single organic unit engaged in a joint enterprise" (Fine 1998). This leads to supply chain synchronisation, manifested in the collaboration in planning and design on the basis of partnerships between companies (Anderson and Lee 1999). This new scope has substantially increased the difficulty of designing and controlling supply chains Vos and Akkermans (1996), therefore demanding new approaches that warrant improved design and management (Akkermans *et al.* 1999) of such supply chains. Mason-Jones and Towill (1998) point out that "companies need to work together and optimise the complete pipeline by establishing a seamless supply chain ('think and act as one')." Researchers have taken up these new challenges in several ways. However, while supply chain co-ordination has been widely discussed (Akkermans 1995, Evans *et al.* 1998, Pol and Akkermans 2000), the development of a model of a collaborative supply chain and collaborative supply chain performance measurement, although often touched, have so far not been adequately addressed.

Anderson *et al.* (2000) carry out an analysis of demand amplification in a supply chain using a system dynamics simulation model. Evidence is presented that volatility decreases productivity and that demand amplification can be significantly reduced by better utilisation of the information flow. They suggest further research to show the relations between partnerships in supply chains, problems addressed and the conditions for success or failure.

Akkermans *et al.* (1999) propose a theoretical model of collaboratively managed supply chains by presenting a causal model of goals, barriers and enablers to international supply chain management. However, their model is limited in scope and they do not test the theoretical model on a wider basis through case studies and simulations.

Childerhouse *et al.* (2002) propose a comprehensive framework for the development of a focused demand chain strategy, suggesting that focused demand chains can retain competitive advantage in a volatile international market. Whilst they consider process improvements and business strategy in some detail, they do not provide evidence that the developed focused strategies enhance the competitiveness of the company as well as their demand chain partners.

Berry (1994), whilst devising a methodology that allows a quantifiable cost-benefit evaluation of supply chain re-engineering strategies, mentions, but not fully explores, the benefits of collaborative management of supply chains. Collaborative supply chain management in terms of a re-engineering approach is described in the research of Berry *et al.* (1994). They use dynamic simulation models to show that demand amplification can be reduced through collaboration, but they neither provide a generic model of a collaborative supply chain, nor do they suggest additional supply chain performance metrics to measure collaborative supply chain performance.

Mavrommati and Migdalas (2002) suggest that there is a need to move from logistics to collaborative logistics. Their supply chain model consists of stakeholders, processes, strategy, and collaboration. Based on the appropriate choice of strategy for a particular supply chain, a logistics strategy is developed. They recognise the need for integration between business processes across the supply chain. Collaborative logistics then is achieved either via 'vertical', 'horizontal' or 'full' collaboration. However, they do not provide a method for assessing the performance of either type of collaboration.

Lewis *et al.* (1997) argue that effective management and control of material flows across the boundaries between companies and their customers and suppliers is vital to the success of their internal operations. They propose a three-level model of strategic, tactical and operational policy. They relate the top level, the strategic policy, as well as the operational level, mainly to issues within the company, which essentially represents a focus on a perspective of the individual firm as stated by Pol and Akkermans (2000). Only the tactical level is defined by Lewis *et al.* (1997) to involve setting up better supplier relationships through collaboration. Thus they provide an incomplete picture of supply chain collaboration, by adopting an individual firm - centred approach and only focussing on the tactical level when it comes to establishing collaboration with suppliers.

Common to all work described above is the need for a model of a collaborative supply chain, and a measurement system to adequately measure the performance of a collaborative supply chain. However, only first steps are taken towards developing such a model and performance measurement system. Consequently, a need arises to establish a collaborative supply chain model and develop measures which permit adequate collaborative supply chain performance measurement. Some of the work described above demands carrying the effort further, in particular, the work of Berry *et al.* (1994) on the improvement in demand amplification through collaborative supply chain management, and the work of Lewis *et al.* (1997) on re-engineering the supply chain interface. This research expands on these initial ideas.

1.3 RESEARCH OBJECTIVE

The aim of this research is twofold. Firstly, it proposes to develop a model of a collaborative supply chain that can capture the complex inter-relationships within and between all parts of such a supply chain. The model will present a holistic and at the same time comprehensive view of a collaborative supply chain. Secondly, it sets out to develop a collaborative supply chain performance indicator, which measures the performance of a collaborative supply chain.

1.4 RESEARCH METHOD

Galliers (1990) distinguishes between information systems research approaches in the context of the scientific and interpretivist philosophies. He uses the word "approach" rather than "method", defining approach as a way of conducting research. Different approaches may embody a particular style and employ different methods or techniques. He then proposes a revised taxonomy of approaches, detailing key features, strengths and weaknesses. Bell *et al.* (1999) adopt Galliers' taxonomy, but draw a clearer distinction (by separating 'Forecasting and Futures Research' and 'Simulation and Game/Role Playing') between the scientific and interpretivist approaches, as shown in Figure 1.7.

Scientific Approaches	Interpretivist Approaches
Laboratory Experiment	Subjective/Argumentative
Field Experiment	Reviews
Survey	Action Research
Case Study	Descriptive
Theorem Proof	
Forecasting	Futures Research
Simulation	Game/Role Playing

Figure 1.7: Scientific and Interpretivist Research Approaches

This PhD research falls into the category of empirical research, grounded in the scientific philosophy. The aim of this research, which is the development of a collaborative supply chain model and a collaborative supply chain performance indicator, suggests that the cases study approach is suitable. To verify this assumption, an 'object-based' ranking of research approaches, based on Gallier's taxonomy, is used (Figure 1.8).

Linking Research Objectives to Research Approach

Research Objectives	Possible Object	Suitable Scientific Approach	Case Study
Development of a model of a collaborative supply chain. Development of a performance indicator to measure the performance of a collaborative supply chain	Organisation or Group	Field Experiment, Case Study, Survey, Forecasting, Simulation	✓
	Theory Building	Case Study, Survey, Forecasting, Simulation	✓
	Theory Testing	Theorem Proof, Laboratory Experiment, Field Experiment, Possibly Case Study	✓/✗

Figure 1.8: Research Objectives and Case Study Approach

Initerpretivist research approaches are inappropriate because they either do not require the existence and use of data or if they do they assume the use of qualitative data whilst focussing on archetypes (Checkland 1981). They attempt to describe, interpret and create understanding of situations from the participants' perspective rather than the data perspective. Therefore, the case study approach, which captures much of 'reality' through a data collection and analysis (Galliers 1990) is considered the most appropriate approach. After putting the research objectives of this PhD research into context with suitable scientific research approaches, the case study approach is confirmed to be the most suitable approach for this research. Figure 1.9 details key features, strengths and weaknesses of the case study approach.

Case Study Approach

Key Features	Strength	Weaknesses
An attempt at describing the relationships which exist in reality, usually within a single organisation or organisational grouping	Capturing 'reality' in greater detail and analysing more variables than is possible using laboratory experiments or surveys	Restriction to a single event or organisation. Difficulty in generalising, given problems of acquiring similar data from a statistically meaningful number of cases. Lack of control of variables. Different interpretation of events by individual researchers

Figure 1.9: Key Features, Strength and Weaknesses of the Case Study Approach

According to Yin (1984), the case study approach has been criticised due to many examples of badly conducted case studies. He therefore proposes a more rigorous approach, which will lead to good research design by following a 'workplan' of five components: the research question, its propositions, its unit(s) of analysis, a logic linking the data to the proposition, and criteria for interpreting the findings. As suggested by Bell *et al.* (1999), we adapt Yin's approach to suit this PhD research. Figure 1.10 shows how Yin's components are used in this research.

PhD Research Design

Yin's Components	Use of Components in this Research
Research question	How can the performance of a collaborative supply chain be improved?
Its proposition(s)	1) Collaborative Supply Chain Model 2) Performance Indicator to measure the performance of a Collaborative Supply Chain
Its units of analysis	Implementation of Collaborative Supply Chain Model and Performance Indicator in a Decision Support Environment
A logic linking the data to the proposition	Evaluation of the Decision Support Environment
Criteria for interpreting the findings	Interpretation of the findings

Figure 1.10: Components of Research Design for this PhD

Due to the complexity of collaborative supply chains, it is not possible within the time limit set for this PhD research, to acquire similar data from a statistically meaningful number of cases. Hence we attempt to overcome this weakness of the case study approach by conducting an in depth case study on one particular supply chain, which represents a type 1 case study. The choice of supply chain is influenced by its historical value to the PhD research (Rainer and Hall 2001). Figure 1.11 shows a matrix representation detailing the four different designs of case studies (Yin 1984).

	Single Case Design	Multiple Case Design
Holistic (single unit of analysis)	*Type 1*	*Type 2*
Embedded (multiple units of analysis)	*Type 3*	*Type 4*

Figure 1.11: Different Types of Case Study Design

1.5 THESIS OUTLINE

Chapter 1 introduces the research area and gives an overview of recent research work in modelling supply chains and explains the choice of PhD research topic. Chapter 2 proposes a model of collaborative supply chain. Chapter 3 describes the development of a performance indicator to measure collaborative supply chain performance. Chapter 4 discusses the implementation of the model and performance indicator in a decision support environment. In Chapter 5 the decision support environment is evaluated. Chapter 6 summarises the contributions made in this thesis along with the strength and weaknesses of the developed model, and suggests areas for further research.

CHAPTER 2: DEVELOPMENT OF A MODEL OF A COLLABORATIVE SUPPLY CHAIN

> *"No company is an island. You may think of your company as a solitary, stand-alone entity served by subsidiary organizations, the collection of which is conveniently called the supply chain. That view, however, vastly underestimates the importance of the chain as a whole and fails to capture its true essence. (...) Properly viewed, the company and its supply chain are joined at the hip, a single organic unit engaged into a joint enterprise."*
>
> (Charles H. Fine, 1998)

This chapter proposes a model of a collaborative supply chain. The constituents relevant to collaborative supply chains are identified and first brought together in a 'Weltanschauung', a model of a collaborative supply chain. The model consists of six constituents, as it is proposed in relevant research and practice (Akkermans *et al.* 2000, 1999, Anderson and Lee 1999, Anderson *et al.* 2000, Baourakis and Stroe 2002, Barlas and Aksogan 1996, Berry *et al.* 1999, Berry 1994, Childerhouse *et al.* 2002, Dejonckheere *et al.* 2002, Disney *et al.* 1997, Evans and Naim 1994, Forrester 1958, Hafeez *et al.* 1996, König 1997, Mason-Jones and Towill 1999, Mavrommati and Migdalas 2002, Pol and Akkermans 2000, SCC 2001, Towill 1996b, Towill and Naim 1993, Vos 1997). The model of a collaborative supply chain requires six constituents to adequately represent such a collaborative supply chain for the purpose of improving performance. A supply chain is a network of suppliers, facilities and distribution options that procure basic materials, transform them into intermediate or finished products, and distribute these products or services to customers (Szuprowicz 2000). Stevens (1989) describes a supply chain as a system whose constituent parts include material suppliers, production facilities, distribution services and customers linked together via the feed-forward flow of materials and the feedback flow of information.

In this thesis, only supply chains for product manufacturing are considered, therefore, the flow of material or products through the chain is the focus of attention. Services are only taken into account as a by-product of manufactured goods. The objective of a collaborative supply chain is to gain competitive advantage, by improving overall performance through taking a holistic perspective of the supply chain. Overall logistics control is to be designed that all 'players' are beneficiaries (Towill and Naim 1993). In order to be efficient and cost effective across the entire system, total costs have to be minimised and activities have to be aligned from the strategic level through the managerial to the operational level (Simchi-Levi *et al.* 2000). By considering a supply chain from a collaborations point of view, several constituents have to be brought together.

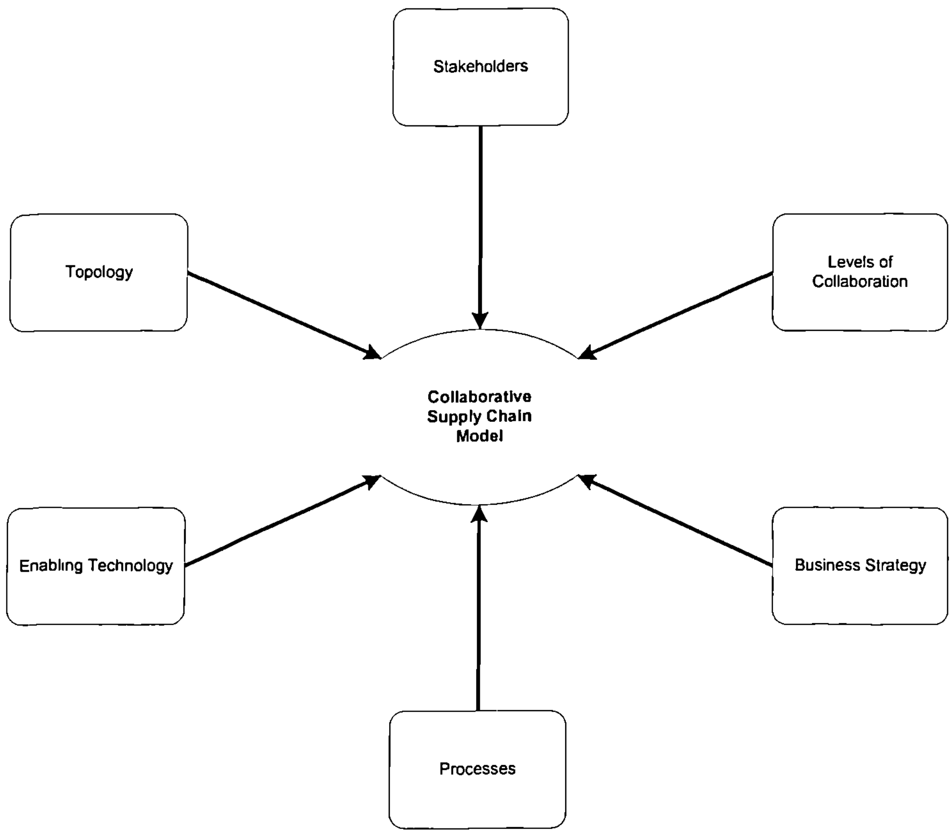


Figure 2.1: Collaborative Supply Chain: Weltanschauung.

Figure 2.1 provides a graphical representation of the proposed model. All six constituents are necessary to form a complete picture of a collaborative supply chain. None of the existing models do incorporate all six constituents and are, therefore, not adequate to address all necessary aspects of collaborative supply chain performance improvement. Only when considering all six constituents, the resulting model will be holistic in nature and permit the assessment of the impact of management decisions on the performance of collaborative supply chains. Whilst all the constituents which are reported by both literature and practice are used to build this model, no formal proof of completeness is available in either. Therefore, for the purpose of this thesis it will be assumed that the list of constituents is a complete one.

Supply Chain Constituents

	Stakeholders	Levels of Collaboration	Business Strategy	Processes	Enabling Technology	Topology
Akkermans	✓		✓	✓	✓	
Anderson	✓		✓	✓		
Barlas	✓		✓	✓		
Berry	✓	✓	✓	✓	✓	
Baourakis	✓			✓	✓	
Childerhouse	✓		✓	✓		
Dejonckheere	✓			✓		
Disney	✓		✓	✓	✓	
Evans	✓			✓		
Forrester	✓			✓		
Hafeez	✓		✓	✓		
König	✓			✓		✓
Mason-Jones	✓	✓	✓	✓		
Mavrommati	✓	✓	✓	✓		
Pol	✓			✓		✓
Supply Chain Council	✓			✓	✓	
Towill	✓			✓		✓
Vos	✓		✓	✓		

Figure 2.2: Supply Chain Constituents used in Existing Research and Practice

Figure 2.2 provides an overview of the use of the six collaborative supply chain constituents in existing research and practice.

Akkermans *et al.* (1999) propose an 'exploratory causal model' which contains *stakeholders*, *business strategy*, *processes* and *enabling technology*. Whilst the model is able to provide an explanation of success or failure in international supply chain management, it does not capture the full complexity of collaborative supply chains. Above all, *topology* is required to show the material flow between the primary players in a supply chain, where processes may be linked within and between companies. Also, the absence of *levels of collaboration* leads to a lack of explanation of the interactions of players in a supply chain. A model by Anderson *et al.* (2000) includes *stakeholders* in the form of three firms and addresses *business strategy* through policy development, but it does not contain *enabling technology*. The model demonstrates that one player's production capacity limitation causes demand fluctuation. However, the management of collaborative supply chain *processes* is supported through *enabling technology*. As Lewis *et al.* (1997) point out, *enabling technology* is essential to the ultimate success of the supply chain. This is due to support of effective management and control of material flows across the boundaries between companies, and the provision of an information flow that is accurate, timely and accessible to all players in the chain. Hence, without considering *enabling technology* the simulation results of Anderson *et al.* (2000) model are limited in scope. The Supply Chain Operations Reference – model (SCC 2001) provides a detailed view of supply chain *processes*, along with *enabling technology* and *stakeholders*, but lacks the *business strategy* constituent. The model, therefore, is able to capture the operational and managerial aspects of a collaborative supply chain, nevertheless it falls short in providing an explanation of the impact of the business strategy on the set-up and the success of the collaborative supply chain in the marketplace. As *business strategy* is developed according to the type of competitive environment entered, it has a great impact on supply chain operations, goals and performance measurement, and, therefore, needs to be considered in a model of a collaborative supply chain. All models listed in Figure 2.2 contain *stakeholders* and *processes*, which are the essential constituents of any supply chain, as *stakeholders* are the primary players of the supply chain and are linked together via collaborative supply chain *processes*. Absence of *stakeholders* would not yield a collaborative supply chain in the first place, and absence of *processes* makes the supply chain a black box whose contents could not be optimised.

The following sections show that all constituents are necessary to form a complete picture of a collaborative supply chain, by discussing the complementary nature of the six constituents.

2.1 STAKEHOLDERS

Stakeholders refers to the primary 'players' of the supply chain, therefore the term describes a particular group that is part of or takes an interest in a supply chain. Stakeholders relates closely to 'supply chain topology', as the topology of a supply chain determines which stakeholders are involved and how. For the purpose of this thesis, stakeholders and players will be used interchangeably. Stakeholders are the supplier, manufacturer, wholesaler, retailer and customer (Forrester 1958, Ross 2000, Sterman 1989b), but also third parties involved in the flow of good along a supply chain. Each stakeholder often stands in multiple relationships to all other stakeholders and may comprise of more than one firm in real life. This subsequently increases the complexity of business systems (Farbey *et al.* 1999), since the decisions taken may be also influenced by several connections.

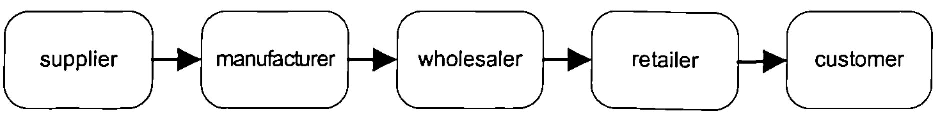


Figure 2.3: Supply Chain.

Figure 2.3 shows a supply chain with its primary stakeholders. The stakeholders in a collaborative supply chain each play a particular role (Ross 2000): The supplier provides raw material and acts as component integrator and single point-of-contact vendor. Integration into the manufacturer's inventory planning and scheduling allow fast cycle times. The primary role of the manufacturer is the development and production of goods for industry or end customer. In many cases, manufacturers take the responsibility for designing and managing the supply chain. The wholesaler, if present in a collaborative supply chain, acts as a middleman in order to consolidate goods from various sources. Retailers form the end of the supply chain and perform the role of selling goods directly to non-business customers. In the past, customers were only viewed as recipients of goods produced by the manufacturers, but in recent years there has been a shift towards the customers becoming the driving force (Sankar 1998).

The next section describes how the stakeholders may collaborate.

2.2 Levels of Collaboration

An increasing amount of partnerships, joint ventures, and various kinds of coalitions substantiate a movement towards collaboration in supply chains (Hieber 2002, Ross 2000), with a wide spectrum of managerial and strategic objectives. Ranging from creating economies of scale to establishing virtual enterprises, the objectives usually aim at gaining competitive advantage. This may be achieved by various means, for example through increasing efficiency and cost effectiveness across the entire supply chain or by teaming up forces to be able to compete against stronger competitors. To further collaboration, the players in the collaborative supply chain must understand their impact on the supply chain, and in particular be aware of the cost structures of each participating player (Szuprowicz 2000). Collaboration may take place on the strategic, managerial or operational level (Figure 2.4).

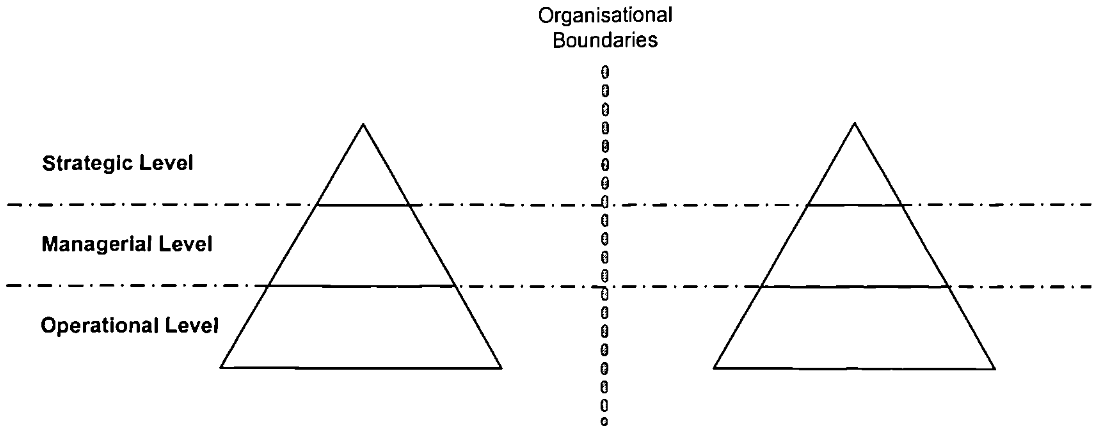


Figure 2.4: Levels of Collaboration.

The strategic level is concerned with decisions that have long-term effects and influence the future direction of the collaborative supply chain, for example capital investment, location decisions for facilities and restructuring the supply network through acceptance or exclusion of players. On the managerial level, the main concern is the optimisation of the flow of goods. Management decisions have a medium decision time frame and involve planning and forecasting, and control of collaborative supply chain resources. Routine and repetitive tasks characterise the operational level. Operational decisions involve the highest level of detail and entail scheduling and execution. They are typically performed on a weekly or daily basis, or even several times per day. Examples are production or transportation scheduling and stock control. Collaboration takes many different forms, including strategic alliances, joint ventures, third party logistics (3PL), agreements, short- and long-term contracts, partnership sourcing, and retailer-supplier partnerships (RSP). Overall logistics control should be designed so that all players are beneficiaries via the mechanism of minimising total costs (Towill 1997). This requires removal of barriers between supply chain processes within and between companies, which then in turn gives rise to the need for centralised control, whereby one player is in command of managing the supply chain. Centralised control in a supply chain network leads to global optimum, whereas decentralised control leads to local optimum. Therefore, a centralised system could be more effective because of the interaction of decisions. Centralised control in a supply chain may not be possible to achieve, yet through collaboration the advantages of centralised control can be approached (Simchi-Levi *et al.* 2000). The decision on which level(s) collaboration is suitable and beneficial is determined by the market environment and business strategy.

The next paragraph illustrates business strategy with regards to a collaborative supply chain and puts it into context to the market environment.

2.3 Business Strategy

In this thesis, the term 'business strategy' is used to describe strategy related to the collaborative supply chain. The market environment determines which strategy is most appropriate. Business strategy consists of three elements, the competitive mission, the core operations strategy, and the player's business goals (Ross 2000), as shown in Figure 2.5.

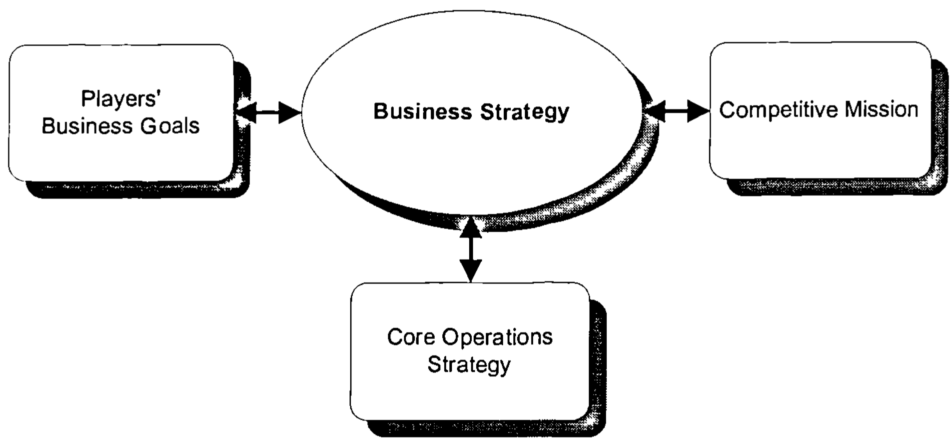


Figure 2.5: Business Strategy

Competitive mission may be derived from two generic competitive strategies. According to Porter (1985) there are only two routes to achieve superior competitiveness, that is lowest-cost production and product differentiation, which can be applied to either a broad market, or to a focused market. Based on that he identifies two generic competitive strategies: (a) cost leadership and (b) differentiation. The strategy of cost leadership implies that a product or service of 'standard' quality, which is not considered to be cheap or of low quality, can be provided at a lower cost than the industry average. This involves leaping ahead of the competition in terms of experience and also gaining a large market share. In turn, low costs enable a company to compete on price or to reinvest profits into improving product quality. A differentiation strategy is based on understanding buyer's needs and values. Therefore, a company can offer unique features, which will be purchased by buyers at a higher price. If costs are under control, the company can increase profitability.

Next, each player's business goals, since they may be different, need to be aligned with those of the collaborative supply chain. The alignment may be achieved through a performance trade-off balancing strategy that aims to achieve a balance between individual and collaborative supply chain business goals. This will involve identifying those objectives that are common and those that are not, and determine an optimal trade-off for objectives that are not common.

Finally, the core operations strategy needs to be designed to work hand-in-hand with the competitive mission. The aim is to support the positioning and measuring of the success of products in the current industry structure, and hence ensure optimum use of all firm's resources. This is initially done by setting up budget, sales, profit and operations performance objectives (Ross 2000), and then by analysing the shift in responsibilities along the supply chain and agreeing the individual responsibilities of the players in order to ensure smooth operations throughout the supply chain. Within their individual area of responsibility, the players need to meet financial and operational objectives.

Traditionally, a supply chain strategy was formulated based on a generic corporate planning approach (Bowman 1990). This approach is not suitable for a collaborative supply chain, as it is targeted at a single firm rather than a supply chain consisting of collaborating players. Developing a strategy for collaborative supply chains may be done by following the approach laid out in Figure 2.6, which constitutes an enhanced version of the original approach as described by Bowman.

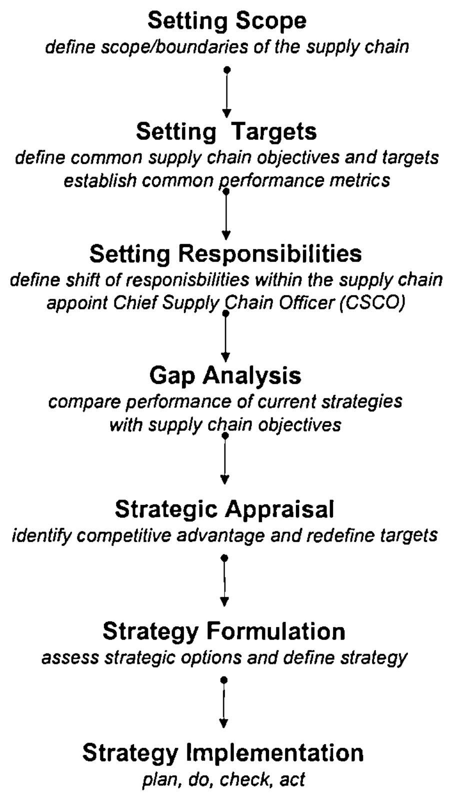


Figure 2.6: Seven Stages of Collaborative Supply Chain Strategy Development.

The first three stages are specifically targeted at collaborative supply chains, whereby the first stage is concerned with defining the boundaries. Stage two is, compared to the original approach, enhanced by including the definition of collaborative supply chain performance measures. Along the supply chain, responsibilities will shift from one player to the next, with some overlaps in responsibilities. In stage three, all involved players come to an agreement on the individual responsibilities. To reinforce the concept of centralised control, a Chief Supply Chain Officer (CSCO) is designated from among the stakeholders. Based on current strategies in place, the performance of the supply chain is forecasted in stage four. Then the gap between the forecast and the set objectives and targets of the collaborative supply chain is assessed. Stage five, strategic appraisal, involves the identification of the competitive advantage and a redefinition of the targets. Strategy formulation takes place in stage six, when the strategic options are assessed and translated into a collaborative supply chain strategy. The final sage is strategy implementation. On an ongoing basis, decisions that are based on the developed strategy are executed and the effects are monitored. If necessary, corrective actions are taken.

The next section describes the collaborative supply chain processes.

2.4 PROCESSES

A collaborative supply chain extends the boundaries of individual companies by linking them through supply chain processes. Figure 2.7 shows the four core supply chain processes 'Plan', 'Source', 'Make', and 'Deliver' (SCC 2001), as laid out in the Supply Chain Operations Reference - model (SCOR). The SCOR is a process reference model that integrates the concepts of business process re-engineering, benchmarking, and process measurement into a cross-functional framework. By taking a process-based view, the SCOR provides the tools to capture the "as-is" and derive the desired "to-be" state of a process, quantify the operational performance, and define management practices and software solutions that lead to improved performance. At the same time, relationships among the four distinct processes are described. The SCOR captures all customer interactions from order through to invoice, all physical material transactions throughout the whole chain, and market interactions through demand and order fulfilment. The four core supply chain processes, 'Plan', 'Source', 'Make' and 'Deliver', are broken down into several sub-processes. 'Plan' defines the planning activities involved in running the other three collaborative supply chain processes. Hence it contains sub-processes dealing with resource planning, demand planning, capacity planning, production planning, inventory planning, and distribution planning.

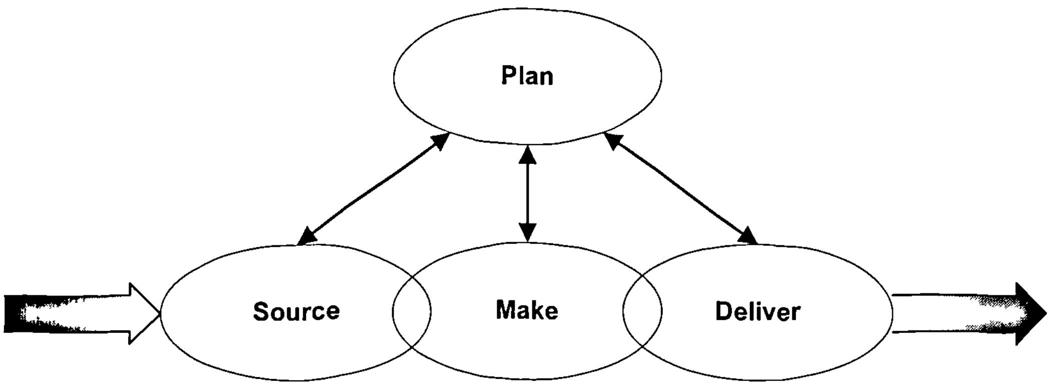


Figure 2.7: Supply Chain Processes

'Source' relates to processes on the supplier side and contains two sub-processes, material acquisition and the management of the sourcing infrastructure. The 'Make' process comprises production execution and the management of the 'Make' infrastructure. 'Deliver' consists of four sub-processes: (1) Order management deals with entering orders, quotations, managing product and customer database, and collections and invoicing; (2) warehouse management is described by packing and labelling products, consolidating orders and shipping products. Closely linked to that, (3) transportation management comprises managing freight and product import and export. And finally, there is a process in place to (4) manage the delivery infrastructure through order rules and inventory control.

The next paragraph describes how the four collaborative supply chain processes are enabled and supported by the use of information technology.

2.5 Enabling Technology

Information Systems are an important enabler of effective supply chain management, with the main goal of linking a product's information trail with its physical trail (Simchi-Levi *et al.* 2000). Collaborative supply chain information systems can be divided into three main groups: Transaction Processing Systems (TPS), Management Information Systems (MIS), and Executive Information Systems (EIS). Each group relates to the different information requirement characteristics of the corresponding level of hierarchy. Although the information requirement characteristics at the different levels of hierarchy are diverse, the information presented is always based on the same data. Figure 2.8 shows the Information Systems Hierachy.

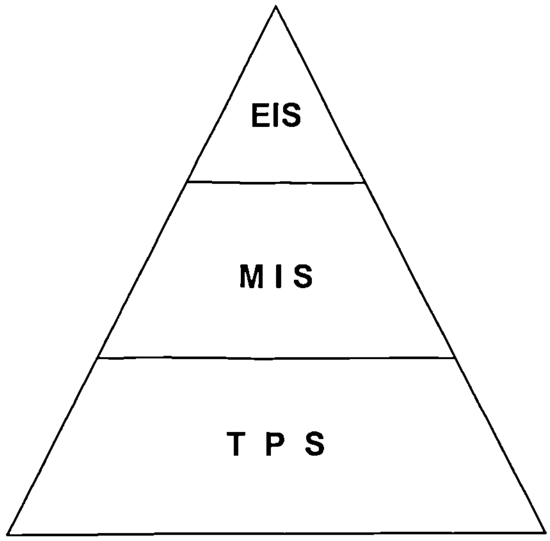


Figure 2.8: Supply Chain Information Systems Hierarchy

Transaction Processing Systems, also called functional or operational systems, are designed to carry out defined functions, transactions or routine business activity (Elliott and Starkings 1998). Transaction processing systems provide the underlying communication facilities and directly support the 'Source', 'Make' and 'Deliver' supply chain processes. The systems need to be integrated to ensure a smooth flow of materials and the efficient use of the available resources. The 'Source' process is supported by material acquisition systems, the 'Make' process through production execution software. Finally, the 'Delivery' process is scheduled and controlled with the help of order management, warehouse management and transportation management systems. Management Information Systems are concerned with provision of relevant, timely and useful information for management control, their primary role being to support planning and coordination of the resources of the business. MIS show characteristics of both the bottom and top-level supply chain information systems, whereby they provide support to managers in optimising the flow of goods along the supply chain. Planning and forecasting systems such as Enterprise Resource Planning (ERP) and Manufacturing Resource Planning (MRP) systems are examples of MIS used in collaborative supply chains. Management

Information Systems, as well as Executive Information Systems, support the 'Plan' supply chain process. Whereas MIS support decisions with a medium decision time frame, strategic decision have a long term effect and influence the future of the collaborative supply chain. Hence, on the top level of hierarchy, Executive Information Systems provide information on strategic areas of the supply chain to senior executives, in order to support strategic decision-making. EIS systems are designed to provide clear, summarised information to highlight weaknesses and opportunities for the collaborative supply chain. The information provided supports senior executives in their decision on facility location, capital investment and restructuring of the collaborative supply chain.

The next section describes collaborative supply chain topology.

2.6 TOPOLOGY

The manner in which supply chain processes are linked together is the 'supply chain topology'. Supply chain topology describes the configuration of the supply chain based on 3 basic flow patterns as shown in Figure 2.9. It is distinguished between single route flow, convergent flow, and divergent flow (Towill 1997). By combining these basic flow patterns, complex supply chain networks can be described. This represents the topology of material flow between the primary players in a supply chain, where processes may be linked within and between companies. Most supply chains consist of many "threads", which tie together a set of "source-make-deliver" supply chain processes, thus representing a supply chain network. Hence a supply chain is a complex network of facilities and organisations (Simchi-Levi *et al.* 2000), linked together through supplier-customer connections.

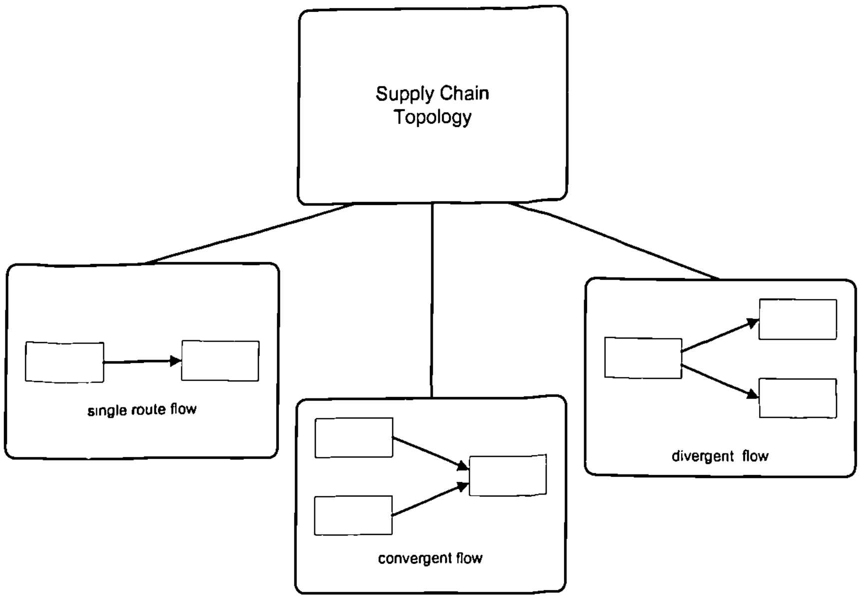


Figure 2.9: Supply Chain Topology.

An example for a divergent flow is a company supplying two or more 'customers' within the supply chain. Having more than one supplier, therefore, constitutes a convergent flow. A single route flow is present when there is an exclusive sole supplier, supplying only to one customer whilst the customer only buys from this supplier.

The next section shows the collaborative supply chain model and six constituents, and gives two examples of a collaborative supply chain.

2.7 A BIRD'S EYE VIEW OF THE MODEL

All six constituents described are required to form a model of a collaborative supply chain, which accounts for the complexity inherent in a system consisting of integrated processes and multiple relationships within and between the involved stakeholders. The collaborative supply chain model, therefore, gives a holistic view of the inter-linkages (i.e. topology) and inter-relationships (i.e. levels of collaboration) of the stakeholders along with processes involved, supporting technology used and business strategy employed.

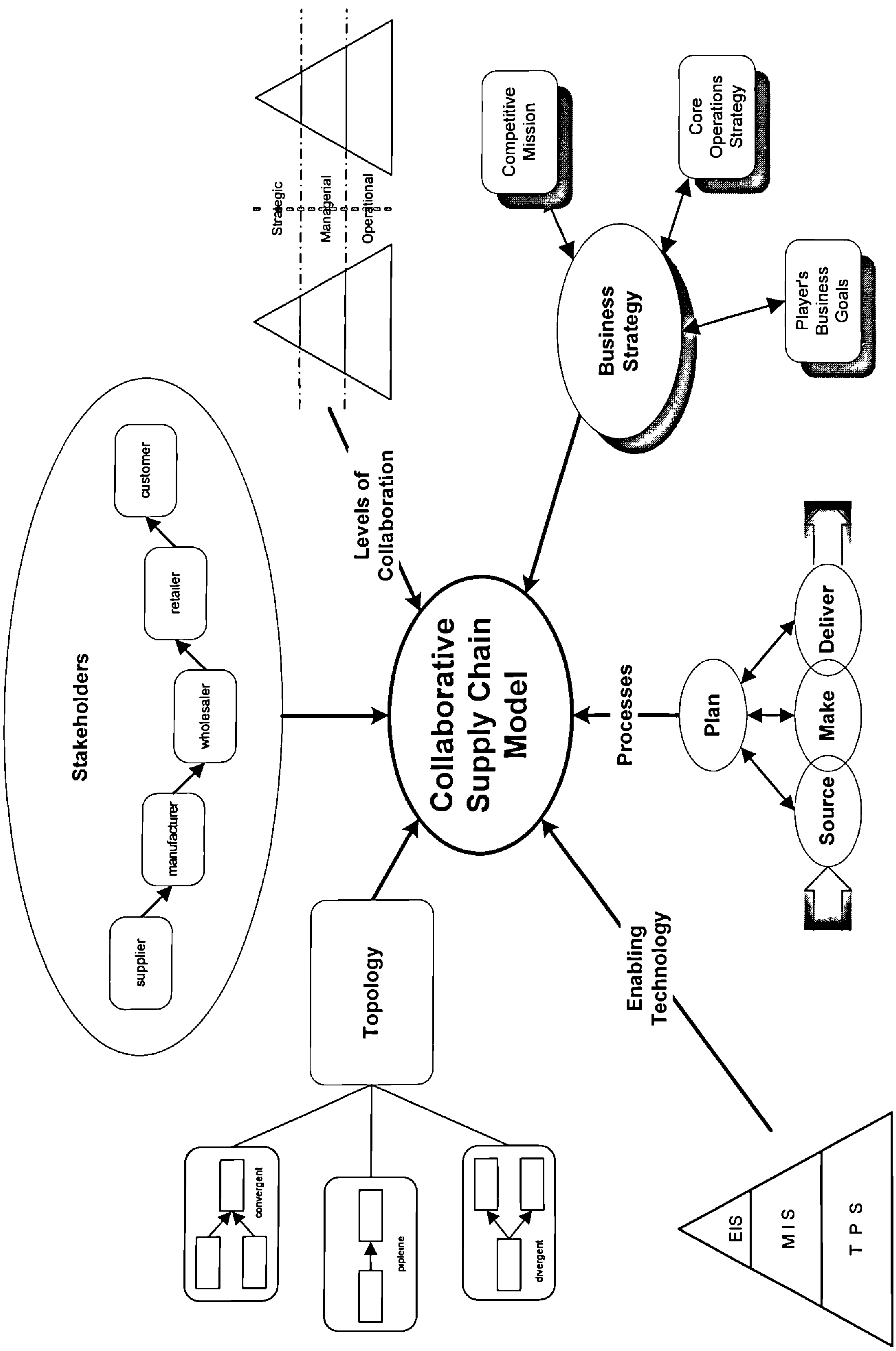


Figure 2.10: Collaborative Supply Chain Constituents

Figure 2.10 shows a decomposition of the collaborative supply chain model into its constituents. All six constituents of a collaborative supply chain are inter-linked. The number and type of stakeholders involved determine the topology of a collaborative supply chain. For example, a collaborative supply chain consisting of three stakeholders, the supplier, manufacturer and customer (Figure 2.11), may be found in the custom product market, such as made-to-order integrated circuits.

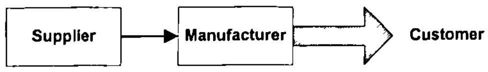


Figure 2.11: Custom Product Collaborative Supply Chain

The competitive mission lies in gaining advantage through product differentiation, the business goal of the involved players is to establish a long-term relationship and reach high profits, and the core operations are optimised to provide high ordering flexibility towards the customer. In this scenario, a manufacturer is supplied with raw material for a particular product only by one supplier, and delivers the finished product to one customer. The topology of the supply chain, therefore, constitutes a pipeline flow, where goods are moved directly from the supplier to the manufacturer and then to the customer. On the process side, sourcing takes place with the sole supplier, the manufacturer represent the make process as well as the deliver process to the customer. This set-up of processes in combination with the business strategy requires the use of enabling technology and collaboration in particular on the strategic and managerial level. In order to be able to provide ordering flexibility to the customer, strategic collaboration agreements need to be set up to ensure that the required resources and capacities are available. The use of executive information systems helps top management to link those commitments to the collaborative supply chain as well as to the individual company's long-term strategies. On the managerial level, the optimisation of the flow of goods along the whole supply chain lies in the centre of attention. This is supported through planning and forecasting systems, which will help to ensure that the agreed order flexibility towards the customer is reached and maintained.

Another example is a supply chain for mass-market products (such as 14" colour television sets), consisting of three suppliers, one manufacturer, two wholesalers and five retailers. The topology of the supply chain is made up of divergent flows and convergent flows (Figure 2.12). The suppliers deliver either raw material or primary products to one manufacturer. After the production of goods by the manufacturer, the stocks of several retailers are replenished via wholesalers. The retailers then sell the product to the customers.

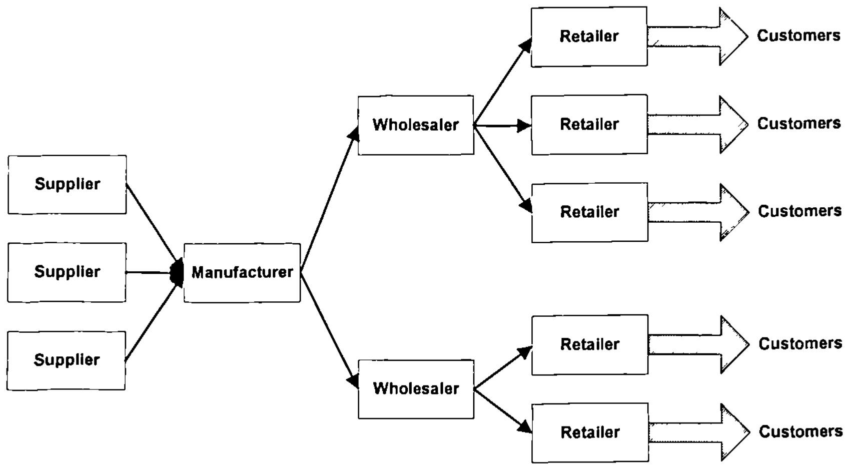


Figure 2.12: Mass Market Collaborative Supply Chain

According to Porter (1985), a mass market set-up requires to gain competitive advantage via lower price at the same quality, therefore, the operations strategy will aim at optimising the collaborative supply chain processes for low costs and high efficiency. Information technology will be used to streamline operations and control major cost factors such as inventory build-up or production yield. Warehousing solutions can help to minimise stocking and delivery costs whilst maximising product availability at the retailers. Continuous evaluation of supply chain performance through appropriate performance measures and the use of benchmarking will then enable collaborative strategic decisions regarding the inclusion of new players or the exclusion or existing players, if required due to poor performance.

2.8 SUMMARY

Chapter 2 describes the proposed collaborative supply chain model and its six constituents and argues that all six constituents are required to form a complete picture of a collaborative supply chain. The next chapter discusses the development of a performance indicator to measure the performance of a collaborative supply chain. Firstly, it unravels which key variables in the supply chain are influenced by each of the constituents in the model, and then derives a performance indicator that utilises this relationship.

CHAPTER 3: DEVELOPMENT OF A PERFORMANCE INDICATOR FOR A COLLABORATIVE SUPPLY CHAIN

"Performance is a function of measurement."

(Charles C. Poirier, 2003)

This chapter derives an indicator for measuring and potentially improving the performance of the collaborative supply chain by examining how changes in any of the six constituents affect performance and, in particular, by identifying the key variables that are responsible for that.

3.1 THE SIX CONSTITUENTS' IMPACT ON PERFORMANCE

Changes in one or more of the six constituents will have an impact on the performance of the collaborative supply chain. This section illustrates how key variables are influenced by the six constituents.

3.1.1 Stakeholders

Stakeholders, the primary players of the collaborative supply chain, are the supplier, manufacturer, wholesaler, retailer and customer (Forrester 1958). The customer plays a different role than the other players in the collaborative supply chain. The customer is considered the 'drain', the receiver of goods, whereas the other players are considered the 'source', the provider of goods. Hence, the customer influences the Sales Quantity (SQ) and Revenue (R) via Customer Demand (CD). This may increase the Profit (P). Customer Satisfaction (CS), hereby, also impacts Customer Demand. For example, if Customer Satisfaction is high, the customer may try to satisfy as much as possible Customer Demand from this one source.

Upstream the supply chain, the remaining players are responsible for the production and distribution of the goods. Any changes in any number of these may have a drastic effect on the performance of the collaborative supply chain (Parker and Anderson Jr. 2002). Adding players influences Costs (C). The supply chain may become more difficult to manage as more players get involved, which is reflected in higher Costs, more Information Delay (ID) and lower Supply Chain Flexibility (SCF). There also is an influence on Forecast Accuracy (FA) and Time to Market (TTM) via additional Information Delays. However, if new players are well integrated and their business strategy is well aligned to that of the whole collaborative supply chain, then the positive impact on collaborative supply chain performance may dominate. Additional players may reduce the risk of StockOuts (SO) and affect Supply Chain Flexibility to give a better overall performance.

3.1.2 Topology

Topology describes the way in which players in the supply chain are linked together (Towill 1997). Linking players via a direct flow, convergent flow, or a divergent flow affects some key variables (Beamon and Chen 2001). Based on the choice of stakeholders, certain topology configurations become possible. For example, if there is one manufacturer, then the type of link between supplier and manufacturer must be either single route or convergent. The downstream link from the Manufacturer to the Wholesaler can only be single route or divergent. Figure 3.1 shows an example of a single manufacturer supply chain with a convergent flow on the manufacturer's upstream side and a divergent flow downstream from the manufacturer.

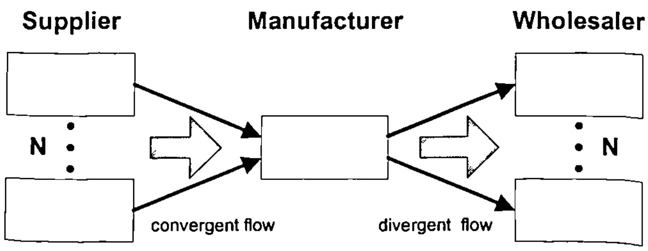


Figure 3.1: Single Manufacturer Supply Chain

Establishing more than one link between manufacturer and wholesalers may increase Costs, but on the other hand could decrease the total time until products reach a retailer and thus Time To Market may go down. Also, if a retailer receives goods from more than one warehouse, the risk of StockOuts at the retailer is reduced, thus ensuring that the fulfilment of Customer Demand is improved. This at the same time may have a positive impact on Supply Chain Flexibility. Additional links will incur an additional cost, for example for extra planning and transportation of goods, which may cause the Costs to increase. Extra investment in Enabling Technology might be necessary to cope with more requirements in demand planning. However, reduced StockOuts may also lead to higher Customer Satisfaction.

3.1.3 Levels of Collaboration

Collaboration between players in the supply chain may take place on a strategic, managerial and operational level. Collaboration at the operational level may take the form of a routine task such as transportation scheduling. For instance, wholesalers and retailers could work together closely to improve the delivery of goods to the various retailers based on actual stocking levels and expected demand at the individual retailer. This may cause some extra Costs, but the benefits in terms of increased flexibility and fewer StockOuts may outweigh those Costs. More collaboration at the managerial level could lead to better planning and forecasting. Through enhanced information flow between the players in the collaborative supply chain, Information Delay could be decreased and Forecast Accuracy improved; the sharing of capacity and inventory information may lead to lower inventories and at the same time an increased Supply Chain Flexibility. Managerial decisions typically work on a short to medium time frame; therefore, the effect of changes may not be visible immediately.

Collaboration at the strategic level may involve decisions that will have medium- to long-term effects. Examples are decisions that have major impacts on the collaborative supply chain, such as capital investment or restructuring of the supply chain. Collaboration at the strategic level also may involve giving visibility to internal figures or structural details of the individual players. Hence, higher levels of collaboration, whilst normally associated with additional Costs, should have a positive effect on key performance variables in the collaborative supply chain. There is, however, a certain risk involved for each player. For example, the information shared could be used by one of the players to its sole advantage, but if well managed the positive effect may prevail (Anderson and Morrice 2002). Through better collaboration the advantages of centralised control can be approached. This will remove barriers between players and processes within the collaborative supply. Centralised control in a collaborative supply chain may lead to global optimum rather than local optimisation, therefore, a centralised system could be more effective because of the *interaction of decisions* (Simchi-Levi *et al.* 2000). Higher levels of collaboration thus have a direct impact on Forecast Accuracy, Information Delay and Supply Chain Flexibility, which in turn may improve Time to Market and Customer Satisfaction. There is a cost with collaboration, which is due to the increased effort in administration and necessary compromising for each of the players.

3.1.4 Enabling Technology

The use of Enabling Technology plays a key role in improving the performance of a collaborative supply chain (Simchi-Levi *et al.* 2000, Szuprowicz 2000). First of all, there are always Costs involved in implementing and using Enabling Technology, generally implementation and maintenance costs. Implementation costs may consist of the cost of hardware and software itself, but also possible costs involved in changing business processes and user training. The potential benefits of Enabling Technology are extensive (Kelley 2002). Transaction Processing Systems provide support to supply chain processes and enable an effective communication infrastructure. For example, an Electronic Data Interchange (EDI) system may allow for fast and reliable data exchange between supply chain players, thus it may provide the basis for appropriate supply and demand planning. Planning and coordination activities are supported by Management Information Systems, which can provide relevant and accurate information in a timely manner. For instance, an integrated ERP system may lead to better Capacity Utilisation (CU) and, therefore, reduce Costs. Together with improved Forecast Accuracy this may lead to better product availability at the retailer, therefore, reducing the risk of StockOuts.

Executive Information Systems aim at supporting decision-makers in strategic decisions that predominantly have long-term effects. By providing clear and summarised information (Ross 2000) they enable decision-makers to choose the right course of action in order to improve supply chain performance whilst ensuring medium- to long-term success. EIS may have an indirect effect on most of the performance variables in the collaborative supply chain, though this effect will show normally only after a certain time. For example, a decision-maker may find through an ad hoc enquiry that many StockOuts occurred whilst Capacity Utilisation was at a high level but below maximum. Thus, a project could be started to determine whether an additional manufacturing site could help overcome this problem. Based on the outcome of this investigation, Production Capacity may be increased, but this might only be available after a certain period of time.

3.1.5 Business Strategy

The business strategy of the collaborative supply chain needs to be appropriate for the market environment in which the supply chain operates. Business strategy consists of the competitive mission, core operations strategy and the players' business goals (Ross 2000). It is essential that those elements be aligned with those of the collaborative supply chain (Harrison and New 2002). Whilst all players need to have a certain amount of individuality, they must serve the needs of the collaborative supply chain.

Level of Alignment (LA) measures how close the individual players' business strategy is to that of the collaborative supply chain. The higher the Level of Alignment, the better centralised control can be approached. This may lead to reduced Information Delay, increased Forecast Accuracy and thus reduce the risk of StockOuts. At the same time Costs may go down due to more effective decisions and their implementation (Mavrommati and Migdalas 2002). According to the competitive environment, an appropriate Unit Selling Price (USP) can be chosen, which in turn will prompt a response in Customer Demand.

3.1.6 Processes

The players of the collaborative supply chain take shared responsibility of the four core supply chain processes: Plan, Source, Make and Deliver (SCC 2001, Szuprowicz 2000). The performance of those processes influences the performance of the whole collaborative supply chain. Each of the four core processes is influenced by changes in the other constituents as well. For example, an increased use of Enabling Technology may improve operations through better production and distribution planning. Better collaboration may improve information visibility and, therefore, lead to better planning. The performance of the processes has a direct effect on several key variables. Improvements in the 'Make' process may lead to better Product Quality (PQ), and shorter Time to Market through improved cycle time (Akkermans 2001). Together with improved performance in the 'Source' process this may lead to better Capacity Utilisation and hence reduce Costs, which in turn could increase Profit. The 'Deliver' process may benefit from better collaboration and use of enabling technology and in turn reduce Time to Market, the risk of StockOuts and increase Supply Chain Flexibility. Improvements in the 'Plan' process could lead to a better Forecast Accuracy and hence allow for a better estimate of the required Production Capacity (PC).

Changes in different constituents may influence the same variable in a variety of ways. The choice of variables used in determining the effect of changes in any of the six constituents on the collaborative supply chain performance will depend on the nature of the specific Collaborative Supply Chain. This means that there may be numerous ways in which changes could be made to influence the value of a key variable or performance indicator. It is then up to the decision-maker to decide which course of action is preferred. Figure 3.2 shows which variables are influenced by which constituent. Three degrees of relationship are used to denote the level of influence: 'insignificant influence (✗)' 'influence (✓)' and 'strong influence (✓✓)'.

	Stakeholders	Topology	Levels of Collaboration	Enabling Technology	Business Strategy	Processes
Capacity Utilisation	✗	✗	✗	✓	✗	✓✓
Cost	✓✓	✓	✓	✓✓	✓	✓✓
Customer Demand	✓	✓	✗	✗	✓✓	✗
Customer Satisfaction	✓	✓	✓	✗	✗	✗
Forecast Accuracy	✓	✗	✓✓	✓✓	✓	✓
Information Delay	✓	✗	✓✓	✗	✓	✗
Level of Alignment	✗	✗	✗	✗	✓	✗
Product Quality	✗	✗	✗	✗	✗	✓✓
Production Capacity	✗	✗	✗	✓	✗	✓
Profit	✓✓	✗	✗	✗	✗	✓
Revenue	✓✓	✗	✗	✗	✗	✗
Sales Quantity	✓✓	✗	✗	✗	✗	✗
StockOuts	✓	✓	✓	✓	✓✓	✓
Supply Chain Flexibility	✓	✓✓	✓✓	✗	✗	✓
Time To Market	✓	✓	✓	✗	✗	✓✓
Unit Selling Price	✗	✗	✗	✗	✓✓	✗

✗: insignificant influence ✓: influence ✓✓: strong influence

Figure 3.2: Constituents Impact on Variables

The next section first describes traditional ways of measuring supply chain performance, considers measures suitable for the assessment of the performance of a collaborative supply chain, and then derives the collaborative supply chain performance indicator.

3.2 Measuring the Performance of a Collaborative Supply Chain

Beamon (1999) argues that qualitative measures such as 'poor, 'average', or 'good' may be used to assess the performance of a supply chain when a direct numerical measurement is not possible. Qualitative measures are not used in any of the reviewed work because they are vague and difficult to utilize in any meaningful way (Beamon 1999). Quantitative measures are normally used when numerical measurement is possible, henceforth measure refers to quantitative measure. A measure may be viewed as a quantification of a process, as a specific instance of assessing a status. Measures are presented numerically from processes, products or other relevant factors, and permit the evaluation and comparison relative to goals, benchmarks, or historic results. A performance indicator is a function of one or more measures. Its purpose is to make a statement of the status of the collaborative supply chain in terms of its performance. All measures and performance indicators chosen to measure the performance of a collaborative supply chain together form a performance measurement system.

3.2.1 Traditional Supply Chain Performance Measurement

Traditionally, cost and customer responsiveness (in form of lead time or service level) have predominantly been used as performance measures in supply chains (Beamon 1999). Hence supply chain performance has been assessed by measurement of key supply chain processes, such as the 'Source', 'Make' and 'Deliver' supply chain processes (APQC 2000, Evans *et al.* 1998, Lee *et al.* 1997, SCC 2001, Szuprowicz 2000), by measurement of demand amplification (Anderson *et al.* 2000, Towill 1996a), or by a composite performance indicator (Hammant *et al.* 1999, Towill 1997). Beamon (1999) suggests three types of measures for supply chain performance measurement, which can also be used to measure the performance of a collaborative supply chain: **resource**, **output**, and **flexibility** measures.

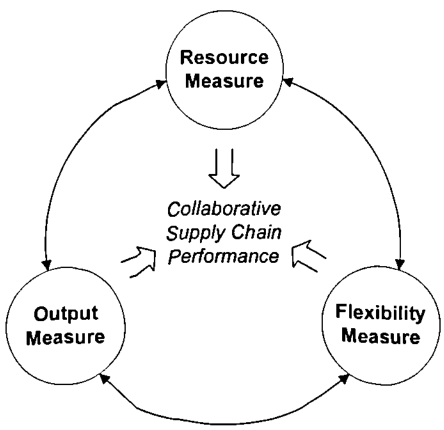


Figure 3.3: Supply Chain Measures

Resource measures, which generally measure costs, will help towards improving supply chain performance by minimising costs, or if they measure efficiency, help towards improving supply chain performance by maximising resource utilisation. Examples of resource measures are production costs, equipment utilisation, or demand amplification. Resource measures constitute the most widely used measures in supply chain performance measurement (Beamon 1998, Hieber 2002), and are typically used in form of performance indicators such as total cost, distribution cost, manufacturing cost and inventory cost (APQC 2000, Evans *et al.* 1998, Johansson *et al.* 1993, Lee *et al.* 1997, SCC 2001, Szuprowicz 2000, Towill 1997). Demand amplification is a supply chain performance indicator frequently used by Anderson *et al.* (2000), Berry *et al.* (1994), Lee *et al.* (1997), Mason-Jones and Towill (1998), Towill (1996a)and Wikner *et al.* (1991). Demand amplification occurs along a supply chain as a result of coordination failures, ration games, and non-stationary demand (Anderson *et al.* 2000). Demand amplification measures the increase in orders upstream from echelon to echelon, starting from the retailer via the wholesaler to the manufacturer. Demand amplification causes inefficiency and directly impacts costs and resource utilisation. Reducing demand amplification leads to enhanced stability and increased responsiveness of the supply chain (Berry *et al.* 1994, Mason-Jones and Towill 1998), hence measuring demand amplification gives a good indication of the operational performance of a supply chain.

Output measures, which measure the outputs of a supply chain, attempt to provide means to optimise performance. Examples are sales and profit, cycle time, and customer related measures such as service level. As an output measure, customer service level defines the service and performance level that will be provided to a customer. Service level is defined commonly as type 1 or type 2 service level (Graves *et al.* 1993): Type 1 service level measures the proportion of periods in which all demand is met, type 2 service level measures the proportion of demand satisfied immediately from inventory.

Flexibility measures are used to measure the supply chain's ability to cope with volume and schedule variations from customers as well as suppliers. For instance, flexibility may be measured in terms of by how much an ordered volume can be changed during specific time periods after the order date or before the delivery date. Thus, flexibility measures determine the potential behaviour of a collaborative supply chain, whereas resource and output flexibility measure the actual performance of a collaborative supply chain. The degree of importance of flexibility to a collaborative supply chain depends on the market environment in which it operates. Regardless, flexibility needs to be measured to assess its impact on collaborative supply chain performance. Beamon (1999) proposes volume flexibility F_v and delivery flexibility F_d as flexibility measures in supply chain performance measurement. Volume flexibility refers to the range of volumes in which a supply chain can run profitably, thus F_v specifies the proportion of demand that can be met by the supply chain:

$$F_v = \Phi\left(\frac{O_{\max} - \overline{D}}{S_D}\right) - \Phi\left(\frac{O_{\min} - \overline{D}}{S_D}\right) \tag{3.1}$$

where $Fv \in [0,1)$, O_{max} is the *maximum profitable output,* O_{min} *is the minimum* profitable output, Φ is the cumulative distribution function for the external demand, and D is the demand volume defined by a random variable with normal distribution. Therefore, $\overline{D}$ is defined as:

$$\overline{D} = \frac{\sum_{t=1}^{T} d_t}{T} \tag{3.2}$$

and

$$S_D = \sqrt{\frac{\sum_{t=1}^{T} (d_t - \overline{d})^2}{T-1}} \tag{3.3}$$

where d_t is the demand during period t, and T is the number of periods considered.

Delivery flexibility F_d quantifies the ability to move planned delivery dates forward in order to accommodate rush and special orders. It is expressed as the percentage of slack time by which the delivery time can be reduced.

F_d is defined as:

$$F_D = \frac{\sum_{j=1}^{J}(L_j - E_j)}{\sum_{j=1}^{J}(L_j - t^*)} \tag{3.4}$$

where L_j is the due date period for a job j, E_j is the earliest time period during which the delivery can be made, t^* is the current time period, and $j = 1,....,J$ are jobs.

Traditionally, a *combination* of **resource** and **output** measures is used to form a supply chain performance indicator (Hammant *et al.* 1999, Towill 1997, 1996b). This combined approach is applied for benchmarking the performance of supply chains (Johansson *et al.* 1993) and is especially useful to continuously measure supply chain efficiency (Towill 1997).

$$PI = \left[\frac{(quality)*(customer\_service\_level)}{(total\_\cos t)*(leadtime)}\right] \tag{3.5}$$

Equation (3.5) shows the performance indicator consisting of four components: quality, customer service level, total cost, and lead-time. The performance indicator allows balanced performance measurement by showing the effect of improving one measure at the cost of another measure (Hammant *et al.* 1999).

Research has shown that in supply chain performance measurement as yet not all three types of performance measures are used simultaneously (Beamon 1999). Traditionally, supply chain performance measurement mainly focuses on resource or output measures used in isolation. Furthermore, the performance indicator described in Equation (3.5) only combines the use of two types of measures. Since only measures of type resource and output are used, the performance indicator cannot measure flexibility of a supply chain. Hence, in traditional approaches the flexibility of a supply chain can only be measured in isolation but not as a composite measure. Figure 3.4 shows supply chain performance measures used in existing research.

Supply Chain Performance Measures

	Resource Measures	Output Measures	Flexibility Measures	*Single Measure or Composite Measure*
Anderson	✓			*S*
Berry	✓			*S*
Evans	✓			*S*
Hammant	✓	✓		*C*
Johansson	✓	✓		*C*
Lee	✓			*S*
Mason-Jones	✓			*S*
Towill	✓	✓		*C*
Wikner	✓			*S*

Figure 3.4: Supply Chain Performance Measures used in Existing Research

3.2.2 Collaborative Supply Chain Performance Measurement

The six constituents of a collaborative supply chain form a system of integrated processes and multiple relationships within and between stakeholders. This system is characterised by complexity due to many inter-linkages and inter-relationships. Changes in any of the six constituents will have an effect on the performance of the collaborative supply chain. In order to adequately measure the performance of a collaborative supply chain, a performance measurement system assures that each type of measure, **resource**, **output**, and **flexibility**, must occur at least once in a performance measurement system. While each type of measure has unique characteristics, there are also interrelationships between the three (Beamon 1999). Hence, only a measurement system which uses all three types can take account of the complex interrelationships in a collaborative supply chain, thus adequately measuring the performance.

The goal of resource measures is to achieve a high level of cost efficiency. If resource measures were missing in a performance measurement system, the collaborative supply chain would constitute an unconstrained system, allowing to realise 100% service levels and total flexibility at the same time, at any cost. Therefore, the results of any performance measurement, where resource measures are omitted, lead to local optimisation and consequently are meaningless in the context of a collaborative supply chain. For example, resource measures are required to measure the impact of the 'enabling technology' constituent on collaborative supply chain performance.

Without output measures no assessment of the operational performance of a collaborative supply chain is possible. A collaborative supply chain exists to produce some output, therefore, output measures are essential in measuring collaborative supply chain performance. Furthermore, the absence of output measures would render resource measures worthless, as any efforts in terms of *costs and efficiency* would not be reflected in the inter-relationship between costs and output levels. For example, the impact of the 'process' constituent on collaborative supply chain performance could not be determined without output measures like cycle time or number of products shipped.

Resources affect the output of a collaborative supply chain, whilst the output is important in determining the flexibility (Beamon 1999). The absence of flexibility measures will prevent to gain a complete picture of supply chain performance. Without flexibility measures there is no means by which the response of a collaborative supply chain to demand schedule and volume variations could be assessed. Measuring the potential to adjust to a changing environment, however, is essential as it reflects the performance trade-off inherent in a complex system such as a collaborative supply chain. Figure 3.5 shows the consequences when any single measure or a combination of measures is missing in a performance measurement system.

Combination of Performance Measures

Resource Measures	Output Measures	Flexibility Measures	*Consequence of measures missing*
✓	✓	✓	All types of measures used: requirements are satisfied.
×	✓	✓	Cannot measure relationship between resource input (capital investment, production costs, etc.) and output (products, cycle time, etc.) thus assuming an unconstrained system.
✓	×	✓	Not a possible combination: flexibility cannot be measured as it assumes that output is measured.
✓	✓	×	Cannot measure the capability of the collaborative supply chain to react to demand fluctuations.
✓	×	×	Cannot measure the capability of the collaborative supply chain to react to demand fluctuations. The absence of output measures renders the measurement system meaningless, there is no relation between effort (input) and result (output). It is exclusively aimed at local optimisation of the input.
×	✓	×	Cannot measure relationship between resource input (capital investment, production costs, etc.) and output (products, cycle time, etc.) thus assuming an unconstrained system, is exclusively aimed at local optimisation of output.
×	×	✓	Not a possible combination: flexibility cannot be measured as it assumes that input and output is measured.
×	×	×	Not a possible combination: Measurement system not existent.

✓ denotes the use of a particular measure, × denote the absence of that measure

Figure 3.5: Combination of Performance Measures

The above requirements suggest the development of a performance indicator that combines the three performance measures. We call this the Collaborative Supply Chain Performance Indicator (CSCPI) and the three performance measures PM1, PM2, and PM3. PM1 is a measure of type resource, PM2 a measure of type output, and PM3 constitutes a measure of type flexibility, thus CSCPI satisfies the requirement of consisting of all three different types of performance measures.

$$CSCPI = \left[\frac{\beta\,(PM\,2) \quad * \quad \gamma\,(PM3)}{\alpha\,(PM\,1)} \right] \tag{3.6}$$

The combination of the multiplication of PM2 with PM3 and the division by PM1 ensures that changes in any one, despite of the magnitude of it, will have a noticeable impact on the $CSCPI$. Hence, low values for PM1 and high values for PM2 and PM3 will yield better results. Each PM may be adjusted by an individual weighting factor $\alpha, \beta, \gamma \in [0.5, 1.5)$, which allows their fine-tuning between ±50% of their original value. For instance, in order to reflect the higher degree of importance of flexibility in a supply chain operating in a custom product market we set $\alpha, \beta = 1$ and $\gamma = 1.2$ in order to give a higher weighting to the flexibility measure PM3.

3.2.3 The Collaborative Supply Chain Performance Indicator

Here a formula for the Collaborative Supply Chain Performance Indicator is derived. Firstly, formulas for important variables are given and the boundaries within which the individual measures operate are stated in assumptions. Then the relevant formulas are put together to form the Collaborative Supply Chain Performance Indicator.

As shown in this chapter, three types of measures are required to adequately measure the performance of a collaborative supply chain: resource measures, output measures and flexibility measures. Measures can either be qualitative or quantitative. Qualitative measures such as 'poor, 'average', or 'good' may be brought into play when a numerical measurement is not possible. However, qualitative measures need to be mapped to a numeric value in order to be used as a part of the collaborative supply chain performance indicator. For instance, customer satisfaction could be 'very low', 'low', 'medium', 'high' or 'very high' and thus be mapped to the numeric values of 1 to 5. On the other hand, quantitative measures display a numeric value derived from processes, products or other relevant factors. Quantitative measures have a unit of measure, which is expressed as a numeric value. Examples of quantitative measures are measures based on 'Système International d'unités' (SI) base units (e.g. mass or time), units outside SI but accepted for use with it (e.g.

hours, days, or litres), or other quantitative measures such as currency units (e.g. €, £ or $). In this thesis, currency hereafter will be measured in €, all time-based units refer to time measured in days. For example, a time interval may be 180 days long and, therefore, the fixed costs are determined by the fixed cost per day multiplied by the length of the time interval. What is important in measuring performance is consistency in using the units of either quantitative or qualitative measure before and after adjustment and not the units themselves. Key variables were chosen according to two requirements: Resource, output and flexibility measures (Beamon and Chen 2001) needed to be derived from those variables, and together they should form a minimum set of commonly used variables across different platforms. The key variables are described as follows, whereby the term 'Units' is used to describe the number of items of the manufactured good in the Collaborative Supply Chain.

Sales Quantity

Sales Quantity is a measure of type output and can be measured in number of Units sold. It is a function of Customer Demand and Retailer Inventory.

$$SQ(t) = \int_{t_0}^{t} sales(s)ds + SQ(t_0) \tag{3.7}$$

where

$$sales(s) = \begin{cases} CD(s), & CD(s) \leq RI(s) \\ RI(s), & CD(s) > RI(s) \end{cases} \tag{3.8}$$

RI is the Retailer Inventory and Customer Demand is an external variable which is determined by market conditions.

$sales(s)$ represents the number of Units sold at any time s in the time interval between the initial time t_0 and the current time t.

Cost

Cost is a measure of type resource and is measured in €. Cost is made up of Fixed Cost (FC) and Variable Cost (VC). Fixed Cost is independent of the number of Units produced and is determined by the time interval passed. Variable Cost is determined on a per Unit basis and is calculated based on the total number of Units produced. Thus Cost is measured as Cost per Unit or as an aggregate Cost over a specific time interval, whereby the time interval must be the same for the whole supply chain.

$$C = VC + FC \tag{3.9}$$

where

$$VC = UVC * TP + RC \tag{3.10}$$

UVC is the Unit Variable Cost, TP is the Total Production and RC is the Repair Cost.

Revenue

Revenue is a measure of type output and is measured in €.

$$R = USP * SQ \tag{3.11}$$

Profit

Profit is a measure of type output and is measured in €.

$$P = R - C \tag{3.12}$$

Capacity Utilisation

Capacity Utilisation measures the amount of utilised Production Capacity in percent.

$$CU = \frac{production}{PC} \tag{3.13}$$

where $production$ is the actual Production of Units taking place.

StockOuts

StockOuts measures the total unsatisfied Customer Demand in number of Units.

$$SO(t) = \int_{t_0}^{t} so(s)ds + SO(t_0) \tag{3.14}$$

where

$$so(s) = \begin{cases} 0, & RI(s) \geq CD(s) \\ CD(s) - RI(s), & RI(s) < CD(s) \end{cases} \tag{3.15}$$

$so(s)$ is the value of so at time s between the initial time t_0 and the current time t.

Forecast Accuracy

Forecast Accuracy is measured as a percentage on a scale of 0% to 100% and shows how close the expected Customer Demand is to the actual Customer Demand.

$$FA = init\_FA + change\_FA \tag{3.16}$$

$init\_FA$ is the initial Forecast Accuracy and $change\_FA$ is the change in Forecast Accuracy.

Level of Alignment

Level of Alignment is measured as a percentage and indicates how close the individual players' business strategy is to that of the collaborative supply chain. It is a qualitative measure and mapped onto a scale of 0% to 100%.

$$LA : \{low...high\} \rightarrow \{0...100\}\% \tag{3.17}$$

Customer Satisfaction

Customer Satisfaction is a qualitative measure that ranges between low and high, therefore, it needs to be represented by mapping it to numeric values.

$$CS : \{low...high\} \rightarrow \{1...10\} \tag{3.18}$$

Customer Satisfaction is also a nonlinear measure of type output. Nonlinear functions are fundamental in the dynamics of all kind of systems (Sterman 2000). For example, low quality of a product will satisfy few customers. Medium quality will then attract a large numbers of customers. Thereafter, big increases in quality are required to attract more customers. Figure 3.6 illustrates this function in form of an s-shaped curve.

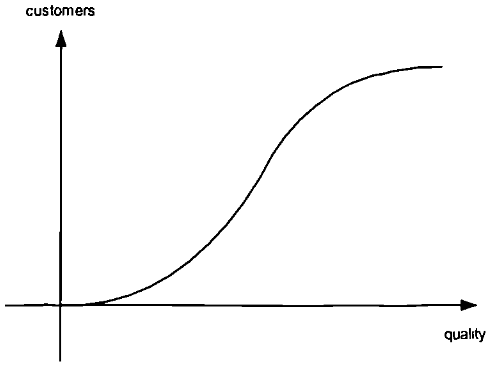


Figure 3.6: Example of a nonlinear function: Quality vs. customers

An s-shaped curve is a commonly observed mode of behaviour in dynamic systems (Sterman 2000), where the state of the system reaches an equilibrium at a certain minimum or maximum level. This may be used to describe the dynamic behaviour of Customer Satisfaction between a minimum and maximum value, whereby any influence on CS has little impact when CS reaches the minimum or maximum value, but greater impact when CS is in between those two values.

Customer Satisfaction is a function of Product Quality and StockOuts:

$$CS(t) = \int_{t_0}^{t} net\_CS(s)ds + CS(t_0) \tag{3.19}$$

where

$$net\_CS(s) = (CS(s) - min\_CS) * (1 - saturation(s)) * ref\_CS(s) \tag{3.20}$$

$$saturation(s) = \frac{CS(s)}{max\_CS} \qquad (3.21)$$

$$ref\_CS(s) = PQ\_on\_CS + SO\_on\_CS(s) \qquad (3.22)$$

PQ_on_CS is the influence of Product Quality on Customer Satisfaction and $SO\_on\_CS(s)$ is the influence of StockOuts on Customer Satisfaction over time. The non-linear behaviour of Customer Satisfaction is modelled by $net\_CS(s)$. Both Product Quality and StockOuts influence Customer Satisfaction independently and therefore are used linearly. Hence, $ref\_CS(s)$, which represents the combined influence of PQ_on_CS and $SO\_on\_CS(s)$, is determined by adding both together. min_CS and max_CS stand for minimum Customer Satisfaction and maximum Customer Satisfaction. They both vary between 1 and 10 to account for the allowed range of values. $ref\_CS(s)$ drives the change in Customer Satisfaction between min_CS and max_CS in an s-shaped curve similar to the one shown in Figure 3.6.

Time to Market

Time to Market is a measure of type output. It gives the time interval from order generation until arrival of the product at the retailer and is measured in days.

$$TTM = ID + PTMT \qquad (3.23)$$

where

$$ID = \sum_i id_i \qquad (3.24)$$

id_i denotes the Information Delay between stages i in the supply chain and $PTMT$ is Production to Market Time. Thus, ID is the amount of time an order requires to "travel" upstream through all stages of the supply chain. $PTMT$ measures the time from production start until the goods are available at the Retailer Inventory.

CSCPI

The Collaborative Supply Chain Performance Indicator is calculated from the Resource Measure (RM), Output Measure (OM) and Flexibility Measures (FM).

$$RM = C \tag{3.25}$$

In order to capture all the costs in the collaborative supply chain, the Resource Measure is set to equal (total) cost C.

$$OM = P * CS \tag{3.26}$$

The Output Measure is obtained from the multiplication of Profit, a quantitative measure, and Customer Satisfaction, a qualitative measure. Their multiplication ensures that changes in either one will have a noticeable impact on the Output Measure.

$$FM = \frac{PC\ ratio * RI\ ratio}{TTM} \tag{3.27}$$

where

$$PC\ ratio = 2 - CU \tag{3.28}$$

$PC\ ratio$ is a measure for the remaining production capacity and $PC\ ratio \in [1, 2)$ to avoid the term becoming 0 in the case of CU reaching 100%. The greater $PC\ ratio$ is, the greater the long-term flexibility of the supply chain is.

$$RI\ ratio = 1 + \frac{RI}{Total\ Inventory} = 1 + \frac{RI}{MI + WI + RI} \tag{3.29}$$

MI is the Manufacturer Inventory, WI is the Wholesaler Inventory and RI is the Retailer Inventory. $RI\ ratio$ is a measure that expresses the relationship of retailer inventory to the total inventory. The greater $RI\ ratio$ is, the higher the short-term flexibility of the supply chain. TTM measures the time from order generation until the goods reach the retailer. Therefore, the greater the term $\frac{1}{TTM}$ is, the quicker the supply chain can react to changes in demand and hence, the greater the flexibility is. Consequently, the Flexibility Measure is set as the product of $PC\,ratio$, $RI\,ratio$ and $\frac{1}{TTM}$ to ensure that changes in each of the factors will have a noticeable impact on the Flexibility Measure.

Hence,

$$CSCPI = \frac{\beta\, OM * \gamma\, FM}{\alpha\, RM} \tag{3.30}$$

with weighting factors α, β, γ, whereby

$$\alpha, \beta, \gamma \in [0.5, 1.5) \tag{3.31}$$

Certain additional variables in the simulation model are only used to perform some supplementary calculations. For instance, the variable *agg_cus_demand* is used to aggregate the Customer Demand over time to determine the total Customer Demand Cus_Demand.

3.3 SUMMARY

This chapter describes the impact of the six constituents on collaborative supply chain performance and in particular the influence of changes in the six constituents on key variables, and details the development of the collaborative supply chain performance indicator. The next chapter discusses the development of a Decision Support Environment for measuring and improving the performance of a Collaborative Supply Chain.

CHAPTER 4: DEVELOPMENT OF A DECISION SUPPORT ENVIRONMENT FOR IMPROVING THE PERFORMANCE OF A COLLABORATIVE SUPPLY CHAIN

"Lacking the ability to see into the future, we are left to make do with learning from case studies of the past to help us peer into the future."

(Charles H. Fine, 1998)

The model of a collaborative supply chain proposed in chapter 2 and the CSCPI derived in chapter 3 are implemented in a Decision Support Environment (DSE). The aim of the DSE is to show the impact on the performance as a result of changes in key variables which are the outcome of changes in one or more of the constituents. Hereby, the focus is on the functionality of the DSE rather than the interface or HCI issues, which are beyond the scope of the thesis. The DSE is not an optimisation tool. Its aim rather is to assist decision-makers in determining how changes in certain variables affect the performance of the collaborative supply chain with the view to improving it. Those changes in variables are linked to one or more of the constituents, thus reflecting target areas for improvement efforts.

The boundaries of the supply chain are incoming raw materials on one side and the customer on the other side. If a new player comes in, he has to behave in exactly the same way as another player of the same type. Thus, uniformity is guaranteed by players of the same type being modelled by delivering the same parts and observing the same rules. For instance, a supplier supplies everything that is needed for production, and where there is more than one supplier then a new supplier increases the availability of raw material. Therefore, suppliers are modelled as having the same attributes and behaviour. Retailers can receive goods from any wholesaler. Suppliers can always supply to meet 100% of the demand. For instance, if there are two suppliers, they can both together supply 100% of the demand, which my change over time.

Then next section describes the modelling environment constraints.

4.1 Modelling Environment Constraints

The DSE was developed using the Powersim™ Studio 2001 simulation platform. Several simulation platforms were examined for use, but the Powersim™ Studio 2001 simulation platform proved to be the most suitable, because it utilises the System Dynamics methodology which has been widely used to support management decision-making (Akkermans 2001, 1995, Childerhouse *et al.* 2002, Corben *et al.* 1995, Dejonckheere *et al.* 2002, Diker *et al.* 1998, Evans *et al.* 1999, Lewis *et al.* 1997, Mason-Jones and Towill 1999) underlined in this thesis. Regardless of choice the implementation of the proposed model in Powersim™ Studio 2001 was constrained because the System Dynamics methodology constraints how a conceptual model is transformed into a simulation model. With System Dynamics (SD) a simulation model is driven by the continuous passing of time, not by events, as it is the case with discrete event simulation. As a result the viewpoint taken is rather holistic and aimed at improving the overall performance, not at optimising certain parts of the collaborative supply chain. The aim of the DSE is exactly that, i.e. to provide support in making decisions on improving a collaborative supply chain. In addition, Powersim™ Studio 2001 constrains part of the implementation of the model. For example, the analysis tools provided are limited in scope. It is not possible to compare several time graphs with each other directly. To overcome this, screen shots of the results of various simulation runs may be taken individually and then compared to each other.

Then next section describes the implementation of the Collaborative Supply Chain Model proposed in chapter 2 as a DSE.

4.2 THE DECISION SUPPORT ENVIRONMENT

The DSE is implemented as a simulation model which first allows experimenting with changing the numeric values of key variables and then calculates the Collaborative Supply Chain Performance Indicator. The results of changes in performance due to user inputs are presented in form of time graphs and values for key variables together with a numeric value for the Collaborative Supply Chain Performance Indicator. Figure 4.1 shows the welcome screen of the DSE.

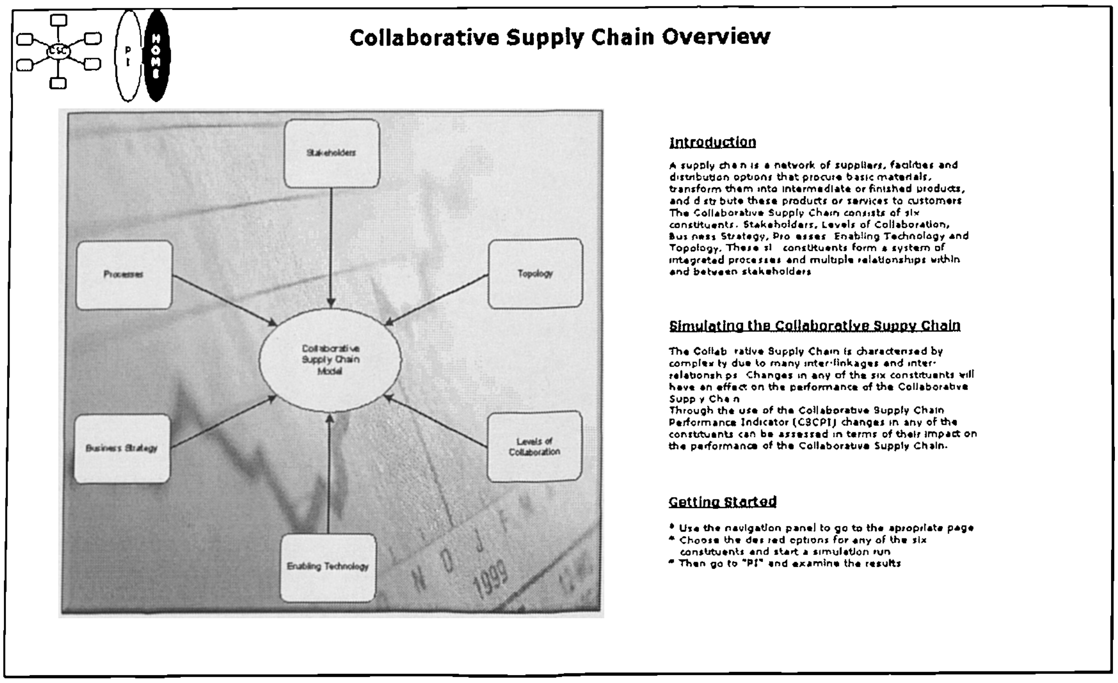


Figure 4.1: DSE opening screen

By clicking on any of the six constituents, the appropriate configuration dialog is displayed. The navigation panel on the top left hand corner of the DSE start screen is available on all model sheets and allows easy navigation between different parts of the model.

4.2.1 Configuration of the Six Constituents

This section describes the configuration dialogs for each of the six constituents. First, each of the constituents configuration dialogs are shown below and the choices of input are explained. Then the Collaborative Supply Chain Model, which is denoted by 'CSC' in the navigation panel, is presented. Finally, the results of changes made to any of the six constituents are explained, the appropriate page may be directly accessed by clicking 'PI' on the navigation panel.

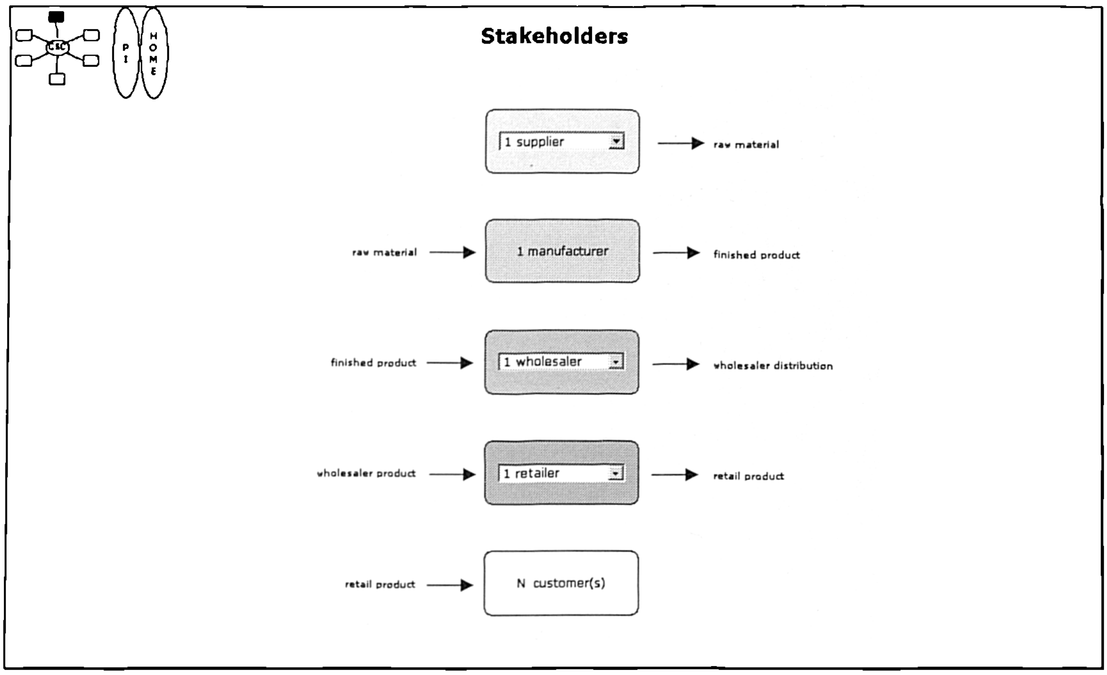
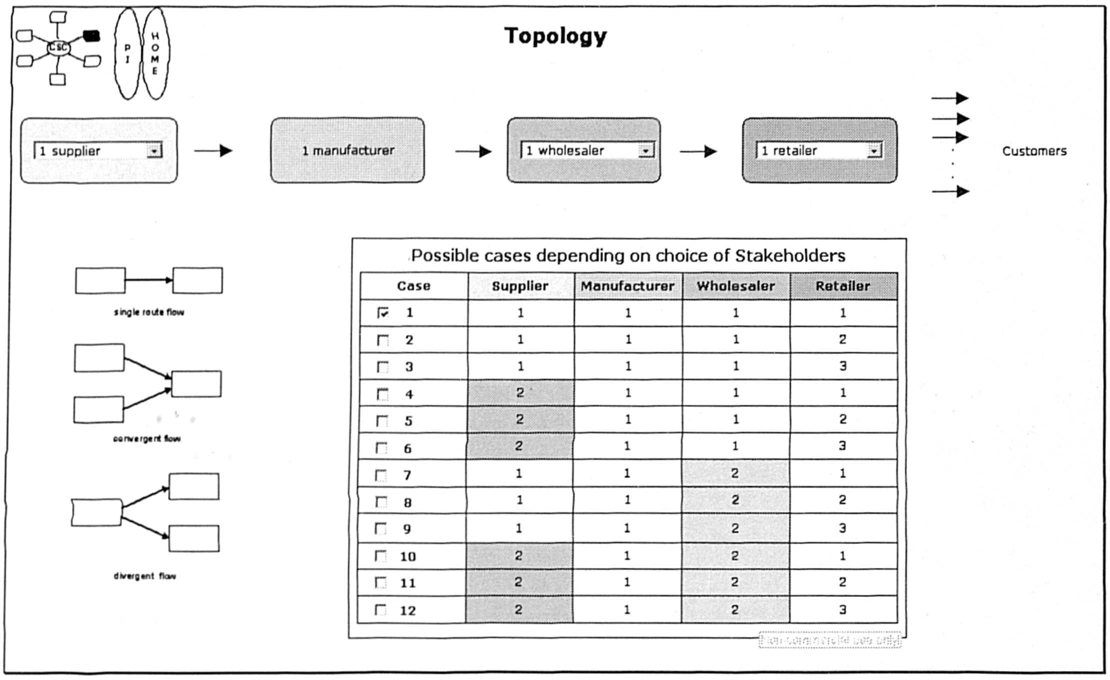


Figure 4.2: Stakeholders configuration dialog

The stakeholders configuration dialog offers a choice of different collaborative supply chain configurations in terms of participating stakeholders. The user may set the number of suppliers and wholesalers between one and two and the number of retailers between one and three. Figure 4.3 shows how the choice of stakeholders may also predetermine the topology of the collaborative supply chain to a certain extent. The case that is determined by the choice of stakeholders is automatically displayed. A hyperlink then allows going to the appropriate Topology configuration page directly.



Case	Supplier	Manufacturer	Wholesaler	Retailer
☑ 1	1	1	1	1
☐ 2	1	1	1	2
☐ 3	1	1	1	3
☐ 4	2	1	1	1
☐ 5	2	1	1	2
☐ 6	2	1	1	3
☐ 7	1	1	2	1
☐ 8	1	1	2	2
☐ 9	1	1	2	3
☐ 10	2	1	2	1
☐ 11	2	1	2	2
☐ 12	2	1	2	3

Figure 4.3: Topology configuration dialog

The choice of topologies is limited according to which stakeholders were selected. For example, if only one stakeholder of type supplier, wholesaler and retailer each, were chosen, then topology is set automatically to case 1 as shown in Figure 4.4.

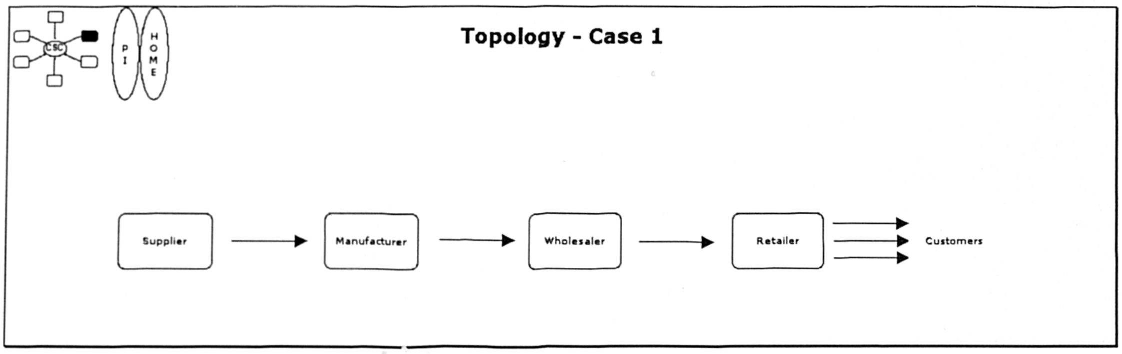
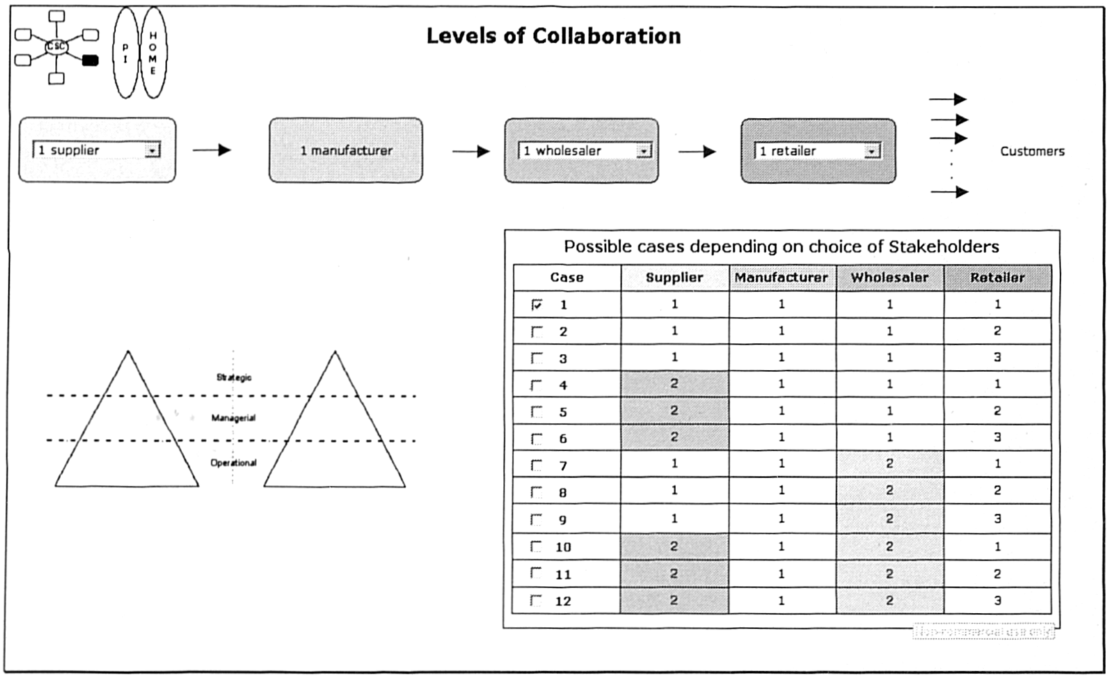


Figure 4.4: Topology - Case 1

The Levels of Collaboration configuration dialogs, as shown in Figure 4.5 and Figure 4.6, allows the user to choose the level of collaboration between the stakeholders.



Case	Supplier	Manufacturer	Wholesaler	Retailer
1	1	1	1	1
2	1	1	1	2
3	1	1	1	3
4	2	1	1	1
5	2	1	1	2
6	2	1	1	3
7	1	1	2	1
8	1	1	2	2
9	1	1	2	3
10	2	1	2	1
11	2	1	2	2
12	2	1	2	3

Figure 4.5: Collaboration configuration dialog

As with Topology, the chosen case is displayed in the Collaborations configuration dialog. Clicking on the hyperlink accesses the configuration dialog.

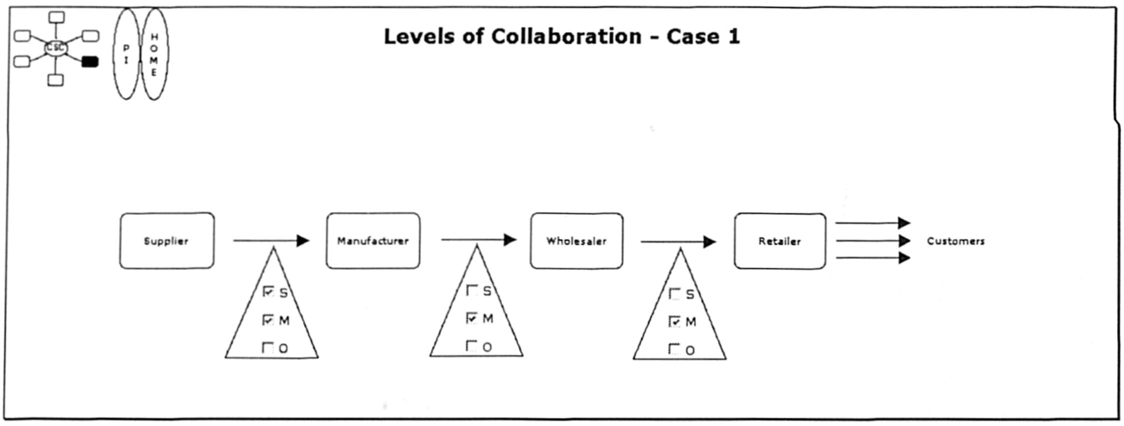


Figure 4.6: Levels of Collaboration – Case 1

The Level of Collaboration between the Stakeholders must be set. 'O', 'M' and 'S' denote collaboration on operational, managerial and strategic levels respectively.

The Enabling Technology configuration dialog assist the user setting the type of enabling technology between stakeholders. Figure 4.7 and Figure 4.8 illustrate case 1, where one stakeholder of each type is present.

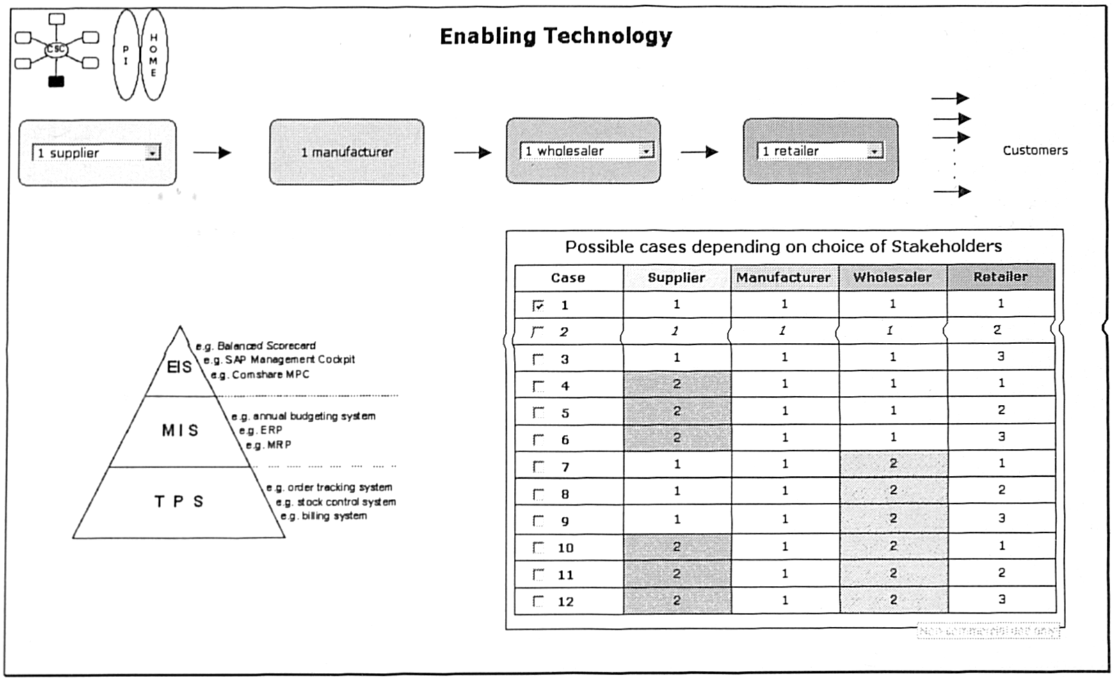


Figure 4.7: Technology configuration dialog

The case determined by the choice of stakeholders is highlighted on the Technology configurations dialog, where a hyperlink allows going to the appropriate case.

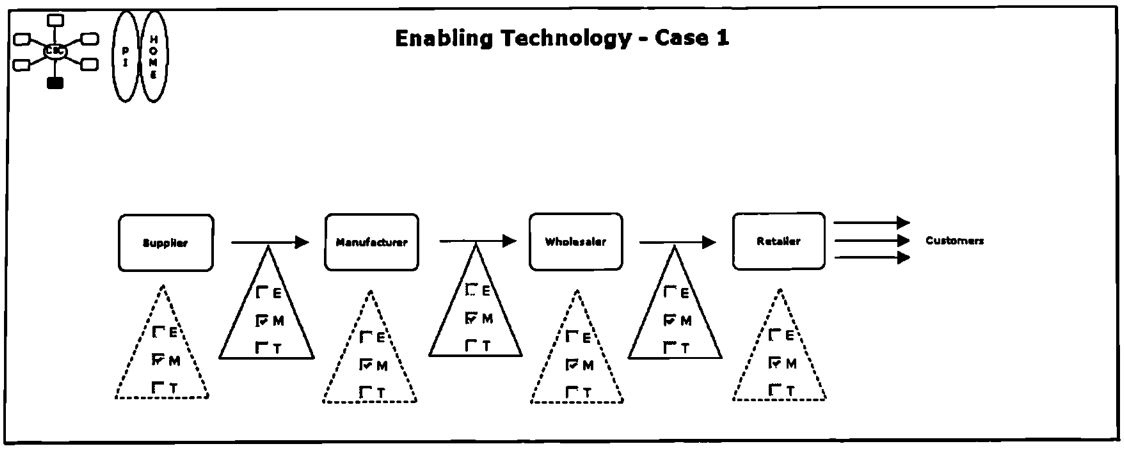


Figure 4.8: Enabling Technology - Case 1

For each Stakeholder and for each link between them, there is a choice of the type of Enabling Technology used. 'T' denotes Transaction Processing Systems, 'M' stands for Management Information Systems and 'E' for Executive Information Systems.

Each of the stakeholders may have their own targets and goals. The Business Strategy configuration dialog in Figure 4.9 provides a rating tool on how closely the individual stakeholders business goals, core operations strategy and competitive mission are aligned to those of the collaborative supply chain as a whole.

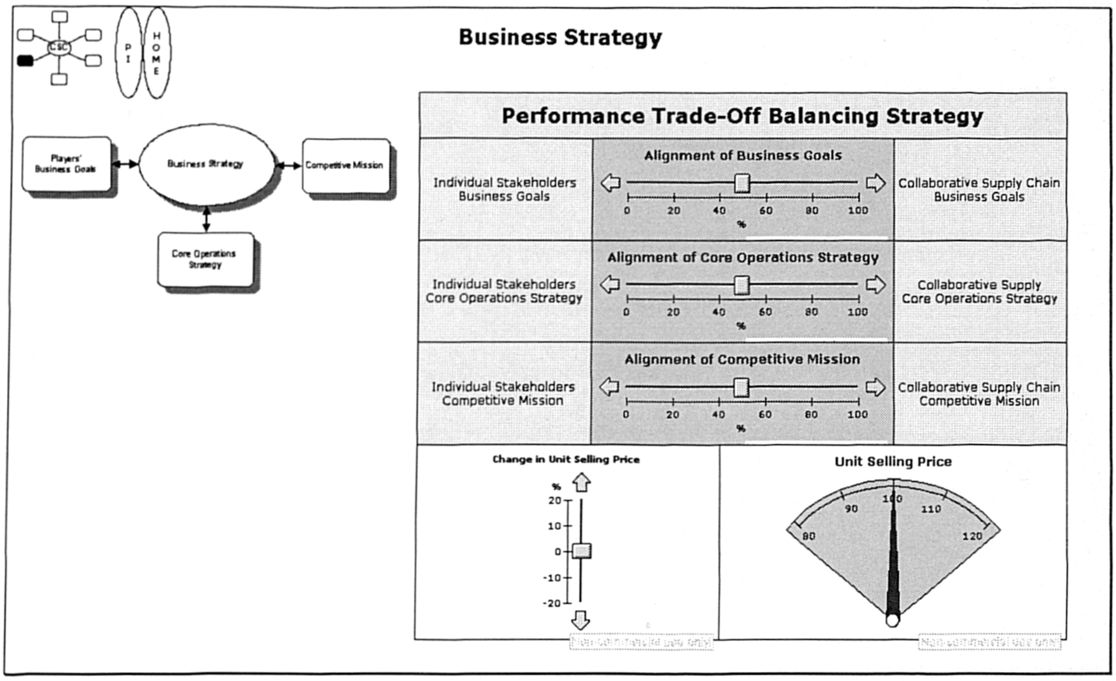


Figure 4.9: Business Strategy configuration dialog

In addition, the Unit Selling Price can be changed in a range between -20% to +20%. This is a strategic decision as it needs to consider the competitive environment in which the collaborative supply chain is operating.

Figure 4.10 shows the process configuration dialog. The user can change variables that directly relate to the performance of business processes.

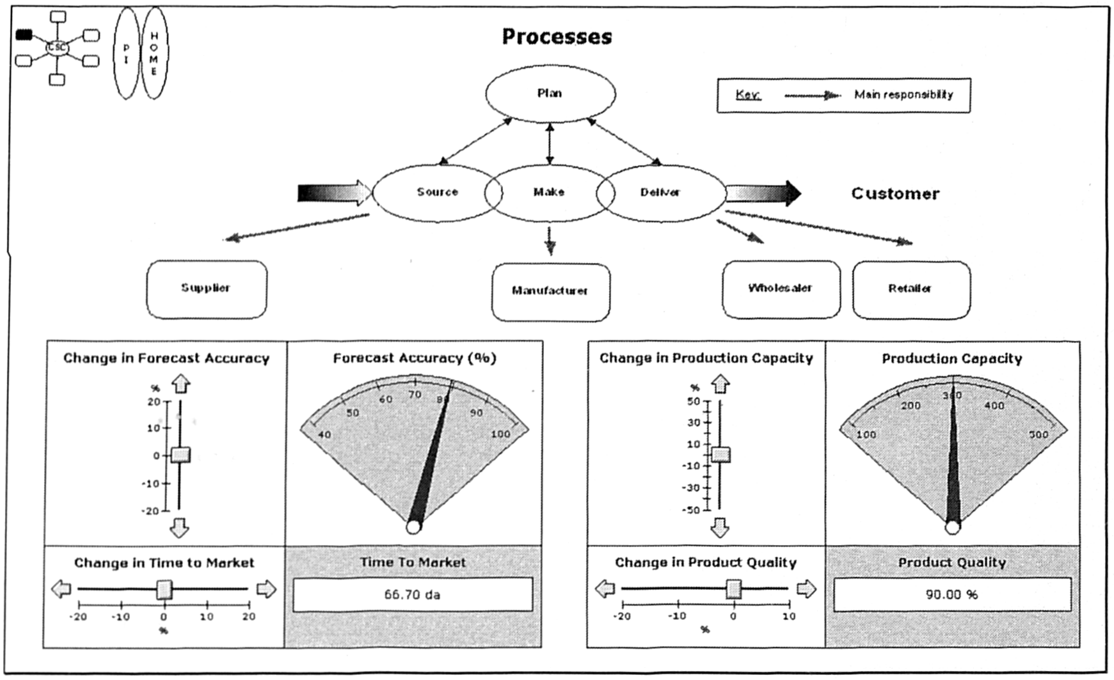


Figure 4.10: Process configuration dialog

Forecast Accuracy may be changed between 80% and 100%, Production Capacity may by varied by ± 50%. Also, Time to Market can be set within a range of ± 50%, and Product Quality can be chosen in a range form 70% to 100%.

4.2.2 Configuration of the Stock & Flow

Figure 4.11 shows the Collaborative Supply Chain Model in 'Stock & Flow' notation. The resulting map is divided into four geographical regions: Northwest (NW), Northeast (NE), Southeast (SE) and Southwest (SW). In the NW region the material flow through the collaborative supply chain begins with Raw material from Supplier, then Manufacturer Inventory to Wholesaler Inventory and finally to Retailer Inventory. The top left corner shows how Capacity Utilisation is influenced by Production Capacity and Production. The calculation of StockOuts is shown in the top right hand corner. The bottom half of NW demonstrates the influence of the choice of Stakeholders, the Level of Alignment and Forecast Accuracy on how demand is perceived in the form of Expected Demand. This also influences Information Delay and Time To Market.

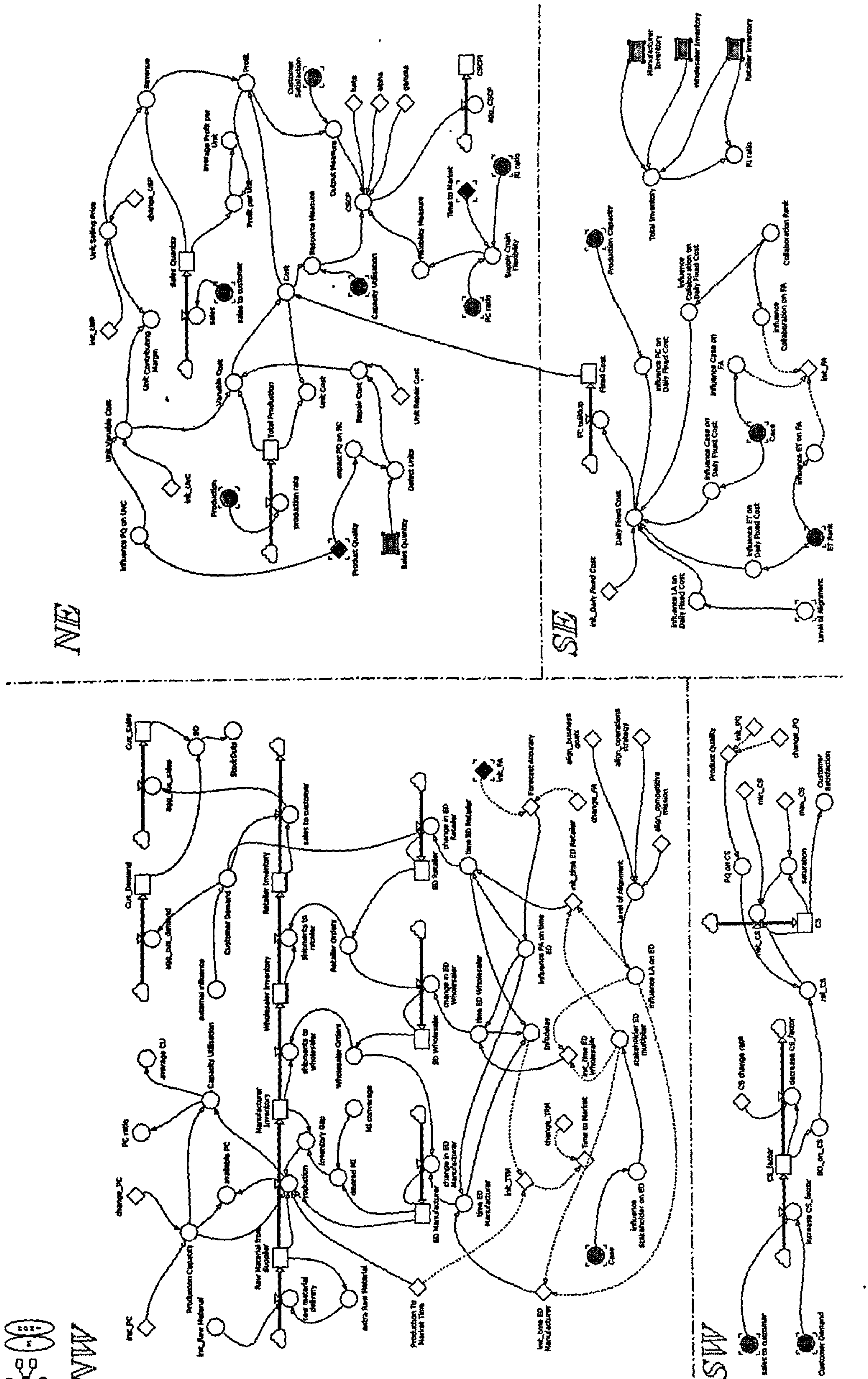


Figure 4.11: Collaborative Supply Chain Model

The top left of the NE region shows how Cost, Revenue and Profit are calculated. Revenue is determined from Sales Quantity and the Unit Selling Price. Cost is made up of Variable Cost and Fixed Cost, whereby Variable Cost is calculated from Total Production and Repair Cost. The bottom right of NE shows the Collaborative Supply Chain Performance Indicator together with Output Measure, Resource Measure and Flexibility Measure.

In the SE region the calculation of Fixed Cost is shown. Fixed Cost accumulates on a day-to-day basis and is affected by Level of Alignment, choice of Stakeholders, Collaboration, Production Capacity and the use of Enabling Technology. On the right hand side of SE the calculation of the Total Inventory is shown.

In the SW region it is shown how Customer Satisfaction is determined from Product Quality and StockOuts.

4.2.3 Simulation Run of the Performance Indicator

A Performance Indicator Simulation Run will produce a set of results, according to the settings set by each of the constituents. Figure 4.12 shows how the time graphs of important variables change throughout the simulation run. On the bottom part of the Performance Indicator Simulation Run, the final values of important variables are shown alongside the model constituent inputs and the CSCPI.

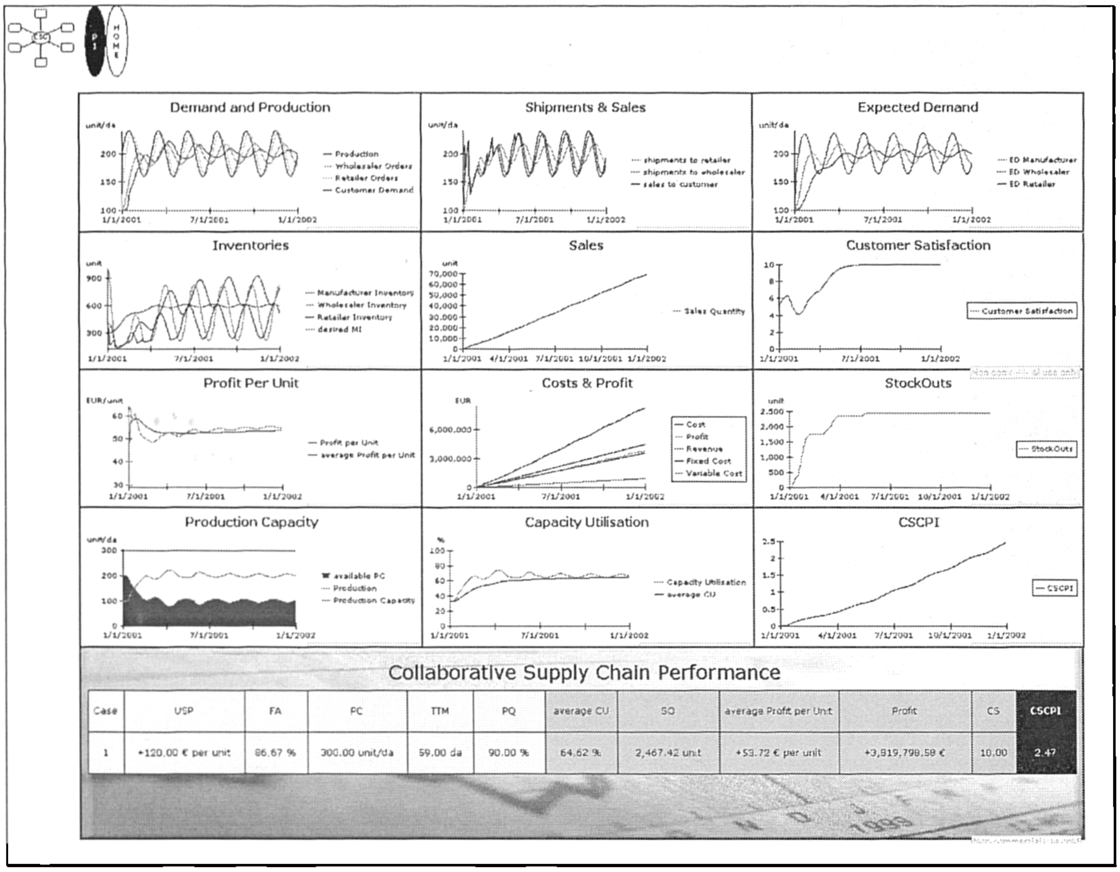


Figure 4.12: Performance Indicator Simulation Run

'Demand and Production' shows Customer Demand together with retailer and wholesaler orders and the resulting Production. Next to that, 'Shipments and Sales' to customer are shown. The 'Expected Demand' time graph allows assessment of the differences in the various stages of the collaborative supply chain. 'Inventories' shows Manufacturer, Wholesaler and Retailer Inventory in comparison to the desired Manufacturer Inventory. The graphs to the right of that show Sales Quantity and Customer Satisfaction. 'Profit Per Unit' illustrates some variation in Profit over time. 'Cost & Profit' demonstrates the change of financial variables with time, whereas the graph to the right of that shows the accumulation of 'StockOuts' over time. Under 'Production Capacity' and 'Capacity Utilisation' the under-utilisation of capacity is demonstrated. Finally, 'CPCPI' shows the Collaborative Supply Chain Performance Indicator based on the performance of the supply chain. The final results of important variables are also shown. The lightly shaded part of the table displays the variables that are set in the constituents' configuration dialogs. Alongside that are the average Capacity Utilisation, StockOuts, average Profit Per Unit, Profit and Customer Satisfaction. Collectively, the Performance Indicator Simulation Run shows how well the collaborative supply chain performed under the chosen settings.

A "what-if" simulation run can indicate what the performance of the Collaborative Supply Chain would be if certain variables that can be influenced through the constituents are changed. Hence, the performance could potentially be improved, perhaps not in the short run, unless the changes become effective immediately, but in the long run.

4.3 Summary

This chapter describes the implementation of both the collaborative supply chain model and the collaborative supply chain performance indicator in the DSE. The next chapter evaluates the configuration, population, and use of the DSE with case study material.

CHAPTER 5: EVALUATION OF THE APPLICATION OF THE DECISION SUPPORT ENVIRONMENT IN AN EXISTING SUPPLY CHAIN

"In model testing, the purpose is to increase our confidence in model accuracy as much as is dictated by the model intended uses."

(Osman Balci, 2002)

The whole process of model Verification and Validation Testing (VVT) (Balci 1998) verifies that the model is correct, and that the actual behaviour compares to the simulated behaviour (Sterman 2000), hence the model produces valid outcomes. During development, corrections to be made and areas for improvements are identified though formative evaluation, whereas at the end of development the model is assessed through summative evaluation. This chapter details the summative evaluation carried out on the DSE. The chapter is organised as follows: first, the VVT techniques to be used are presented. Next, an overview of the existing high tech supply chain used to configure the model is given alongside a summary of data acquired over a period of one year in order to populate the collaborative supply chain model. The implementation of the model is then verified against the principles on which it was developed (Siemer and Angelides 1998), followed by validation of the outcomes produced by the DSE.

5.1 IDENTIFYING VERIFICATION AND VALIDATION TESTING TECHNIQUES FOR EVALUATING THE DECISION SUPPORT ENVIRONMENT

Various testing techniques are available for model verification and validation testing (Balci *et al.* 2002, Balci 1998, Barlas 1996, Sterman 2000). VVT is an iterative process carried out continuously from start of model development to final model testing which in this case tests how the performance of the collaborative supply chain model is influenced by changes through any combination of the six constituents. In order to assess whether the DSE has been modelled and developed correctly, appropriate testing techniques need to be selected. The same techniques may be applied for both verification and validation testing (Balci 1998). Model verification testing deals with transformational accuracy, i.e. building the model right, whereas model validation testing deals with behavioural or representational accuracy, i.e. building the right model (Balci *et al.* 2002). In order for the model implementation to fulfil its purpose, it must show how changes in the six constituents affect the performance of the collaborative supply chain. Testing will attempt to answer four key questions, which are chosen in order to aid the assessment of the model implementation and the suitability of the model for the purpose. Questions one to three deal with model verification testing, question four deals with model validation testing. The questions will provide evidence as to whether or not "the model was built right and the right model was built", by addressing implementation issues as well as model behaviour reproduction issues.

1. Is the model implementation structurally consistent?
   This question addresses the consistency of the model built with the knowledge which has been acquired from the real supply chain. *Model Structure Assessment* tests whether the model structure, implementation of decision rules and level of aggregation is consistent with the findings from information and data analysis. This test is conducted in several ways. First, the conformance of the supply chain model to the knowledge of the real system is checked. Next, implemented decision rules are assessed to see if they match the approaches to decision-making in the existing supply chain. Finally, the results produced by a more detailed model are compared to those of the DSE to check whether or not model behaviour is changed significantly with respect to the model purpose.
2. Do model equations hold true under extreme variable values?

This question addresses the robustness of the model in extreme conditions. *Extreme Conditions Testing* verifies whether the model is as stable under extreme conditions as under normal conditions. Extreme condition tests may be performed in two main ways (Sterman 2000), either by inspection of model equations or by simulation. The first case examines if an equation produces a reasonable output when its variables approach or take on minimum and maximum values. In the second case, a simulation with test inputs is performed to find problems in model behaviour. For example, if the price for the product approaches infinity, the demand must approach zero.

3. Are the units of measurement used for model variables correct and consistent with each other?

   This question addresses the correctness and consistency of the units of measures used in order to unravel errors in the understanding of the structure of the real supply chain and the decision processes modelled. *Dimensional Consistency Testing* ensures that the model is correct with respect to the units of measurement used. Therefore, each equation is examined to ensure the correct use of units of measurement. Also, the consistent use of the same unit of measure for the same type of variables is verified. For example, if time is measured in days, then this unit of measurement must be used for the whole model.

4. Is the reproduction of system behaviour by the model as expected?

   This question serves as a basis for discussing if the model fulfils the purpose for which it was developed, i.e. if the right model was built. *Behaviour Reproduction Testing* assesses the qualitative and quantitative adequacy of the reproduction of system behaviour with respect to the model purpose. Furthermore, *Plausibility Checks* show if this behaviour is as expected. To assess the quality of behaviour reproduction, two approaches are commonly used. The first one is to plot graphs over each other and compare them whilst using *Plausibility Checks* to check if differences in the two curves are reasonable. The second approach uses statistical methods to perform a comparison between two data series. Commonly used methods are Correlation Coefficient (ρ) and Mean Absolute Percent Error (MAPE).

Testing Technique	Formative Evaluation		Summative Evaluation	
	Verification	Validation	Verification	Validation
Model Structure Assessment	✓		✓	
Extreme Conditions Testing			✓	
Dimensional Consistency Testing	✓		✓	
Behaviour Reproduction Testing		✓		✓
Plausibility Checks		✓		✓

Figure 5.1: Verification and Validation Testing of the Decision Support Environment

The next section describes the case study methodology used to collect data and process information.

5.2 MODELLING THE EXISTING SUPPLY CHAIN

The underlying question that motivates data and process information gathering is: "How is the performance of the collaborative supply chain influenced by changes in any of the six constituents?" A case study was conducted over a period of one year, hence the data is primary. The next section describes the methodology that was used to collect data.

5.2.1 Data Collection Methodology

This section describes the case study methodology used. The aim hereby is to gain an in-depth understanding of the collaborative supply chain and to collect sufficient data to enable the configuration and population of the DSE. Therefore, the case study uses multiple sources of information: documentation, interviews and historical data.

In order to gain an initial understanding of the collaborative supply chain, current process documentation and existing contractual agreements between the stakeholders were inspected. Thereafter, informal semi-structured interviews with line managers and other decision-makers were conducted. Discussions covered the input and output of the processes each manager is responsible for, data and information they use or produce, and the decision-making they undertake. The focus was on how decisions are taken based on the information available to the decision-makers and the format in which the data is presented.

The interviews were complemented with an investigation into the use and specification of information systems, so that the information obtained thought the interviews with the managers and decision-makers can be put into context with the availability and presentation of data through the information systems. In addition to that, a financial investigation into the costing structure of the collaborative supply chain provided a different viewpoint of supply chain operations. This approach helped to put together a comprehensive picture of the collaborative supply chain.

At the same time, historical data were collected from information systems in use. The data was put into a format which seemed appropriate for analysis with Microsoft ™ Excel. In addition, a system was set up to record current data of interest on an ongoing basis, in order to speed up the process of data collection and analysis. The process analysis and data collection reflects the current view and knowledge of the collaborative supply chain in the timeframe from January 2000 to December 2000.

The next section describes briefly the collaborative supply chain and results of the data analysis.

5.2.2 Data Analysis

The existing supply chain produces and delivers telecommunications end-user equipment in large quantities. The supply chain consists of one supplier, two manufacturers, one wholesaler and one retailer. The boundaries of the system are production start using raw materials on the upstream, and sales to customers on the downstream. The supply chain is upstream capacity-constrained with long production lead times and an increasingly dynamic market in combination with decreasing product life cycles. This puts pressure on time to market, product quality and supply chain flexibility. Supply chain operations are forecast-driven, while production starts are based on expected customer demand. This is due to the fact that the manufacturing process including shipments to the retailer takes around 60 to 70 days. Figure 5.2 shows the Sales figures for the time period from January 2000 to December 2000, the Production Starts and the average Production to Market Time (PTMT).

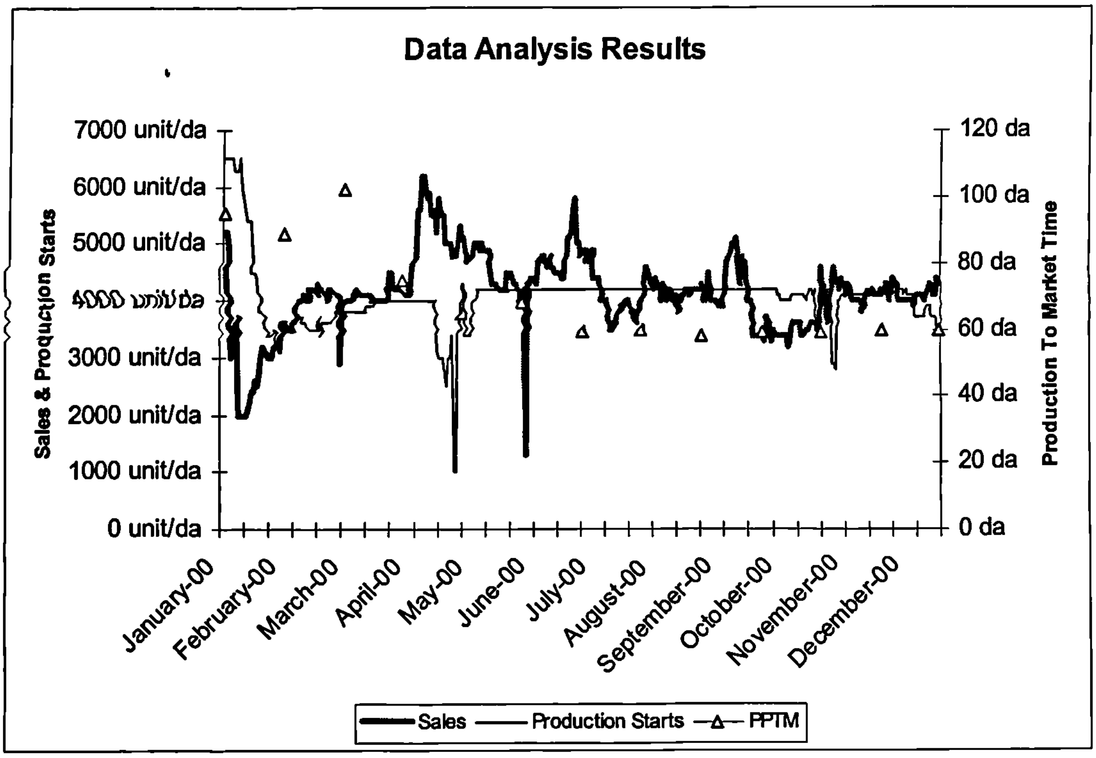


Figure 5.2: Sales, Production Starts and Production to Market Time

Based on information obtained from analysis of the supply chain, the six constituents are configured and the model is populated with real data. Scenario 1 models the current situation whereas scenarios 2 and 3 demonstrate the results from changes in variables and reconfiguration of constituents retrospectively.

5.2.3 Scenario 1: Existing Supply Chain Model

Figure 5.3 shows the variable settings for scenario 1. The supply chain consists of one supplier, two manufacturers, one wholesaler, and one retailer selling products to the customers, as shown in Figure 5.4.

USP	LA	FA	PTMT change	PC	PQ
€14	47%	77%	0%	4200 unit/da	90%

- There is no influence by the Unit Selling Price and Customer Satisfaction on Customer Demand

Figure 5.3: Scenario 1 Variable Settings

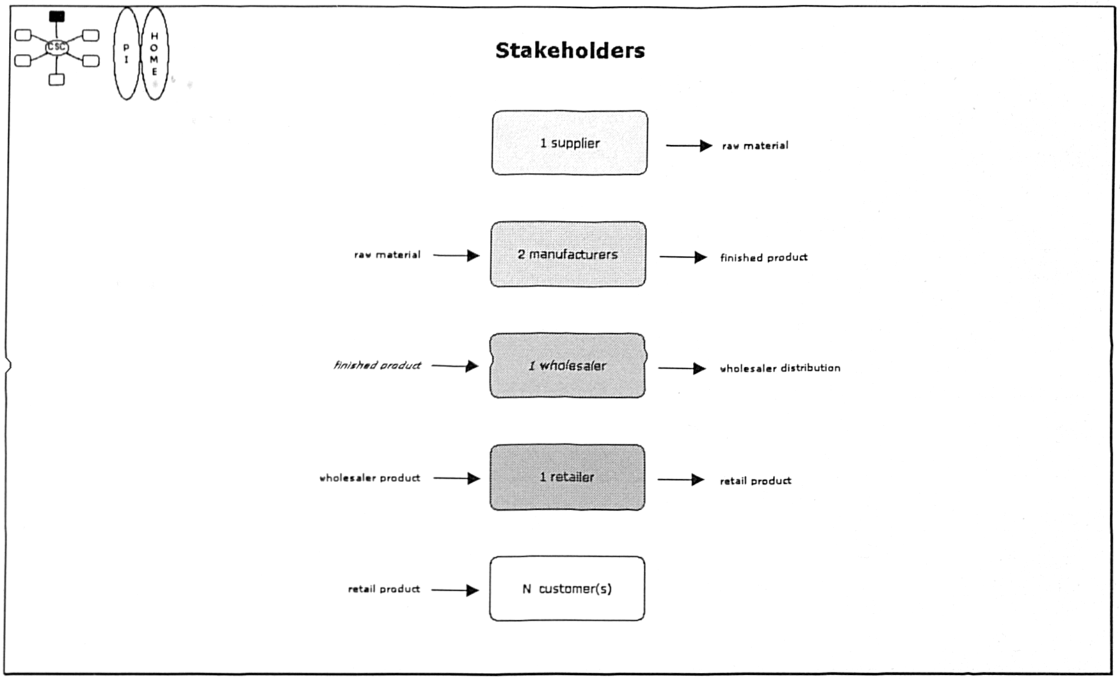


Figure 5.4: Scenario 1 Stakeholders

Figure 5.5 shows the topology with a divergent flow between supplier and manufacturers, a convergent flow between manufacturers and wholesalers and a single route flow between wholesaler and retailer. Levels of Collaboration in the supply chain are shown in Figure 5.6. Between the supplier and manufacturers collaboration is taking place at the operational and managerial level. For instance, at the operational level transportation scheduling is enhanced through exchange of stock level information, whereas at the managerial level monthly demand forecasts by the manufacturer help the supplier with demand planning. Manufacturers and wholesaler collaborate on the operational level through a stock replenishment system. In the same way the wholesalers and retailers collaborate to replenish retailer stocks.

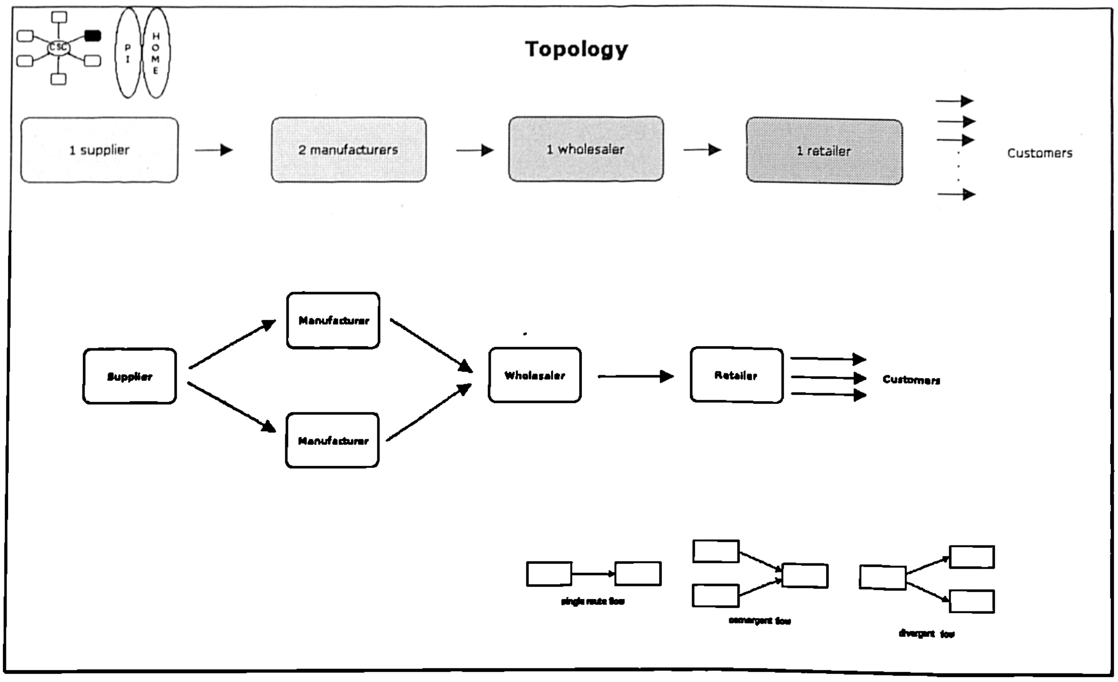


Figure 5.5: Scenario 1 Topology

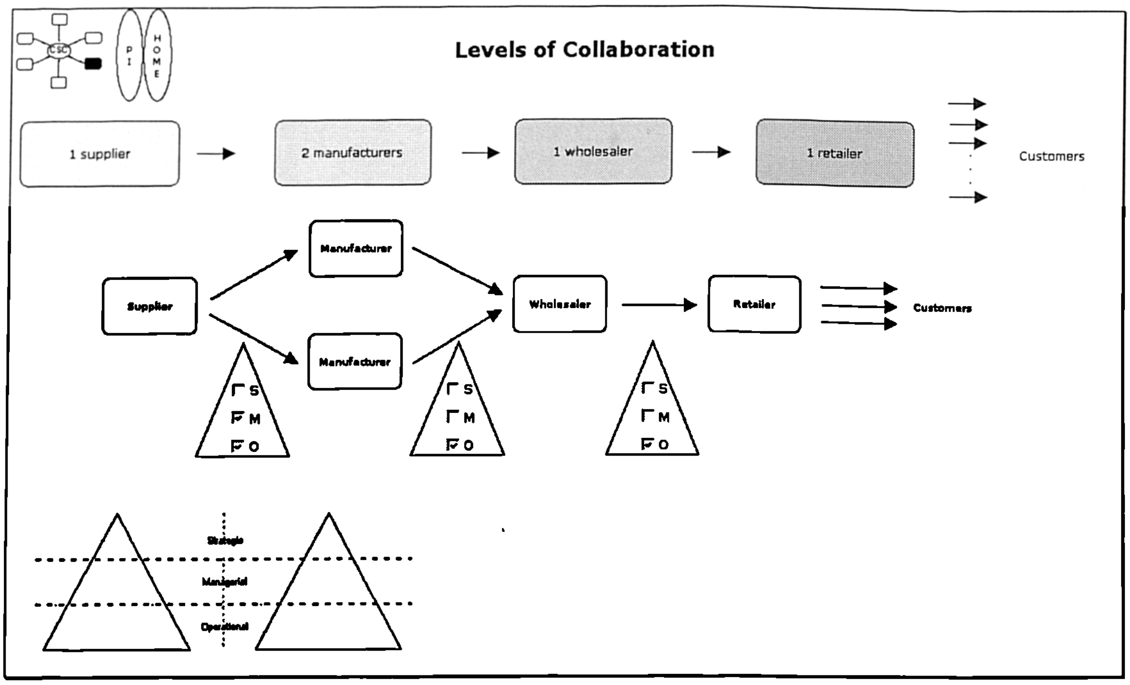


Figure 5.6: Scenario 1 Levels of Collaboration

Figure 5.7 describes the use of Enabling Technology within and between the stakeholders. Supplier and Wholesaler use TPS and MIS for their internal operations, whereas the Retailer only uses TPS to control incoming stock. On the other hand, the Manufacturers use TPS, MIS as well as EIS, which helps with their strategic planning. In between Supplier, Manufacturers and Wholesaler, TPS and MIS are used. Wholesaler and Retailer use TPS, which takes the form of an email communication between them to place and confirm orders.

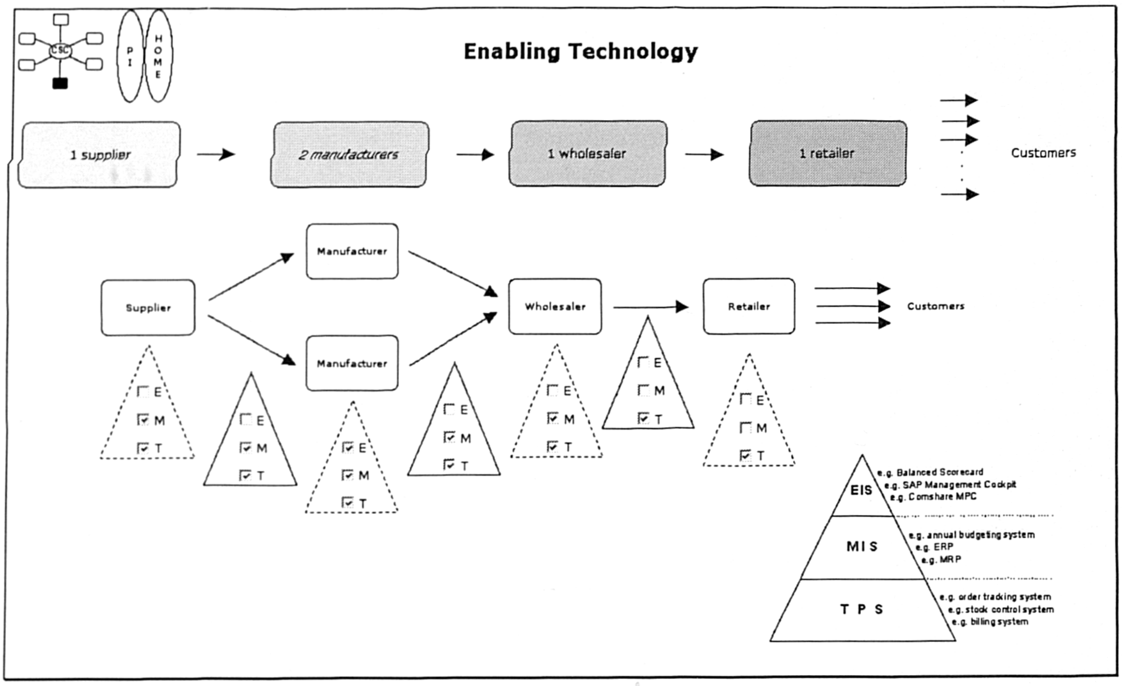


Figure 5.7: Scenario 1 Enabling Technology

Figure 5.8 and Figure 5.9 show the Collaborative Supply Chain Model after configuration and population based on the information and data as described. Figure 5.10 shows the Collaborative Supply Chain Model in 'Stock and Flow' notation.

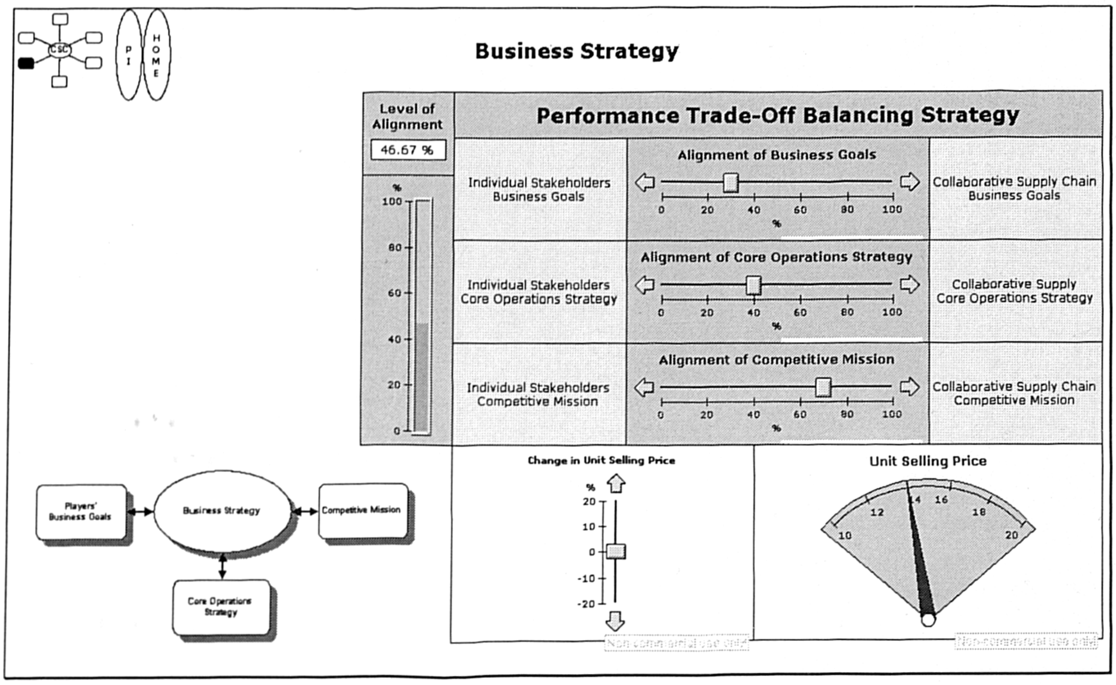


Figure 5.8: *Scenario 1 Business Strategy*

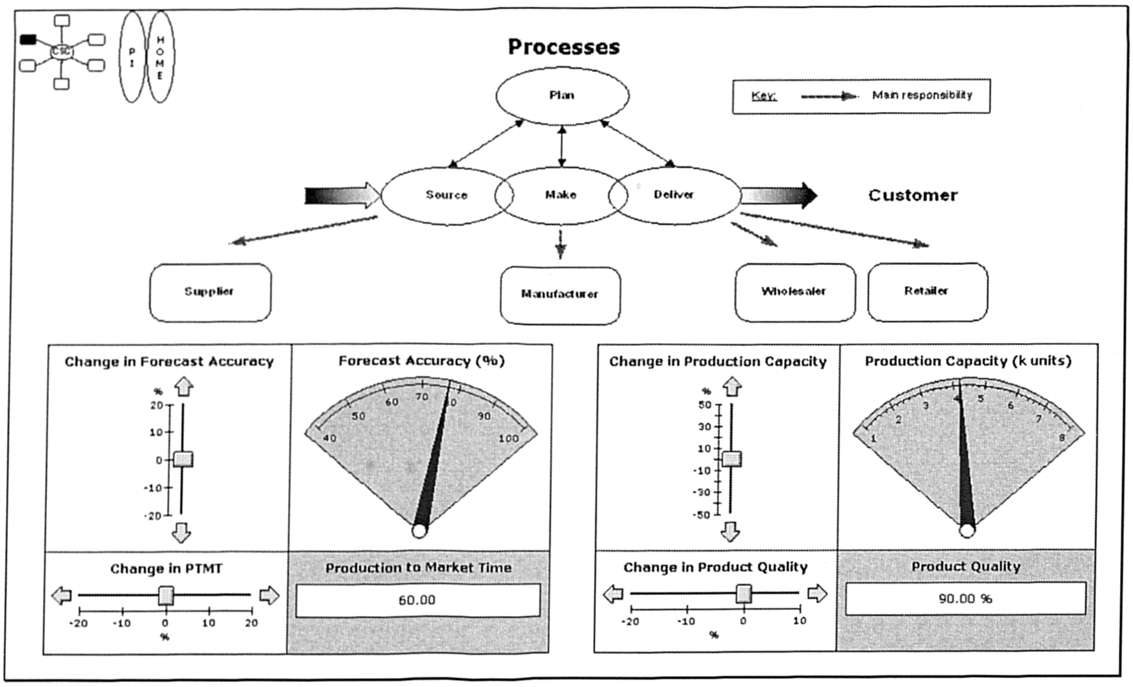


Figure 5.9: Scenario 1 Processes

This illustration is incomplete & is to be replaced. 6/08.

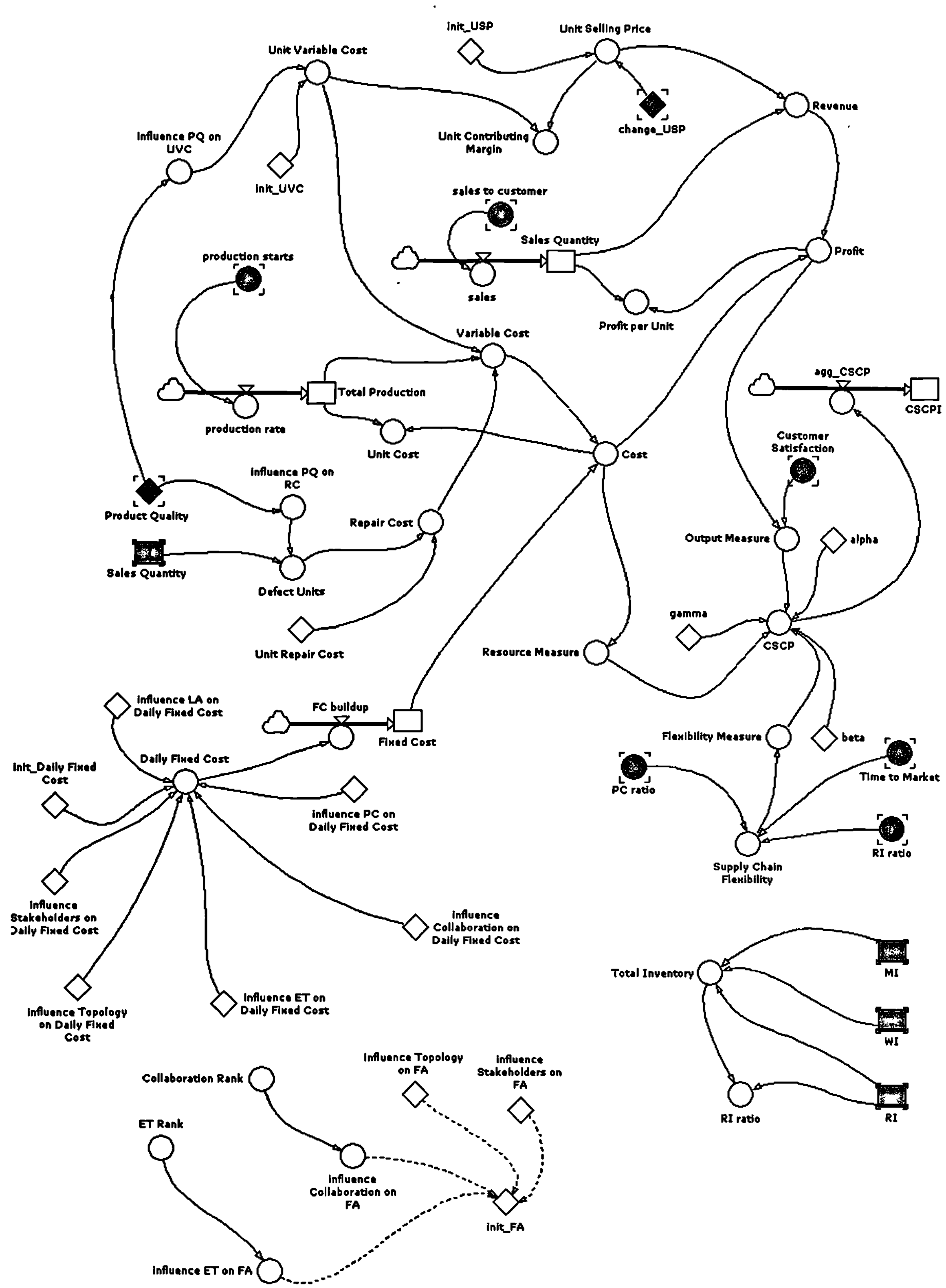
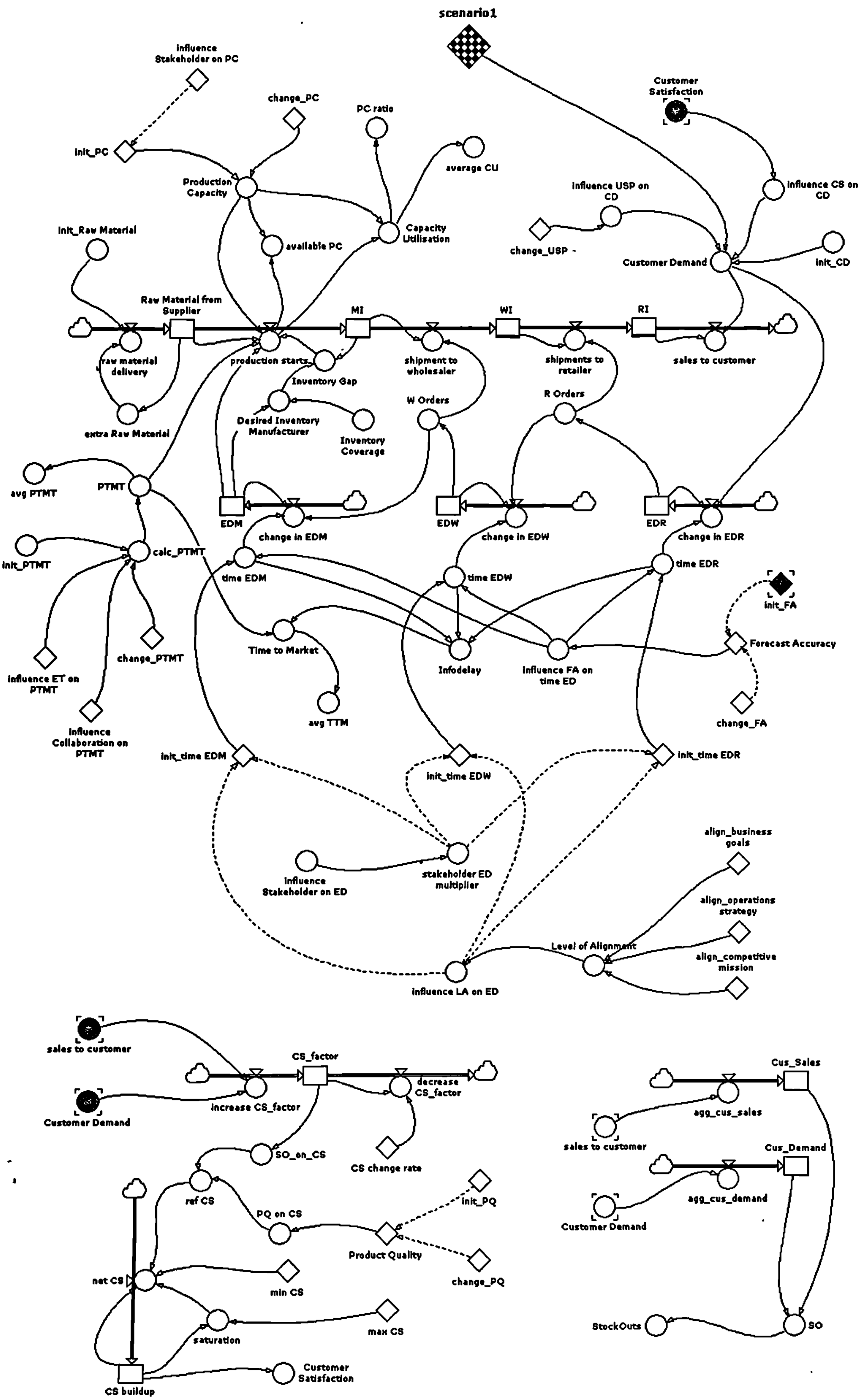


Figure 5.10: Scenario 1 Collaborative Supply Chain Model



scenario1
influence Stakeholder on PC
change_PC
PC ratio
init_PC
average CU
Customer Satisfaction
Production Capacity
influence USP on CD
influence CS on CD
Capacity Utilisation
init_Raw Material
available PC
change_USP
Customer Demand
init_CD
Raw Material from Supplier
MI
WI
RI
raw material delivery
production starts
shipment to wholesaler
shipments to retailer
sales to customer
Inventory Gap
W Orders
R Orders
Desired Inventory Manufacturer
Inventory Coverage
extra Raw Material
avg PTMT
PTMT
EDM
EDW
EDR
change in EDM
change in EDW
change in EDR
init_PTMT
calc_PTMT
time EDM
time EDW
time EDR
init_FA
Forecast Accuracy
Time to Market
Infodelay
influence FA on time ED
influence ET on PTMT
change_PTMT
avg TTM
change_FA
influence Collaboration on PTMT
init_time EDM
init_time EDW
init_time EDR
align_business goals
influence Stakeholder on ED
stakeholder ED multiplier
align_operations strategy
Level of Alignment
align_competitive mission
influence LA on ED
sales to customer
CS_factor
Customer Demand
increase CS_factor
decrease CS_factor
Cus_Sales
agg_cus_sales
sales to customer
SO_on_CS
CS change rate
Cus_Demand
ref CS
init_PQ
agg_cus_demand
PQ on CS
Customer Demand
Product Quality
change_PQ
net CS
min CS
max CS
StockOuts
SO
saturation
CS buildup
Customer Satisfaction

Figure 5.11 shows the results of the performance indicator simulation run. Some of the production start figures produced by the model might be slightly different to the original data. This is due to the fact that the process for arriving at production starts does not necessarily incorporate all the fine tuning done in the DSE.

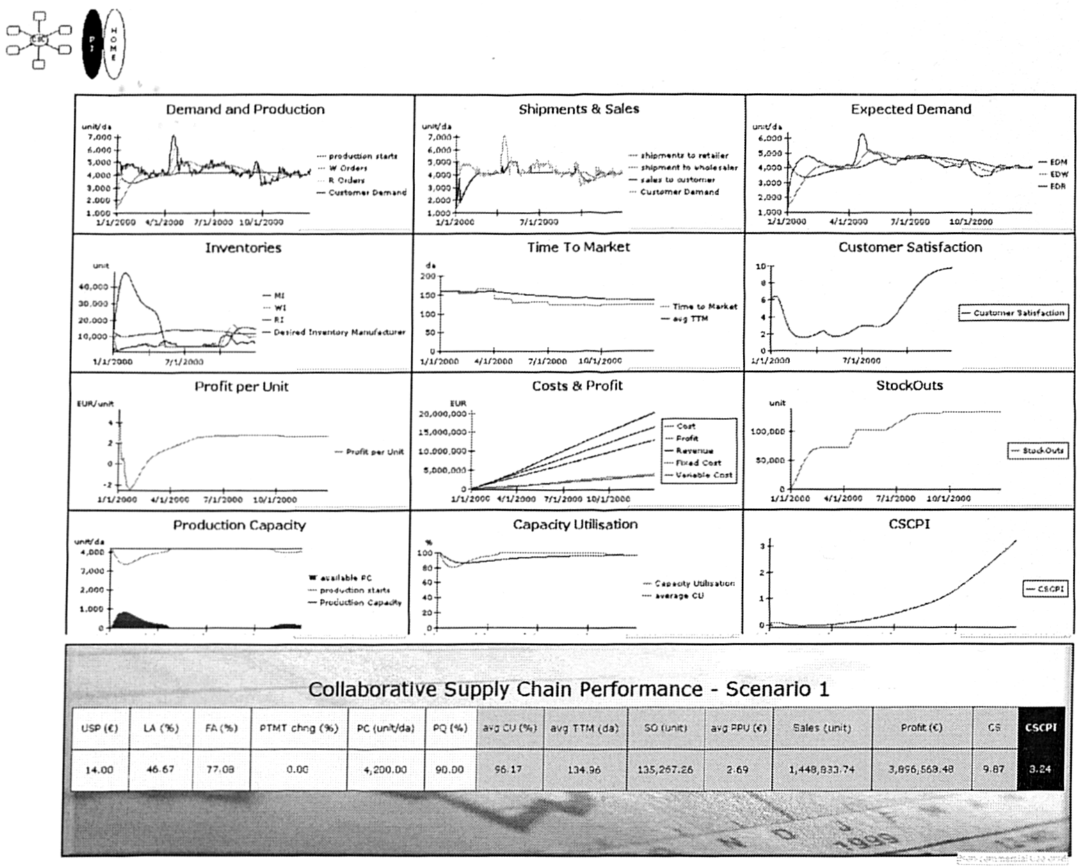


Figure 5.11: Scenario 1 Performance Indicator Simulation Run

In the following two sections, which describe scenarios 2 and 3, only those figures in which changes have been made will be shown. Based on what-if questions, the constituents are changed accordingly. This allows an assessment of the impacts of changes on the collaborative supply chain performance in a risk free environment prior to actual implementation.

5.2.4 Scenario 2: Retaining Infrastructure, Modifying Variables

Figure 5.12 gives an overview of variable settings for scenario 2. Figure 5.13 shows the Levels of Collaboration. In contrast to the current situation, there is now collaboration at the managerial and the strategic level between Manufacturers and Wholesaler and also between Wholesaler and Retailer.

USP	LA	FA	PTMT change	PC	PQ
€14	47%	83%	0%	4620 unit/da	95%

- No Changes in Stakeholders and Topology.
- Changes in Levels of Collaboration and Enabling Technology.
- There is an influence by the Unit Selling Price and Customer Satisfaction on Customer Demand

Figure 5.12: Scenario 2 Variable Settings

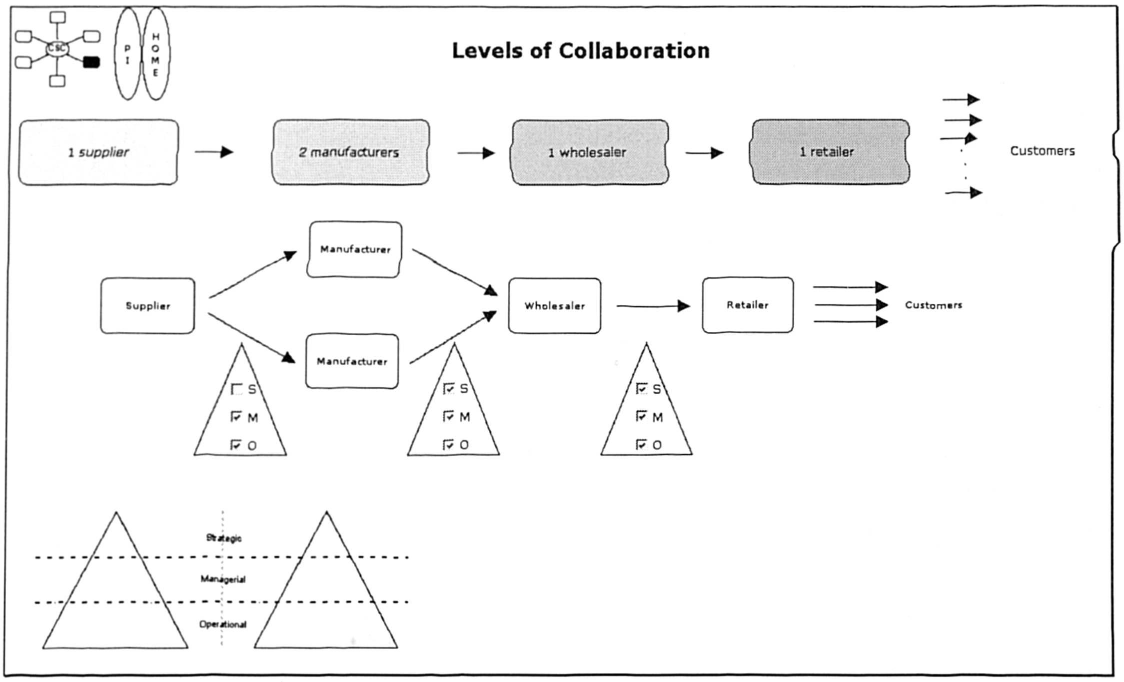


Figure 5.13: Scenario 2 Levels of Collaboration

Figure 5.14 displays the use of Enabling Technology within and between stakeholders. There were two changes to the current situation: The Retailer uses MIS in addition to TPS, and MIS are introduced between Wholesaler and Retailer.

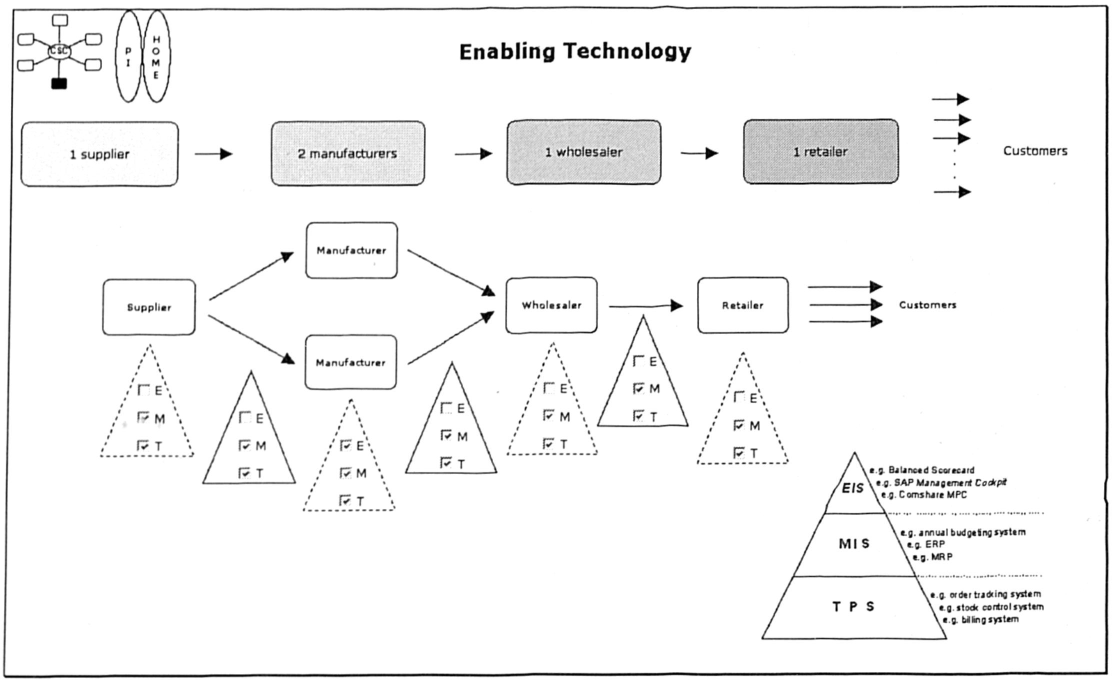


Figure 5.14: Scenario 2 Enabling Technology

In scenario 2 Forecast Accuracy is 83%, the Production Capacity is 4620 units/da and Product Quality is increased to 95%, as in Figure 5.15.

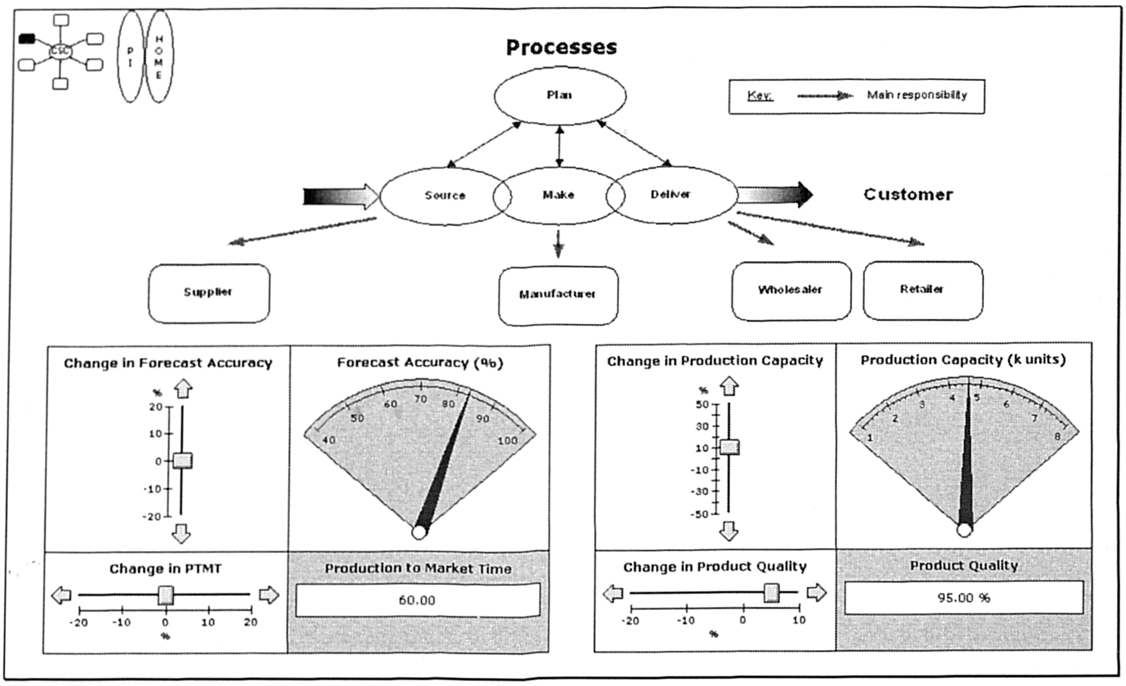


Figure 5.15: Scenario 2 Processes

The results of the performance indicator simulation run for scenario 2 are shown in Figure 5.16. The CSCPI rose to 6.72. Although the average Capacity Utilisation went down to 93%, Profit and Sales went up. This is due to less StockOuts and increased Customer Satisfaction.

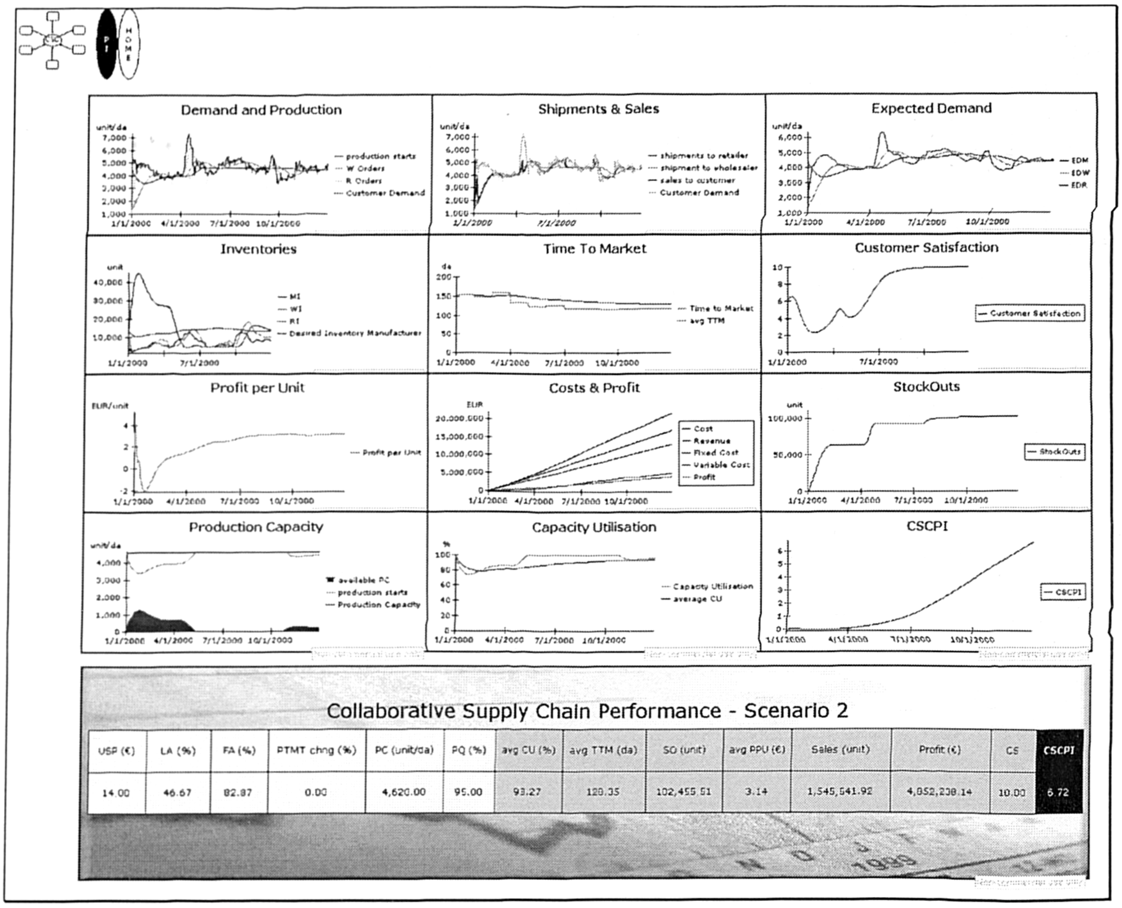


Figure 5.16: Scenario 2 Performance Indicator Simulation Run

5.2.5 Scenario 3: Modifying Infrastructure, Modifying Variables

Figure 5.17 shows the variable settings for scenario 3 alongside with a short description of the infrastructure settings. In scenario 3 an additional retailer is added, hence Stakeholders and Topology change. This does not result to a change to the other constituents. Figure 5.18 shows the stakeholder configuration for scenario 3.

USP	LA	FA	PTMT change	PC	PQ
€14	47%	81%	0%	4200 unit/da	90%

- Increase in number of Stakeholders to two retailers and change Topology between Wholesaler and two Retailers to divergent flow
- There is an influence by the Unit Selling Price and Customer Satisfaction on Customer Demand

Figure 5.17: Scenario 3 Variable Settings

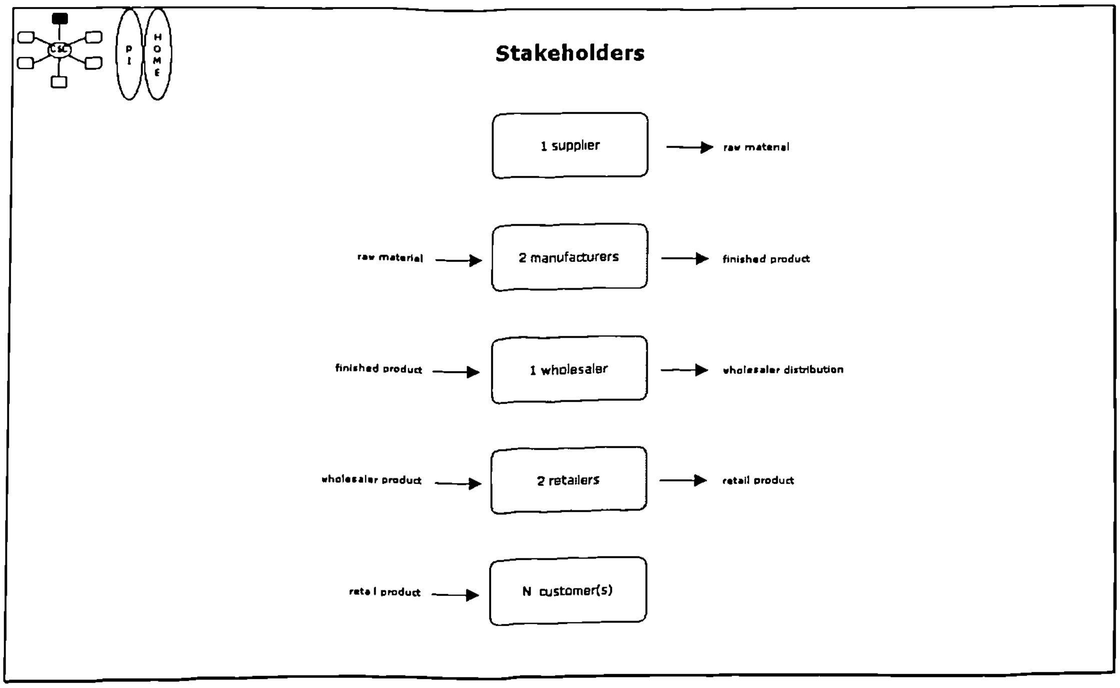


Figure 5.18: Scenario 3 Stakeholders

Figure 5.19 shows the scenario 3 Topology, with a divergent flow between wholesaler and retailers. Forecast Accuracy is not influenced by the Process constituent, but increases due to the fact that there is an additional retailer. In this case more data on customer demand leads to a better Forecast Accuracy because of the increased sample size. Figure 5.20 shows a Forecast Accuracy of 81%, whilst there is no additional influence on Forecast Accuracy. Hence the change on Forecast Accuracy remains at 0%

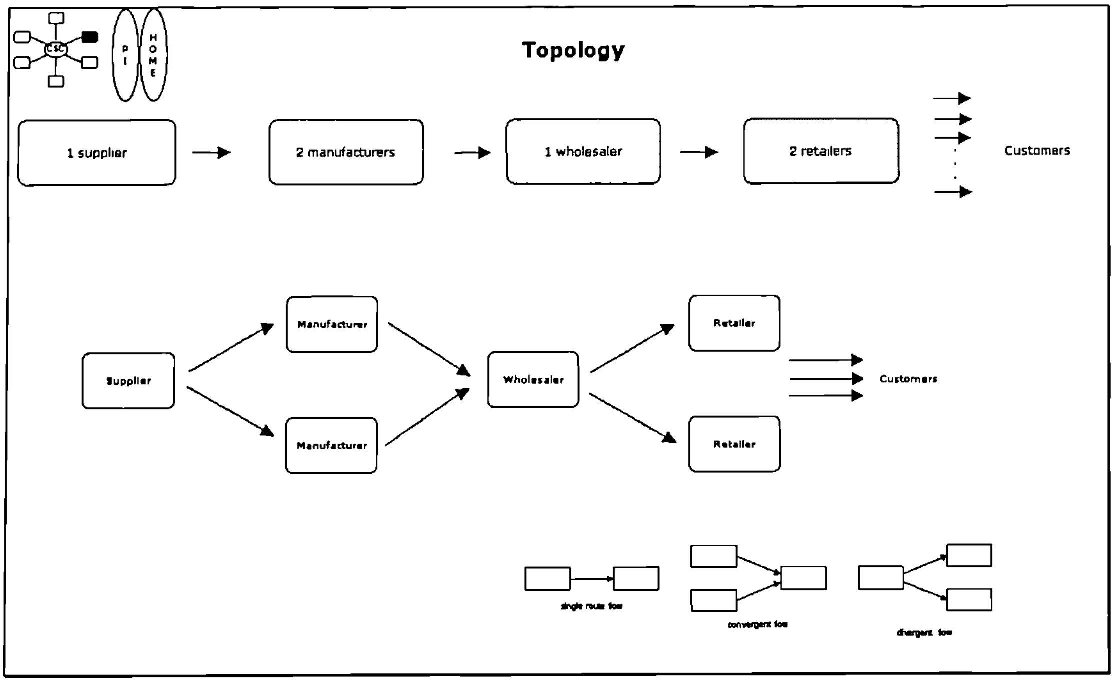


Figure 5.19: Scenario 3 Topology

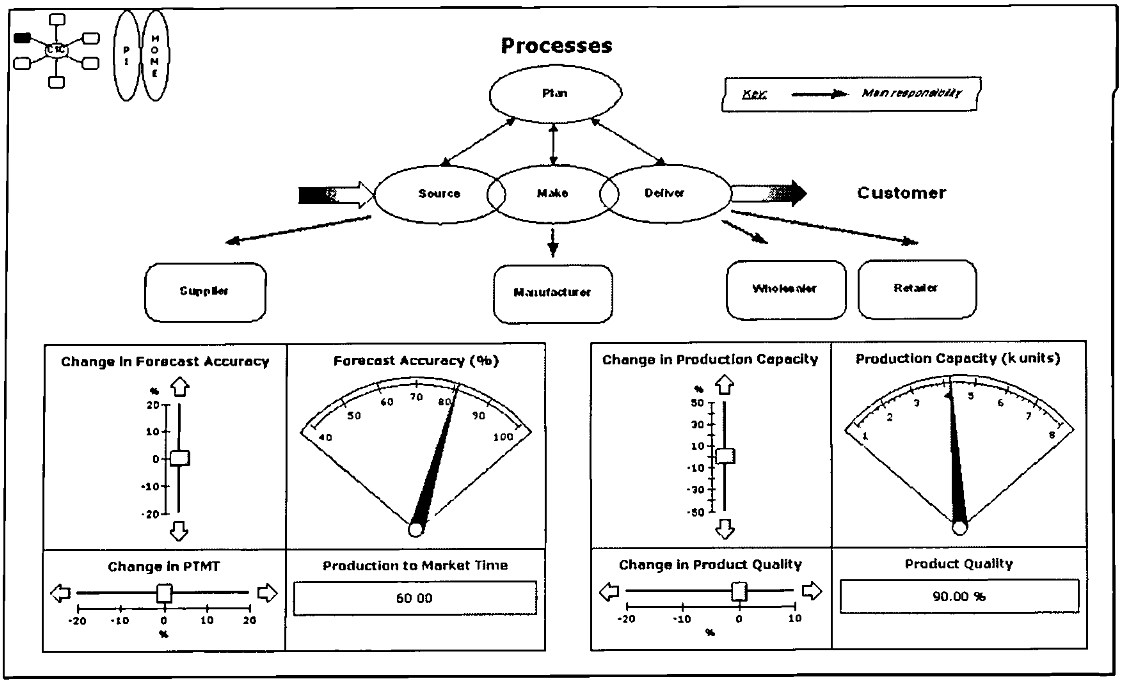
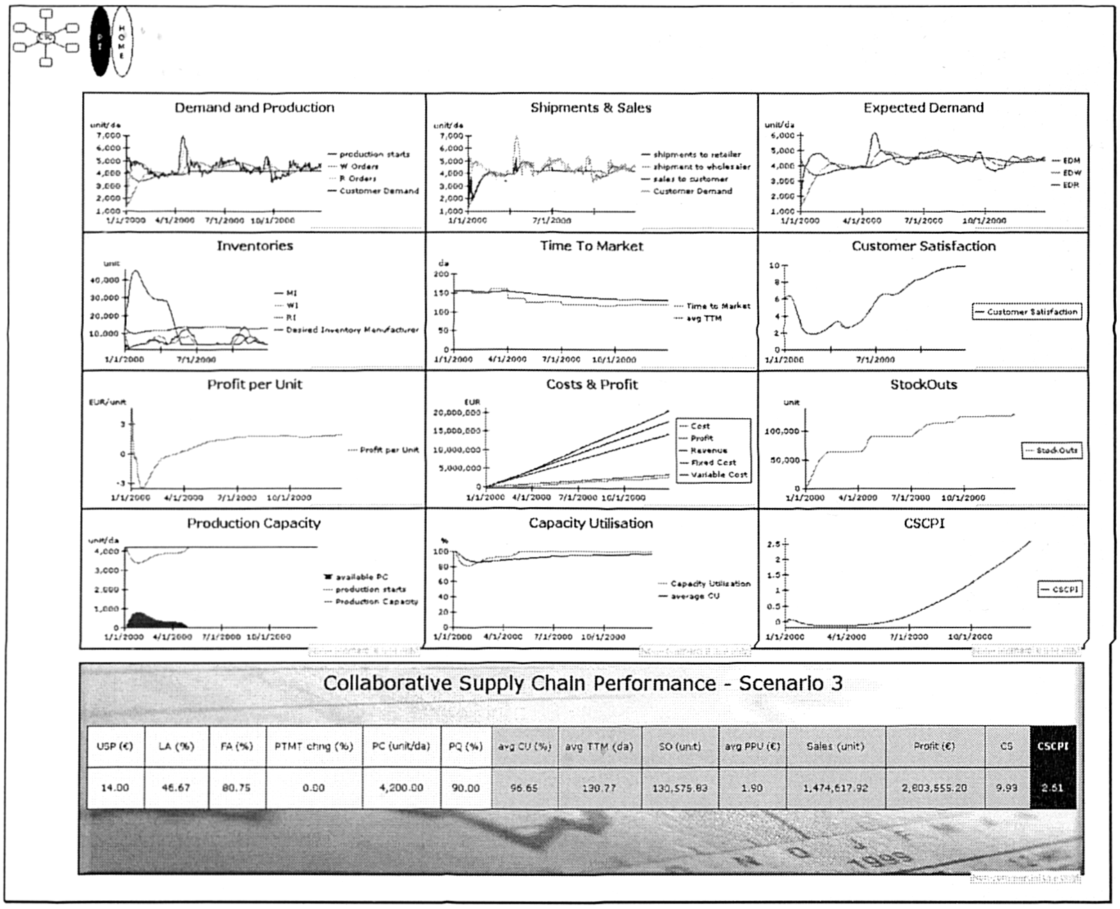


Figure 5.20: Scenario 3 Processes

Figure 5.21 shows the time graphs and final variable values of the performance indicator simulation run for scenario 3. The average Capacity Utilisation is 97%, Stockouts went down due to the increased Forecast Accuracy of 81%. Sales figures remain almost the same, but despite that the CPSI decreased to 2.61. The reason for that is that there is no real need for an additional retailer. Thus, due to increased costs, the profit decreased whilst sales stayed at comparatively the same level.



USP (€)	LA (%)	FA (%)	PTMT chng (%)	PC (unit/da)	PQ (%)	avg CU (%)	avg TTM (da)	SO (unit)	avg PPU (€)	Sales (unit)	Profit (€)	CS	CSCPI
14.00	46.67	80.75	0.00	4,200.00	90.00	96.65	130.77	130,575.83	1.90	1,474,617.92	2,803,555.20	9.93	2.61

Figure 5.21: Scenario 3 Performance Indicator Simulation Run

The next section presents the verification testing of the DSE based on the implementation and simulation runs of the three scenarios.

5.3 VERIFICATION TESTING OF THE DECISION SUPPORT ENVIRONMENT

The purpose of this kind of evaluation is to assess whether the DSE has been modelled and developed correctly. Three types of testing techniques are employed to verify the DSE: Model Structure Assessment, Extreme Condition Testing, and Dimensional Consistency Testing.

5.3.1 Model Structure Assessment

Model structure assessment is accomplished through conformance testing, decision rule inspection and the assessment of the level of aggregation. To carry out conformance testing, the model was presented to the group of line managers who verified that its level of representation of reality is acceptable. In particular, the physical flow of goods through the supply chain and the costing structure which has been set up is confirmed to be operationally acceptable. To carry out decision rule inspection, the original decision making rules acquired in interviews with line managers during the case study are converted into decision diagrams. Then both the original decision making rule and the decision making formula developed for the DSE are compared and data from the case study is filtered through each and both the intermediate and final results are evaluated. All decision rules were tested in a similar fashion. For instance, Production Starts (PS) is defined as a function of Raw Material (RMat), Production Capacity, Expected Demand Manufacturer (EDM), current Manufacturer Inventory, desired Manufacturer Inventory (DMI), desired Inventory Coverage (IC) and Inventory Gap (IG). Equation (5.1) shows the decision making formula for Production Starts as it is implemented in the DSE, whereas Figure 5.22 illustrates the decision diagram for production starts developed from the information obtained during the case study.

$$PS = MIN((IF(RMat > (EDM + IG), (EDM + IG), RMat)), PC) \tag{5.1}$$

where

$$IG = DMI - MI = EDM * IC - MI \tag{5.2}$$

If Equation (5.1) is converted into a decision diagram the result will be identical to that in Figure 5.22.

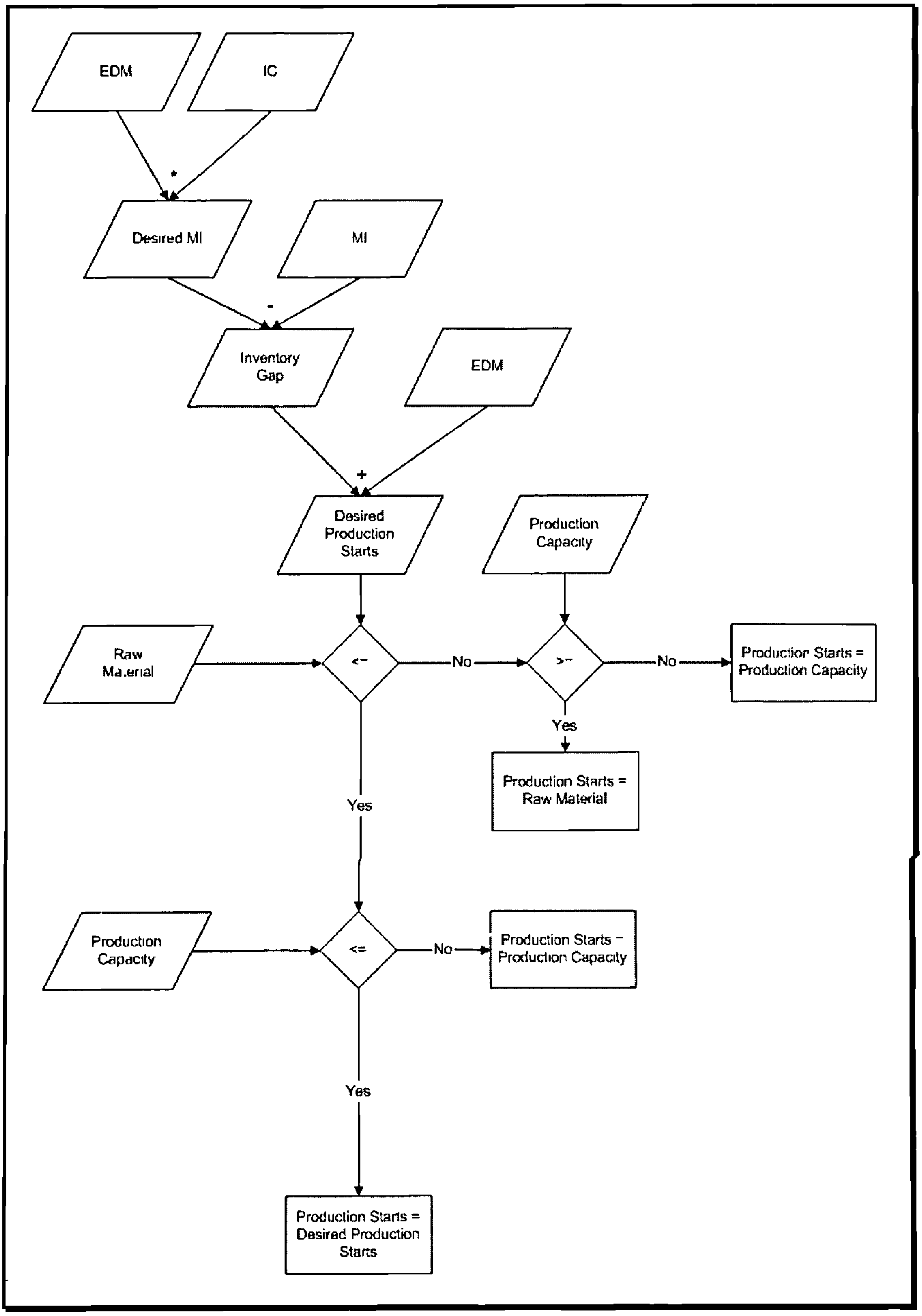


Figure 5.22: Decision Diagram for Production Starts

A comparison between the decision trees developed from the case study and the decision formulas implemented in the DSE confirms either an absolute or a close match.

To test the level of aggregation of the model, a more detailed model is produced and the results from the simulation run of this are compared to those produced by the DSE in order to check whether or not model behaviour does change with a more detailed model. In the DSE, the number of goods already in the chain at production start and the goods still in the supply chain at the end of a simulation run are insignificant, although in the detailed model the model structure is extended to include the initial total inventory and delta inventory, which is the difference between the total initial inventory and the total inventory. The changes in model structure are pointed out in Figure 5.23. Variables that have been added are indicated by black and white shading.

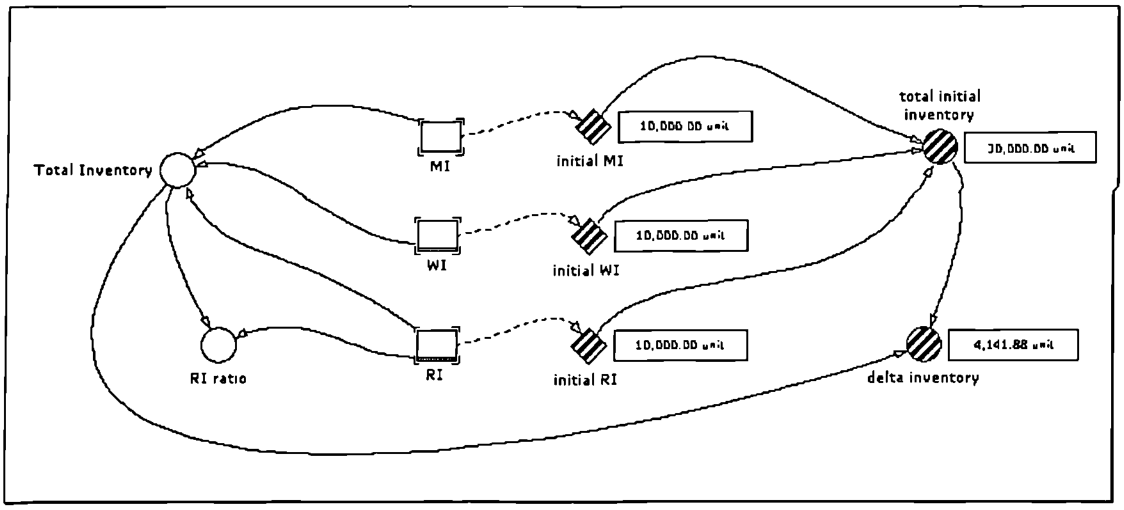


Figure 5.23: Extended Model Structure

Tests show that the delta inventory fluctuates between 1% and 2.5% of total Sales. This is deemed insignificant hence the level of aggregation chosen for the DSE is adequate.

5.3.2 Extreme Condition Testing

Extreme condition testing can be performed by either setting the variables of an equation to extreme values or through simulation. With the former, for example, shipments from the Wholesaler to the Retailer are defined by

$$Shipments = MIN(Retailer\ Orders, Wholesaler\ Inventory) \tag{5.3}$$

Extreme Condition Testing ensures that there will be no shipments when the Wholesaler Inventory reaches zero, and, therefore, the Wholesaler inventory will never go below zero, no matter how large the Retailer Orders become. All DSE equations are similarly tested to ensure that the results are as expected even when variables approach extreme values.

Using simulation, for instance, as shown in Figure 5.24, the Product Quality is varied between the minimum of 70% and the maximum of 100% and the final variable values are calculated. All variables stay within the expected limits and no 'out-of-range' errors occur.

USP (€)	LA (%)	FA (%)	PTMT chng (%)	PC (unit/da)	PQ (%)	avg CU (%)	avg TTM (da)	SO (unit)	avg PPU (€)	Sales (unit)	Profit (€)	CS	CSCPI
14.00	46.67	82.87	0.00	4,200.00	70.00	94.05	128.35	82,768.92	2.78	1,398,657.46	3,887,231.39	2.91	1.28

USP (€)	LA (%)	FA (%)	PTMT chng (%)	PC (unit/da)	PQ (%)	avg CU (%)	avg TTM (da)	SO (unit)	avg PPU (€)	Sales (unit)	Profit (€)	CS	CSCPI
14.00	46.67	82.87	0.00	4,200.00	90.00	96.82	128.35	131,086.52	2.89	1,477,097.50	4,268,359.68	9.93	5.01

USP (€)	LA (%)	FA (%)	PTMT chng (%)	PC (unit/da)	PQ (%)	avg CU (%)	avg TTM (da)	SO (unit)	avg PPU (€)	Sales (unit)	Profit (€)	CS	CSCPI
14.00	46.67	82.87	0.00	4,200.00	100.00	97.08	128.35	169,491.56	2.70	1,481,110.11	3,998,673.44	9.99	5.50

Figure 5.24: Extreme Condition Testing with Product Quality

Testing all variables likewise confirms that the DSE equations are robust and the DSE behaves rationally when exposed to extreme variable values.

5.3.3 Dimensional Consistency Testing

Dimensional consistency testing is carried out in two ways: First, every equation in the DSE is examined for the correct use of units of measurement. For example, $R = USP * SQ$ uses the following units of measurement: $R:[€]$, $USP:[€/unit]$, and $SQ:[unit]$. Hence the test is carried out by inserting the units into the equations:

$$R = USP * SQ \quad \rightarrow \quad [€] = [€/unit]*[unit] \tag{5.4}$$

Equation (5.4) shows that the units of measurement are used correctly, since the left hand side of the equation equals the right hand side. Secondly, unit consistency is assessed. Therefore, all variables of the same type are checked for the use of the same unit of measure. For instance, the unit of measure for the goods produced is [unit], hence Inventories, StockOuts, Total Production and Sales Quantity are confirmed to be measured in [unit]. On the other hand, Demand, Shipments and Production Capacity are measured in [unit/da]. All financial variables such as Cost, Revenue and Profit are checked to be measured in [€]. Dimensional consistency testing on the DSE is complete after all equations are checked and unit consistency is confirmed.

The next section presents the validation testing of the DSE based on the implementation and simulation runs of the three scenarios.

5.4 Validation Testing of the Decision Support Environment

Validation Testing assesses the behavioural accuracy. Behaviour Reproduction Testing and Plausibility Checks are used to determine if the right model was built for the set purpose.

5.4.1 Behaviour Reproduction Testing

Two approaches are used to assess whether the simulated behaviour is close enough to the real behaviour. First, real and simulated behaviour are plotted onto one graph to display differences. Then the statistical tests of the Correlation Coefficient and Mean Absolute Percent Error are carried out.

The Correlation Coefficient is defined as:

$$\rho = \frac{1}{n}\sum \frac{(X_h - \bar{X}_h) * (X_s - \bar{X}_s)}{\sigma_h \; * \; \sigma_s} \tag{5.5}$$

where

$$\bar{X} = \frac{1}{n} X \tag{5.6}$$

$$\sigma = \sqrt{\frac{1}{n}\sum (X - \bar{X})^2} \tag{5.7}$$

X is the data series, subscript h and s denote historical and simulated data respectively.

ρ measures how well a historical data series and a simulated data series match and has a range of $-1 \leq \rho \leq 1$. If there is no relationship between the historical and simulated values, then $\rho = 0$. $\rho = -1$ and $\rho = 1$ denote perfect inverse correlation and perfect correlation respectively.

MAPE gives the mean absolute error as a percentage of the mean and, therefore, is easier to interpret than the mean absolute error. MAPE is defined as:

$$MAPE = \frac{1}{n}\sum \frac{|X_s - X_h|}{X_h} \tag{5.8}$$

MAPE measures the deviation of the simulated data from historical data, thus the lower the MAPE, the more accurate the reproduction of data is.

Figure 5.25 shows historical Production Starts and simulated Production Starts plotted onto one graph. The DSE in the default setting works with a maximum production capacity of 4200 unit/da, therefore the simulated Production Starts never exceeds that value. After an initial time span the simulated data series closely approaches historical data. Exceptions are drops to 1000 unit/da in May and 2900 unit/da in November and those are due to random manufacturing problems and, therefore, are not reflected in the decision rules implemented in the DSE. According to Sterman (2000), a model should not be considered faulty if it does not reproduce the random component of a data series. Hence, the visual inspection of the graphs in Figure 5.25 shows that the behaviour of the simulated data series matches closely that of the real data series.

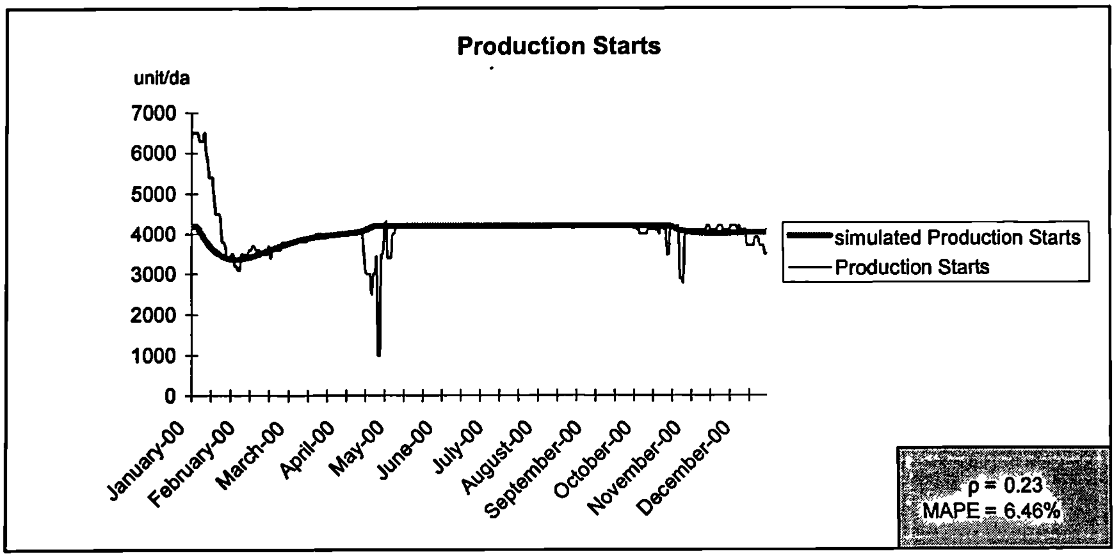


Figure 5.25: Historical vs. Simulated Production Starts time series

The Correlation Coefficient of 0.23 suggests that, although there are strong deviations between historical and simulated behaviour, this is due to randomness resulting from uncertainty. On the other hand, a MAPE of 6.46% indicates that the differences of historical and simulated data overall are relatively low.

Figure 5.26 shows historical and simulates sales time series on one graph. Extreme swings in sales in April, June and July are not replicated by the decision rules implemented in the DSE. Still, the overall time behaviour of sales is adequately represented in the simulated data series.

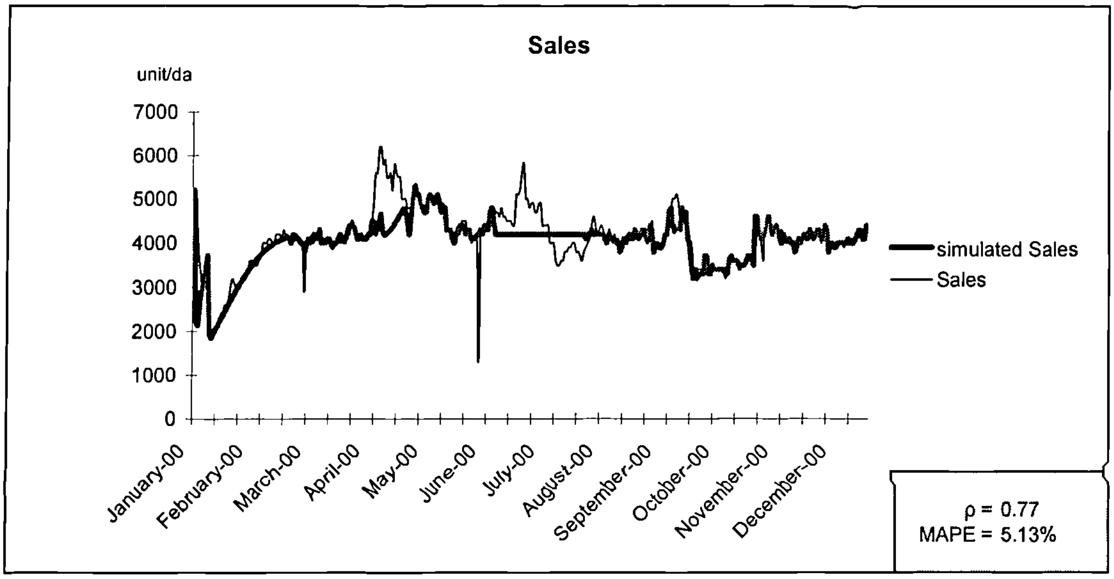


Figure 5.26: Historical vs. Simulated Sales time series

The Correlation Coefficient of 0.77 and the MAPE of 5.13% show that the simulated data series matches closely the real data series.

5.4.2 Plausibility Checks

A structured developer-driven approach is chosen to carry out Plausibility Checks. The purpose hereby is twofold: the first aim is to test the effect changes in variables have on the final variable values and the Collaborative Supply Chain Performance indicator; the second aim is to check whether the changes are reasonably acceptable to line managers. Figure 5.27 gives a summary of the final variable results and the CSCPI in 4 tests. Case one shows the current settings, cases two and three display the results of changing USP to -20% and then to +20% respectively. Cases 4 and 5 show the final variable values when PQ is set to 70% and 95%.

	USP (€)	LA (%)	FA (%)	PTMT chng (%)	PC (unit/da)	PQ (%)	avg CU (%)	avg TTM (da)	SO (unit)	avg PPU (€)	Sales (unit)	Profit (€)	CS	CSCPI
1	14.00	46.67	82.87	0.00	4,200.00	90.00	96.82	128.35	131,024.87	2.89	1,477,078.09	4,268,134.19	9.93	5.01
2	11.20	46.67	82.87	0.00	4,200.00	90.00	99.21	128.35	695,130.03	0.30	1,513,304.97	451,715.85	1.00	0.03
3	16.80	46.67	82.87	0.00	4,200.00	90.00	67.15	128.35	37,009.28	0.62	948,400.91	591,472.71	10.00	0.69
4	14.00	46.67	82.87	0.00	4,200.00	70.00	94.05	128.35	82,744.55	2.78	1,398,526.33	3,885,545.30	2.92	1.28
5	14.00	46.67	82.87	0.00	4,200.00	95.00	96.95	128.35	150,880.30	2.79	1,479,027.79	4,132,874.92	9.97	5.31

Figure 5.27: Plausibility Checks

Case1

Case 1 is the default case and used as a starting point for comparison. Hence any changes in final variable values and CSCPI observed in cases 2 to 4 are compared to case one.

Case2

The Unit Selling Price is decreased by 20% to € 11.20. This increases the customer demand, therefore, Sales increase within the limits of availability to 1513k units. Due to the lower Unit Selling Price the Profit goes down to € 451,715, which results in an average Profit per Unit of € 0.30. At the same time StockOuts dramatically increases to over 695k units, which, despite an average Capacity Utilisation of 99.21%, is caused by limits in production capacity. Hence the Customer Satisfaction is very low and stays at the numeric minimum value of 1. This leads to a CSCPI of 0.03.

Case3

The Unit Selling Price is increased by 20% and now is € 16.80. As an effect Sales drop to 948k units, which in turn reduces the Profit to € 591,472 and the average Profit per Unit to € 0.62. The average Capacity Utilisation is 67.15% On the other hand, StockOuts is only 37k units, which is due to many potential customers not buying the product because of the higher price. Customer Satisfaction, which is determined by the number of StockOuts and Product Quality, therefore, reaches a high of 10. The CSCPI is slightly higher than in case 2 and now reaches 0.69.

Case4

Case 4 assumes a Product Quality of 70%. This leads to lower customer demand and, therefore, Sales are reduced to 1399k units whilst StockOuts drop to 83k units. Profit amounts to € 3,885,545, which leads to an average Profit per Unit of € 2.78. However, with an average Capacity Utilisation of 94.05% and a Customer Satisfaction of 2.92, the CSCPI stays much below that of case 1 and reaches 1.28.

Case5

With Product Quality set to 95%, Sales reach 1479k units, which is almost identical to case 1. Due to increased costs the Profit goes down slightly to € 4,132,874 and, hence, the average Profit per Unit is € 2.79. StockOuts now is 151k units, whilst average Capacity Utilisation is 96.95% and Customer Satisfaction is 9.97. The CSCPI reaches a value of 5.31.

During discussions with the line managers, it was confirmed that the right choice of Unit Selling Price is of crucial importance to this particular Collaborative Supply Chain, hence cases 2 and 3 are deemed to provide realistic outcomes. At the same time, only raising Product Quality has little effect on the average Profit per Unit, but still is considered as being an important factor in the medium to long term rather than the short term. It was confirmed that this is adequately represented in the final variable values as displayed in cases 4 and 5, where there is a strong influence of Product Quality on Customer Satisfaction as well as on the CSCPI.

The same four tests were also applied when the collaborative supply chain infrastructure was modified by adding one retailer more. Thus case 6 shows the settings and summary of the final variable values for the new configuration. Cases 7 and 8 show the results of changing USP to -20% and +20%, whereas cases 9 and 10 show the final variable values when PQ is set to 70% and 95% respectively. Figure 5.28 shows the summary of these tests.

	SP (€)	LA (%)	FA (%)	PTMT chng (%)	PC (unit/da)	PQ (%)	avg CU (%)	avg TTM (da)	SO (unit)	avg PPU (€)	Sales (unit)	Profit (€)	CS	CSCPI
6	14 00	46 67	80 75	0.00	4,200 00	90 00	96 65	130.77	130 550 57	2 87	1 474,604 28	4,239,396.75	9 93	[illegible]

	USP (€)	LA (%)	FA %)	PTMT chng (%)	PC (unit/da)	PQ (%)	avg CU (%)	avg TTM (da)	SO (unit)	avg PPU (€)	Sales (unit)	Profit (€)	CS	CSCPI
7	11 20	46 67	80 75	0 00	4,2 0 00	90 00	99 18	130.77	695,734 99	0 30	1,512,797.88	447,245.00	1 00	0.01

	USP (€,	LA (%)	FA (%)	PTMT chng (%)	PC (unit/da)	PQ (%)	avg CU (%)	avg TTM (da	SO (unit)	avg PPU (€)	Sales (unit)	Profit (€)	CS	CSCPI
8	16 80	4 67	80 75	0 00	4 200 00	90 00	67 18	130 77	38,365.10	0 59	946,452 13	557,662.34	10 00	0.51

	USP (€)	LA (%)	FA (%)	PTMT hng (%)	PC (unit/da)	PQ %)	avg CU (%)	avg TTM (da)	SO (unit)	avg PPU (€)	Sales (unit)	Profit (€)	CS	CSCPI
9	14 00	46 67	80 75	0 00	4 200 00	70 00	93 93	130 77	85,589.01	2 74	1,393 020 77	3,812,652.45	2.54	1.12

	P (€)	LA (%)	FA (%)	PTMT chng (%)	PC (unit/da)	PQ (%)	avg CU (%)	avg TTM (da)	SO (unit)	avg PPU (€)	Sales (unit)	Profit (€)	CS	CSCPI
10	14 00	46 67	80 75	0 00	4,200 00	95 00	96 78	130 77	150 595 47	2 78	1 476,495 23	4,103,729 34	9 97	5.00

Figure 5.28: Plausibility Checks with one additional retailer

Case6

Case 6 is the default case with one additional retailer and it is used as the starting point for comparisons.

Case7

A 20% decrease sets the Unit Selling Price to € 11.20. This increases Sales to 1513k units and at the same time StockOuts to 696k units. Whilst running with a Capacity Utilisation of 99.18%, the profit drops to € 447,245 and the average Profit per Unit to € 0.30. With Customer Satisfaction at the minimum of 1, the CSCPI results in 0.01.

Case8

A Unit Selling price of € 16.80 reduces customer demand and hence Sales drop to 946k units, with StockOuts also down to 38k units. This results in a Profit of € 557,662 and an average Profit per Unit of € 0.59. In this case the Capacity Utilisation drops to 67.18% due to reduced Sales. Although the Customer Satisfaction is very high, the CSCPI results in 0.51.

Case9

In this case the Product Quality is set to 70%. As a result, Sales go down to 1,393k units and along with sales the Capacity Utilisation decreases to 93.93%. StockOuts also drop to 86k units. The Profit is € 3,812,652 and the average Profit per Unit € 2.74. Consequently a low Customer Satisfaction of 2.54 together with the other resulting variables leads to a CSCPI of 1.12.

Case10

With Product Quality increased to 95%, Customer Satisfaction is 9.97 despite of the StockOuts or 151k units. Sales are 1,476k units, which gives a Profit of € 4,103,729 and an average Profit per Unit of € 2.78. In this case, Capacity Utilisation is 96.78%. The resulting CSCPI is 5.09.

The outcomes of cases 7 to 10 were discussed with the line managers. Those cases show that the effect of changes to variables results in similar behaviour as in cases 2 to 5. This is attributed to the fact that, although there is an additional retailer, the limiting factor is the Production Capacity.

The next section provides a critical analysis of the evaluation results.

5.5 Critical Analysis

The DSE is not a panacea of solutions. Verification and Validation Testing of the DSE is purely based on a particular case study. Therefore, for a different collaborative supply chain, this DSE may have to be re-calibrated whilst undergoing significant changes. However, this assertion is based purely on personal observation of a fast evolving collaborative environment and is not an outcome of the research undertaken or the testing of the DSE. Hence, the analysis is based on the results obtained during the verification and validation of the DSE as applied to the case study.

This section is organised as follows: First the constraints encountered in configuring, populating, and evaluating the DSE are described. Then the analysis of the evaluation of the application of the DSE is described and the level of confidence of this particular application of the DSE based on its VVT is summarised in a Kiviat diagram. Finally, potential improvement of DSE implementation and testing are discussed.

5.5.1 Implementation and Testing Constraints

The DSE development and testing is constrained by several issues encountered in the modelling environment and the case study carried out. The Powersim™ Studio 2001 simulation platform was used to implement the DSE. Powersim™ Studio 2001 uses the System Dynamics methodology for its underlying simulation engine. This suggests a rather holistic and more high-level point of view of the conceptual model being transformed into a simulation model. However, during the case study several managers appeared to focus on the accuracy or numerical data rather than the decision rules that are responsible for generating those. This contradicts the SD approach which is holistic. Hence, the model outcomes sometimes were only considered from the point of view of numerical accuracy, which results in a lower level of confidence in some of the tests. At the same time the provision of analysis tools in Powersim™ Studio 2001 is limited. For example, the display of several time series on one graph and the statistical analysis of those time series are not directly possible. Therefore, data series were exported into Microsoft™ Excel in order to complete the analysis.

During the case study, one of the main obstacles was the difficulty of retrieving accurate and comprehensive data. This was mainly due to the way information systems were set up and the limited visibility of data across stakeholder boundaries, together with some of the line managers being rather protective of their knowledge of the supply chain. A plethora of information systems was in use throughout the collaborative supply chain, many of which were bespoke systems. In addition, some data was kept in the required format only for a limited period of time. During discussion with line managers it was often found that they were happy to provide data which was directly accessible via some of the information systems, but were trying to hide how they processed the data and how they made decisions based on the data that was available to them. The process of knowledge elicitation regarding managerial decision making was also constrained by the limited time available for the case study. Finally, there was a limited amount of time available when Plausibility Checks were conducted on the DSE outcomes on a group of line managers.

5.5.2 Implementation and Testing Analysis

From the outcome of Verification and Validation Testing several conclusions are drawn. Model Structure Assessment verified that the level of representation of reality is acceptable, the implemented decision rules adequately represent the way decisions are taken by line managers, and the model is detailed enough to produce results that are accurate with respect to the model purpose. Despite simulation environment constraints and difficulties in knowledge elicitation Model Structure Assessment provided satisfactory results. Extreme Condition Testing is carried out on model equations and through simulation. The DSE passed all tests successfully, which leads to a high level of confidence in these particular results of model tests. Dimensional Consistency Testing also was passed successfully.

Behaviour Reproduction Testing was performed through plotting real and simulated behaviour of Production Starts on one graph and Sales on another. The matching of the data series was discussed under consideration of the Correlation Coefficient and the Mean Absolute Percent Error. Especially those line managers who adopt a low-level point of view and focus mainly on numerical data, were sceptical that the simulated data series did not follow the real data series more closely. Others stated that a MAPE between 5% and 7% could be acceptable, since the aim of the DSE is not to produce exact results, but to give an indication of the effect of changes in variables on collaborative supply chain performance. Hence, overall a medium level of confidence in this aspect of the DSE was expressed. Plausibility Checks were impacted especially due to the limited amount of time the line managers were able to spend discussing the different test cases. Whilst it was commonly agreed that the crucial importance of finding the right Unit Selling Price is well traced and presented in the DSE, opinions on the impact of Product Quality on performance differed. Some line managers argued that the CSCPI should not be affected as much by lower Product Quality as it is shown in cases 4 and 9, since in this market segment product life cycles are very short. This leads to customers buying new products within a relatively short period of time, hence the influence of Product Quality may be less than shown by the DSE. In addition, there also seems to be a trend to more functionality and design issues rather than Product Quality. On the other hand, some line managers regarded Product Quality as an important factor which may impact future sales.

Figure 5.29 shows a Kiviat diagram displaying the level of confidence in the DSE originating from each of the Verification and Validation Tests. The inner circle presents lower, the outer circle higher levels of confidence.

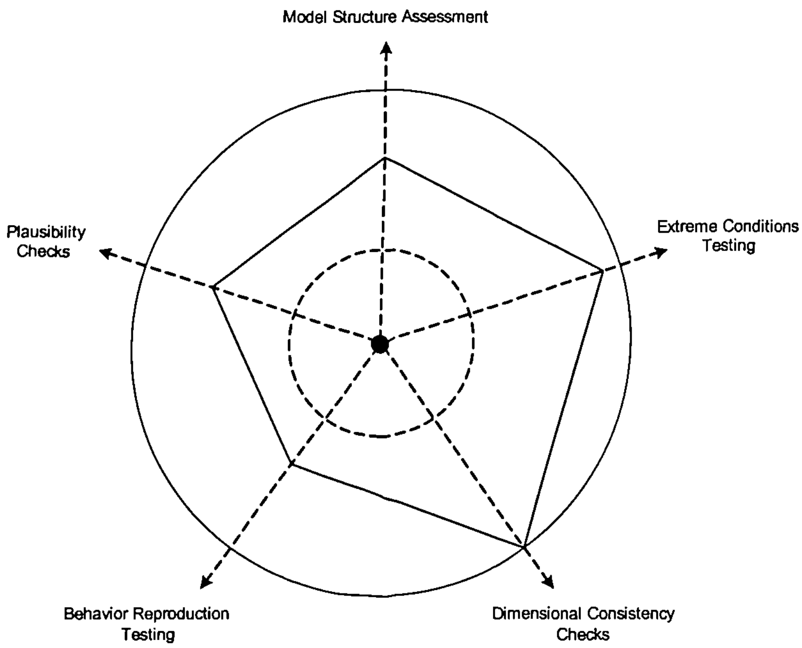


Figure 5.29: Kiviat Diagram of Model Verification and Validation Tests

Overall, the implementation of the DSE is deemed to fulfil the purpose it was developed for, that is to show how the performance of the collaborative supply chain is influenced by changes in any of the six constituents.

5.5.3 Implementation and Testing Improvements

Verification and Validation Testing highlight some areas for potential improvement.

The collaborative supply chain had undergone significant changes between the time of data collection and final model testing, as it happens with dynamic systems, which left us with the need to revise. Proprietary information systems in use at the time of data collection were upgraded to open standard integrated systems. For instance, SAP™ implementation at the manufacturers was successfully completed in July 2000, which naturally lead to some rethinking of business processes and decision-making. This leads to this becoming a constraint to implementation and subsequently an issue for re-populating and re-calibrating rather than a re-implementation decision.

Behaviour Reproduction Testing suggests that a closer visual mach of simulated and real data series, along with a higher Correlation Coefficient and lower MAPE, is desirable. Naturally, many managers rely on the accuracy of data when making decisions, hence they may feel uncomfortable when there is a clearly visible discrepancy between historical and simulated data. Although a more accurate reproduction of historical data is not required with respect to model purpose, it could still improve the level of confidence in the DSE.

Plausibility Checks reveal that the accuracy of forecasted Customer Demand, which is an external input to the DSE, is around 70%. Although the data used to forecast the Customer demand was not recorded in the collaborative supply chain, nevertheless the results accuracy does not take this into account. However, the DSE's purpose is to show the impact of changes in any combination of the six constituents on collaborative supply chain performance, not accurately replicating a historical time series. Hence, it is of paramount importance to use the forecasted Customer Demand consistently rather than accurately. Naturally, both are essential and the final result can be adjusted to reflect the 70% accuracy of the forecasted Customer Demand. In a re-implementation of the DSE all data that is used in forecasting Customer Demand will be recorded and the DSE then extended to replicate the process of forecasting to calculate the Customer Demand instead of assuming the forecasted Customer Demand as an external input.

During Model Structure Assessment, conformance testing exposed a discrepancy between the daily use of financial information in the collaborative supply chain and how the DSE simulated the financial structure. The collaborative supply chain is driven by quarterly reports of financial figures, the financial variables in the DSE are continuously updated, hence the information provided is more timely and accurate as the one used in the collaborative supply chain. With the changes that took place with the implementation of SAP™, the financial reporting now is closer to how it is portrayed in the DSE, which is one important achievement of the DSE. Re-implementation of the DSE should take into account how financial reporting influences decisions made in the collaborative supply chain.

5.6 SUMMARY

This chapter describes the Verification and Validation Testing used and the configuration, population, and use of the DSE with case study data. It also describes potential areas for improvement that verification and validation testing reveal.

In the last chapter the thesis is concluded with the contributions summarised and future research and development arising from both personal observation and the evaluation is discussed.

CHAPTER 6: CONCLUDING DISCUSSION

This chapter summarises the thesis and the contributions and makes suggestions for further research and development.

6.1 Thesis Summary

This thesis proposes a model of a collaborative supply chain which consists of six constituents and devises a collaborative supply chain performance indicator to measure the performance of such a collaborative supply chain. The model and the performance indicator are then implemented in a decision support environment, whose aim is to show how changes in any of the six constituents affect collaborative supply chain performance. The decision support environment is configured and populated with case study data. Through verification and validation it is shown that the decision support environment fulfils adequately its purpose.

Chapter 1 introduces the area of research and lays out the research method adopted. Recent research is grouped into three main areas: Firstly, recent research work concerned with demand amplification; secondly, research work using a supply chain model for analysis and design; thirdly, research work concerned with modelling international supply chains. Demand amplification research shows a link between collaboration and decision-making in the supply chain and the oscillatory behaviour of supply chains. Analysis and design research shows how to improve inventory management, cycle time, and material and information flow through time compression, inventory control, information sharing, and collaboration. International Supply Chain Management research shows how to adopt active participation of decision-makers in the analysis and implementation phases to overcome globalisation bottlenecks. Common to all three research strands is the need for a model of a collaborative supply chain.

Chapter 2 proposes a model of a collaborative supply chain which consists of six constituents: Stakeholders, Levels of Collaboration, Business Strategy, Processes, Enabling Technology, and Topology. First, the shortcomings of existing research are shown. Until now no model exists which combines all six constituents, hence the existing models do not adequately address all necessary aspects of collaborative supply chain performance improvement. The proposed model is a solution to overcome these shortcomings. Chapter 2 then shows that all six constituents are essential and describes them in detail. 'Stakeholders' are the primary players of the collaborative supply chain. 'Levels of Collaboration' describes whether the players in the supply chain collaborate at the operational, managerial or strategic level. 'Business Strategy' consists of three elements, the competitive mission, the core operations strategy, and the player's business goals. The four core supply chain 'Processes' are plan, source, make and deliver. They link the individual companies together across the whole collaborative supply chain. 'Enabling Technology' describes the use of collaborative supply chain information systems within and between stakeholders. Finally, 'Topology' shows how supply chain processes are linked together, based on three basic flow patterns. The complete collaborative supply chain model is then graphically shown in a bird's eye view, detailing how the six constituents together form the model of a collaborative supply chain.

Chapter 3 details the development of a performance indicator to measure collaborative supply chain performance. First, it discusses how changes in any of the six constituents effect collaborative supply chain performance. This is accomplished by linking the six constituents to the collaborative supply chain performance indicator via key variables affected by the constituents. Next, three types of measures are described: Resource Measures, Output Measures, and Flexibility Measures. 'Resource Measures', which generally measure costs, may be used to improve supply chain performance by reducing costs. Examples of 'Output Measures', which measure the output of the supply chain, are sales and profit. 'Flexibility Measures' measure the supply chain's ability to cope with volume and schedule variations. Current research does not use all three types of performance measures simultaneously when measuring supply chain performance. Chapter three then shows, that, in order to measure the performance of a collaborative supply chain adequately, all three types of performance measures need to be used simultaneously. The consequences of one or more types of measures missing are discussed and presented as an overview. Next, the relationship between key model variables, as identified in the first section of chapter 3, are explained and formulated in an equation. From that the formula for the collaborative supply chain performance indicator is constructed.

Chapter 4 describes how the model or a collaborative supply chain, proposed in chapter 2, and the performance indicator described in chapter 3, are implemented in a decision support environment. The aim of the DSE is to show the impact of changes in any of the six constituents on collaborative supply chain performance. Firstly, the boundaries of the collaborative supply chain are set, general assumptions are stated and the modelling environment constraints are listed. Then the implementation of the DSE in a simulation model is described. The DSE provides a configuration dialog for each of the constituents, giving choice of different infrastructure and variable settings. A 'stock & flow' map, divided into 4 geographical regions, provides a graphical representation of the mathematical equations on which the simulation model is based. The results of a performance indicator simulation run are shown as an output of the DSE. Time graphs display how important variables evolve throughout a simulation run. Also, the settings chosen in the constituents' configuration dialogs are displayed alongside the end results of key variables and the CSCPI.

Chapter 5 describes and summarises the evaluation carried out on the Decision Support Environment based on data collected in a case study. First, appropriate verification and validation techniques are identified and explained regarding their use in the evaluation of the collaborative supply chain DSE. Model Structure Assessment shows whether model structure, implementation of decision rules and level of aggregation in the DSE is consistent with the findings from the case study. Extreme Conditions Testing then tests whether the model is as stable under extreme conditions as under normal conditions. Dimensional Consistency Testing examines the model with respect to the correct and consistent use of units of measurement. Behaviour Reproduction Testing assesses if the reproduction of system behaviour by the model is adequate with respect to the model purpose, whilst Plausibility Checks determine whether the differences in historical to simulated behaviour are reasonable. Next, the modelling of the existing supply chain and the configuration and population of the model based on data obtained during a case study is described. The DSE was set up in three scenarios: Scenario 1 reflects the original system without any changes. Scenario 2 incorporates changes in model variables whilst retaining the infrastructure of the scenario 1. Scenario 3 assumes changes in model variables as well as changes in the infrastructure of the collaborative supply chain. Verification Testing of the DSE shows, that, despite of simulation environment constraints, Model Structure Assessment yields well acceptable results. Extreme Condition Testing yields good results and Dimensional Consistency Checks shows that there are no errors in the use of units of measurement. Validation Testing reveals a discrepancy between historical and simulated data, hence the level of confidence in the DSE due to Behaviour Reproduction Testing only reaches acceptable levels. However, Plausibility Checks demonstrate slight higher levels of confidence, hence with respect to the model purpose the implementation of the DSE overall is suitable. Chapter 5 concludes with suggestions of potential areas for improvement for the DSE.

The next section provides a summary of contributions made by this thesis.

6.2 Summary Of Contributions

Two major contributions are made by this thesis: The model of a collaborative supply chain, and the Collaborative Supply Chain Performance Indicator for measuring the performance of such a collaborative supply chain.

6.2.1 Collaborative Supply Chain Model

The Collaborative supply chain model consists of six constituents, all of which are necessary to form a complete picture of a collaborative supply chain. Figure 6.1

shows the collaborative supply chain model with the six constituents. Unified together in the collaborative supply chain model, the complementary nature of the six constituents forms a holistic and comprehensive picture.

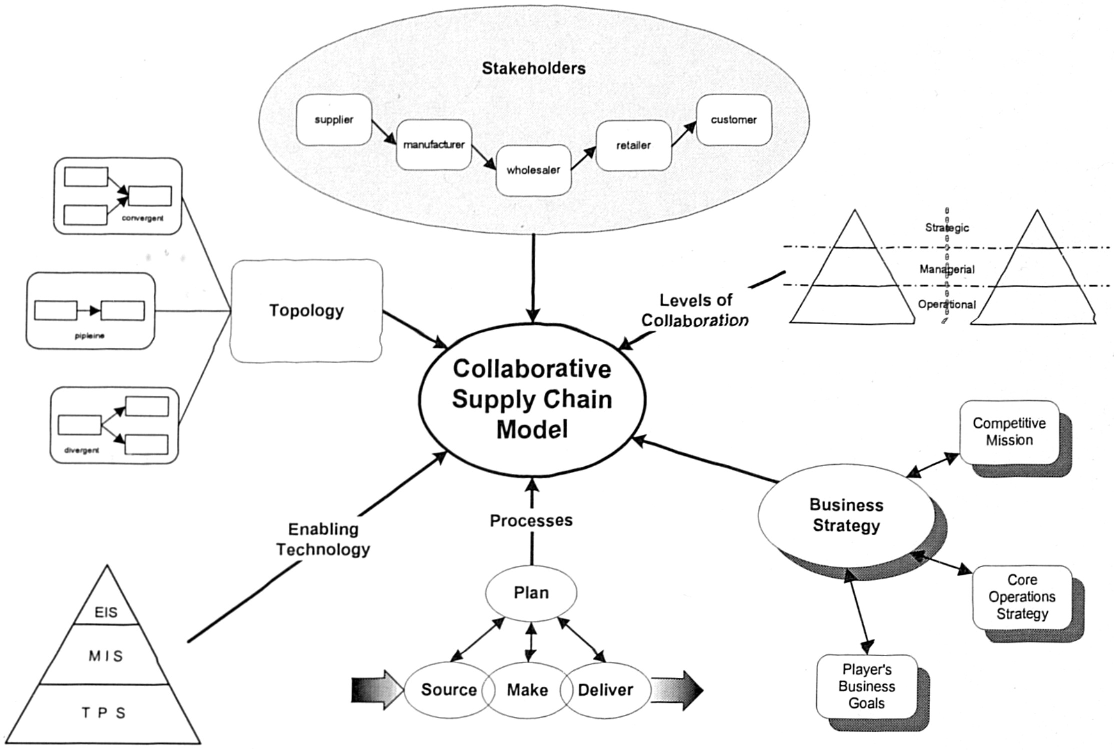


Figure 6.1: Collaborative Supply Chain Model

Stakeholders, the primary players of the collaborative supply chain, are the supplier, manufacturer, wholesaler, retailer and customer. Each stakeholder, who may comprise of more than one firm in real life, plays a particular role in the collaborative supply chain. Stakeholders are a central component, as their complete absence would not lead to a collaborative supply chain in the first place. There is a choice of three *levels of collaboration* on which the stakeholders may collaborate. The strategic level deals with decisions that have an impact on the future direction of the collaborative supply chain. The managerial level is mainly concerned with the optimisation of the flow of goods. The operational level involves decisions with a high level of detail, typically performed in a repetitive manner. Levels of collaboration is an important constituent in the collaborative supply chain model, as its absence would lead to a lack of explanation of the interactions between the stakeholders. *Business strategy* consists of the competitive mission, core operations strategy and player's business goals with respect to the collaborative supply chain. Each of those components of collaborative supply chain business strategy also exist within the supplier, manufacturer, wholesaler and retailer, hence those individual components need to be aligned with those of the collaborative supply chain in order not to compromise its functioning. Without the business strategy constituent, the interaction between market forces and the collaborative supply chain would be neglected, leading to an unrealistic model. The boundaries of individual firms are extended by linking them through collaborative supply chain *processes*, consisting of the plan, source, make and deliver process. The plan process sits as an umbrella process above the other three processes. The source process describes the raw material acquisition on the supplier side of the supply chain. The make process deals with the manufacturing of goods, while the delivery process entails sub-processes for order-, warehouse-, and transportation management. The absence of the processes constituent in the collaborative supply chain model would make it a black box whose contents cannot relate to any changes in performance. Hence processes play an important part in the model. *Enabling technology* describes the role of information systems as an enabler of collaborative supply chain functions. The main goal thereby is linking together physical and information flow in the collaborative supply chain. It is distinguished between three main groups of systems. TPS carry out routine business activity, they provide the underlying communication and data exchange facilities and directly support the source, make and deliver supply chain processes. MIS operate to support management decisions with the appropriate information to enable efficient planning and coordination of business resources. EIS, on the other hand, provide information in a more summarised format to highlight weaknesses and opportunities of the collaborative supply chain. Hereby the same data is used in all three groups of systems. Enabling technology is an important part of the collaborative supply chain model, since, without it, there would be no effective control of material flows across the supply chain, there would be a lack of communications infrastructure, and there would be no grounds on which collaborative supply chain performance measurement could be established. *Topology* describes the manner in which supply chain processes are linked together, describing the flow of material between the primary players in the collaborative supply chain. It is distinguished between single route flow, convergent flow and divergent flow, whereby these three basic flow patterns may be combined to form a complex supply chain network. Topology is an essential constituent, as without it there is no way to describe the material flow between players in the collaborative supply chain, where processes may be linked within and between firms.

6.2.2 Collaborative Supply Chain Performance Indicator

The performance indicator provides a way to adequately measure collaborative supply chain performance. The requirements for this performance indicator are defined with respect to the collaborative supply chain model proposed and the components of the performance indicator are developed purely based on its requirements.

Performance measures are grouped into three types of measures, which are resource, output and flexibility *measures. The six constituents* form a system of integrated processes and multiple relationships within and between stakeholders, which is complex due to many inter-linkages and inter-relationships. Only a measurement system that uses each type of measure can take account of the complex nature of a collaborative supply chain, and, therefore, adequately measure its performance. Changes in different constituents may influence the same variable in a variety of ways, which in turn may influence other variables as variables are sometimes interlinked. A formula for resource measure, output measure and flexibility measure is deduced from the key variables, and then combined into a formula for the collaborative supply chain performance indicator.

$$RM = C \tag{6.1}$$

$$OM = P * CS \tag{6.2}$$

$$FM = \frac{PC\ ratio * RI\ ratio}{TTM} \tag{6.3}$$

$$CSCPI = \frac{\beta\, OM * \gamma\, FM}{\alpha\, RM} \tag{6.4}$$

hence

$$CSCPI = \frac{\beta\,(P * CS) \quad * \quad \gamma\,(PC\ ratio * RI\ ratio)}{\alpha\, C \quad * \quad TTM} \tag{6.5}$$

The next section describes further research and development.

6.3 FURTHER RESEARCH AND DEVELOPMENT

By nature, collaborative supply chains are complex systems, since they represent an amalgamation of firms, processes and inter-relationships. As a result, the refinement of the collaborative supply chain model could be continued almost *ad nauseam*. However, implementation and then the evaluation of the DSE through a case study was carried out at a fixed point in time, hence the evolving complexity of the real system represents reality at that point in time. There are areas where further research would be considered an improvement. From personal observation throughout the whole process of the PhD research, and from the evaluation of the DSE, two main areas for further research can be suggested. The first area is the implementation of the theoretical model as a computer simulation, and the second area relates to the theoretical model, especially with respect to the assumptions made.

6.3.1 Implementation Improvements

The implementation of the collaborative supply chain model into the DSE is constraint by the simulation environment and by the complexity of the real system investigated during the case study. The results of validation testing suggest that a closer visual match of historical to simulated data is desirable, and processes in the real system should be represented as closely as possible in the DSE. Also, the representation of customer demand as an external model variable has implications on the accuracy of results produced as well as on the comprehensiveness of influences considered on collaborative supply chain performance. In addition, the consideration of product life cycles and seasonality is desirable. The implementation of the DSE would benefit from improvements in these areas, which could be achieved by a re-implementation of the collaborative supply chain model in the DSE, using the next version of the Powersim™ Studio simulation platform, or potentially by either using a different simulation environment, or by programming the DSE using any third generation programming language.

In addition, the use of optimisation techniques in the DSE may help to decide the best combination of changes in constituents. Furthermore, the user interface, which was beyond of the scope of this thesis, could greatly benefit from improvements. Also, the process of data collection and representation in a format appropriate for use with the DSE is relatively complicated and time consuming. A solution could be an interface between the DSE and collaborative supply chain information systems to automatically record data required for performance indicator simulation runs.

6.3.2 Model Improvements

The proposed model of a collaborative supply chain assumes that decisions are taken on the level of the whole supply chain. Whilst the model allows for discrepancies in stakeholders and collaborative supply chain business strategy, there is a shortcoming in the representation of how control is actually exercised. Centralised vs. decentralised control in supply chains is regarded as an optimisation problem, which may be addressed by the inclusion of optimisation in the DSE.

This research shows that there are six essential constituents in a collaborative supply chain. The trial and error approach to prove that those constituents are required is to show the deficiencies of a model lacking one or more of the constituents. One weakness of this thesis is that this assumes that the list of constituents is exhaustive and exclusive. Therefore, further research in the form of a longitudinal case study may investigate whether any worthwhile contribution could be made by adding other constituents.

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