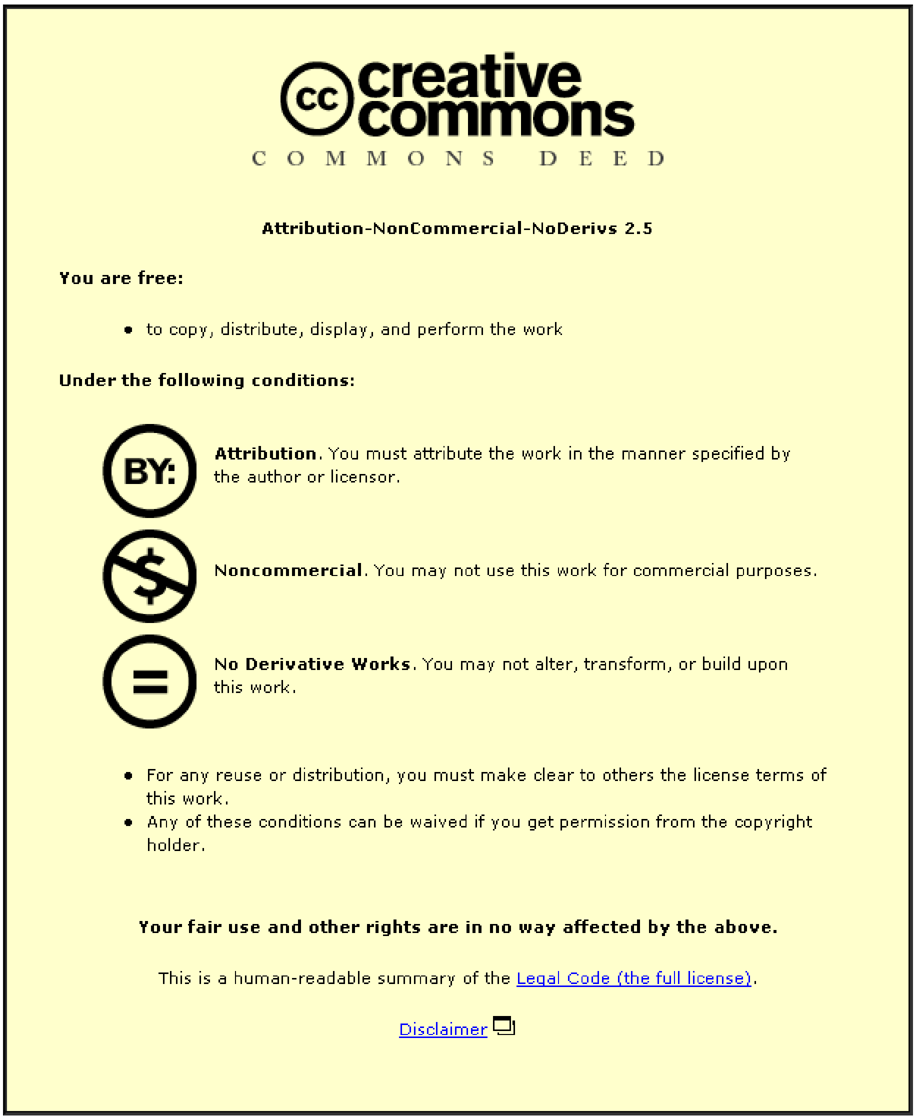


Multi-product cost and value stream modelling in support of business process analysis

by

Kwabena Agyapong-Kodua

Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of

Doctor of Philosophy
of Loughborough University

November 2009

Dedicated to my beloved wife, Vida, for her tremendous support and in memory of my parents, the late Mr Tweneboah and Mrs Elizabeth Kodua, who toiled and waited for this moment, but the Giver of life thought otherwise.

Acknowledgements

I gladly give thanks to God Almighty for the grace He offered me to be able to accomplish this research study.

Words cannot express how grateful I am to Professor Richard Henry Weston, whose supervision, fatherly care, direction and concern enabled me to successfully complete this work.

I am also indebted to the Wolfson School of Mechanical and Manufacturing Engineering of Loughborough University, for their financial support throughout my studies.

I acknowledge the support of all staff and PhD Researchers at the MSI Research Institute: Dr R.P Monfared, Rev. Dr Joseph Ajaefobi, Dr Aysin Rahimifard, Miss Zihua Cui, Mr Shahid Rashid, Mr Bilal Wahid and all Researchers of the Distributed Systems Engineering group of MSI. Mrs Margaret Carden, Ms Jo Mason and Mrs Sue Beaumount deserve my appreciation for their administrative support.

I would also like to express my sincere appreciation to my wife, Vida and children: Nana and Mirabel, for their encouragement, support and cooperation during the research period. To my siblings, extended families and in-laws, I thank you all for your understanding and prayer support.

Abstract

To remain competitive, most Manufacturing Enterprises (MEs) need cost effective and responsive business processes with capability to realise multiple value streams specified by changes in customer needs. To achieve this, there is the need to provide reusable computational representations of organisational structures, processes, information, resources and related cost and value flows especially in enterprises realizing multiple products. Current best process mapping techniques do not suitably capture attributes of MEs and their systems and thus dynamics associated with multi-product flows which impact on cost and value generation cannot be effectively modelled and used as basis for decision making. Therefore, this study has developed an integrated multiproduct dynamic cost and value stream modelling technique with the embedded capability of capturing aspects of dynamics associated with multiple product realization in MEs.

The integrated multiproduct dynamic cost and value stream modelling technique rests on well experimented technologies in the domains of process mapping, enterprise modelling, system dynamics and discrete event simulation modelling.

The applicability of the modelling technique was tested in four case study scenarios. The results generated out of the application of the modelling technique in solving key problems in case study companies, showed that the derived technique offers better solutions in designing, analysing, estimating cost and values and improving processes required for the realization of multiple products in MEs, when compared with current lean based value stream mapping techniques. Also the developed technique provides new modelling constructs which best describe process entities, variables and business indicators in support of enterprise systems design and business process (re) engineering. In addition to these benefits, an enriched approach for translating qualitative causal loop models into quantitative simulation models for parametric analysis of the impact of dynamic entities on processes has been introduced.

Further work related to this research will include the extension of the technique to capture relevant strategic and tactical processes for in-depth analysis and improvements. Also further research related to the application of the 'dynamic producer unit' concept in the design of MEs will be required.

Key words: Value Stream Mapping (VSM), Business Process Reengineering (BPR), Computer Integrated Manufacturing Open Systems Architecture (CIMOSA), Enterprise Modelling, Simulation Modelling, System Dynamics Modelling

Table of contents

Table of figures

Table of Tables

1. Introduction to Research

1.1 Emerging challenges in Manufacturing Systems design

In general terms, manufacturing contributes significantly to the world's economic growth. This is achieved through various manufacturing technologies and processes which transform raw materials to finished goods, which satisfy various customer requirements. Currently, manufacturing systems are challenged by intense competition characterized by changes in customer requirements. There is a drive towards the production of affordable high quality customized products (Vernadat 1996). Hence manufacturing systems should be responsive to changes in product functions, cost, quality and timeliness based on customer requirements (Weston 1999). Quite apart from the changing customer requirements is the drive towards establishing global networks of companies in view of maximizing profit through low material and resource cost as well as maintaining a closed market niche. This has led many manufacturing enterprises to reorganize themselves to suit the global challenges. In effect products and markets are now globally centred. This raises a lot of issues for many manufacturing companies on where to target and the availability of resources to harness knowledge and maintain product and process quality. This is critical because knowledge transfer in manufacturing enterprises is a key issue and should be managed properly to achieve optimal results. Advancing information and machine technologies have also impacted on how manufacturing enterprises operate (Vernadat 1999). Computer technologies are nowadays used to support planning and scheduling, designing, purchasing, controlling, and various production activities. The development and utilization of microelectronics, computer communication networks; software engineering; object oriented database systems; distributed artificial intelligent systems; multimedia and multimodal environments as well as open systems architectures are impacting on the manufacturing world (Vernadat 1996). This impact is actually moving manufacturing industries from highly data-driven environments to more cooperative information-driven environment, taking into account more of enterprise knowhow, commonsense and application semantics. As a result of the fast space by which these computer technologies are developed and operate, manufacturing industries will need to constantly upgrade their IT resources and train their human resources to match with the demand. Also some of these IT resources are capital intensive and reasons for their investment may have to be strongly justified.

Because of competition, customers at all levels of the supply chain are trading to maximize profit. There is therefore the stress for price cuts along the chains of suppliers and customers. The added challenge of legislation and the drive towards sustainability and 'environmental-conscious' products is causing many manufacturing enterprises to reform their processes. The most recent economic recess has also impacted negatively on manufacturing industries.

As a result of these challenges, manufacturing enterprises are subjected to pressures which induce dynamics in their operations and management. Literature has shown that in general terms the problems often faced by most manufacturing enterprises can be rooted to the phenomenon of complexity which stems from the complexities involved in current markets (Wiendahl and Scheffczyk 1999). The structural and dynamic complexity of the markets can be found in the structure and processes of the enterprise too (Rumelt 1974). Hence the complexity of the products has their counterparts in the complexity of the manufacturing systems. For most MEs the dynamics of complexities can be enormous. Partly because MEs are highly organic (people-centred) and achieve their goals only through the integration of people, machines and technology. As a result of the interaction between these functional elements, changes related to any of the elements trigger effects on other elements which are causally related to other elements hence producing ‘chains of reactions’ in the ME. Therefore complex dynamic behaviours can occur along a process thread based on the slightest change in the transient operational state of the process.

To therefore manage such complexities in these dynamic environments, it is required that decisions associated with these functional elements be made properly so that they can best be coordinated to achieve optimal results. A number of solution technologies exist to help implement strategies based on well defined philosophies for managing various degrees of complexity. One of these enabling strategies adopted by most manufacturing enterprises in recent times is Computer-Integrated Manufacturing (Ranky 1986; Waldner 1992; AMICE 1993; Vail 1998). With the introduction of Computer-Integrated Manufacturing (CIM) and the use of modern Information Technologies (IT), in principle manufacturing enterprises are able to achieve increased levels of flexibility in terms of organization, operations, product design and manufacturing. Also in principle, flexibility can be increased by adopting quick responsive modelling techniques to capture interrelated information and physical flows supported by control flows and use as basis to control and manage on ongoing basis various processes required to achieve enterprise objectives. This is the concept behind the model driven approach to manufacturing systems design.

1.2 Model driven Manufacturing systems design

Due to the challenges imposed on MEs as a result of complexities, MEs will have to design and control their systems such that complexities can be maintained within acceptable levels in order to meet customer requirements and remain competitive. To remain competitive, MEs have to continuously and flexibly adjust through the redesign and organization of their processes and resource elements with the aim to improve their key performance indicators. This is however, not simple to achieve because of the inherent and ongoing dynamics experienced by MEs. Most MEs will therefore need cost effective and responsive business processes with capability to realise multiple value streams specified by changes in customer needs. Models of MEs can play a critical role in enabling enhanced enterprise process and systems design and change based on analysis of their performance, and ongoing management and control of their operation. To manage complexities, processes in manufacturing enterprises need to be controlled and integrated. Product variance and resources may also need to be managed together with other flows like material and information. All these flows cannot conveniently be managed without the support of appropriate scientific tools. It is therefore envisaged that to fairly manage complexities in manufacturing enterprises there is the need to model and integrate: products; resources; information; organizations and decisions; business processes and humans (Bernus and Nemes 1996; Vernadat 1996; Weston 2005). The application of these model driven approach to manufacturing systems design will promote a better understanding and uniform representation of the enterprise with the benefit of capitalization of enterprise knowledge and knowhow (Burns and Ulgen 2002) and enable business process reengineering (Curran and Keller 1998; Hammer and Champy 2001). In an attempt to render scientific support in solving problems of ‘complexities, change and dynamics’ in MEs, various methods have emerged. This includes fuzzy logic (Batur, Srinivasan et al. 1991; Wang 1992; Yester, Sun et al. 1993), neural networks (Minsky and Papert 1969; Gardner and Derrida 1988; Spooner, Maggiore et al. 2002), Bayesian networks (Pearl 1985), non-linear control dynamics, enterprise modelling (Bernus and Nemes 1996; Vernadat 1996; Weston 2005), systems dynamics (Forrester 1961; Burns and Ulgen 2002), statistical and other parametric modelling techniques. By choosing a suitable modelling technology, aspects of organizational structure, business processes and their associated resource systems can be captured and instrumented to help MEs generate expected outputs whilst constraining unwanted behaviours. Typical models of MEs can provide reusable computational representations of organisational structures, processes, information, resources and related value flows in an enterprise (Agyapong-Kodua, Ajaefobi et al. 2009). The ability to accurately select the appropriate modelling methodology and apply to meet requirements of the enterprise is an issue for the enterprise designer.

1.3 Identification and definition of Research problem

The drive to meet customer needs has challenged manufacturers to develop and utilise innovative technologies and operate globally. Satisfaction of customer needs means designing organisations and their processes in a way that value would be added along process threads at possible minimal cost, thus allowing products to remain competitive in their life time (Agyapong-Kodua, Ajaefobi et al. 2009). How this is achieved has changed dramatically over the years due to increase in global competition, changing customer requirements, varying technologies, political, economic and environmental constraints.

In addition to the effect of these factors on Manufacturing Enterprises (MEs), the general trend of business has shifted towards customised products and services leading to increase in product variety and reduction in product lifetimes. Despite this trend, some MEs concentrate on their core competencies and form partnerships with other groups of entities with complementary competencies, making industries to compete based on both economies of scope and scale (Vernadat 1996; Weston 2005). In each of these cases, it behoves on the business entity to make well-informed decisions within a shorter time span in order to maintain larger market shares and remain competitive. The proper application of scientifically proven strategies, methodologies and tools in making such decisions is vital. Typical among the strategies that Manufacturing Enterprises (ME) adopt in managing these challenges include the development of new products or product variants; deployment of new businesses, manufacturing and logistical policies; use of alternative forms of computer and machine technology, reorganization of product and process flows and critical analysis of the efficiencies of human resources. Each of these strategies has impact on the performance of the ME. Significant benefit from any of these strategies can arise in terms of increasing the efficiency of ME processes by observing the difference between the total value generated by a process in unit time and the total process cost associated in that value generation. Lean expects have recommended the use of value stream mapping technique (Womack, Jones et al. 1990) as a means of ensuring that processes are redesigned to ensure delivery of products in time; at a lower cost, of high quality and on continuous basis. In principle value stream analysis can help specify processes with: integrated single piece flow; defect prevention; production pull; continuous waste reduction; flexible team based work and active involvement and close integration with suppliers (Bicheno 2000). In practice, value stream maps are known to help identify (and therefore help eliminate or at least reduce) the wasteful activities that customers would not wish to pay, hence making it a useful tool for process improvement. However a critical consideration in this research is to better understand whether value stream mapping is an effective process redesign and improvement tool for manufacturing systems that need to realise multi-product flows. This is necessary because most MEs are characterised by complex systems of processes which need to be resourced with technical and human systems. These systems need to be properly coordinated and controlled to allow variety of products to be realised through them over varying periods of time. Current approaches to the identification and reorganization of processes to realise highest values and minimal process costs, which are essential key performance indicators, has not been adequate. This is because current approach to value stream mapping and process costing do not encode time dependencies related to product flows, controls, process instants and time dependent causal effects. This implies that analysis of alternative flows of product (volume and mixes) through a shared process cannot accurately be modelled by current generation value stream maps to mimic real time instances in a ME.

Another key challenge in real world manufacturing enterprises is that, systems are interconnected such that flows can be hard to 'see' when products have multitude of options, with variations in lead times and cycle times, and processed through repetitive and multiple processes or cycles. Further process complexity arises where there are significant product mixes, shared resources with unsteady changes in information flow. In such circumstances, it becomes fairly difficult to identify product families and map their operational processes as it is recommended by current mapping theories.

Most decisions taken in industries are based on experience, which might not be accurate in some cases. It is therefore possible to suggest that suitable scientific tools are necessary to assist in making informed decisions. Also MEs are inherently complex and influenced by a lot of factors which tend to induce dynamics in the MEs operations. Thus a suitable way of capturing value streams and process cost must go beyond static mapping schemes which essentially take into considering a state in point condition without giving much indications for predicting future performances. An approach which makes it possible to model the dynamics in MEs which are related to values and cost generation will perform better in MEs operating in dynamic environments.

1.4 Research scope

Based on the problem domain described in the preceding section, the scope of this research is:

- Review of process mapping technologies with clear emphasis on value stream mapping.
- Review of best practice value and cost engineering principles.
- Review of enterprise modelling techniques with emphasis on their relative strengths and capability to support value stream modelling.
- Investigation of the application of system dynamics and simulation modelling tools to manage enterprise systems complexity.
- The unification of ideas from current manufacturing solution technologies and enterprise/simulation modelling techniques.

2. Literature Survey

2.1 Introduction

To provide a comprehensive analysis of current theories and methodologies deployed in solving issues related to value streams and process costing in MEs, a survey of existing literature in the subject was conducted. The main idea, in addition to understanding current practices, was to understand the limitations and gaps existing in the area and hence identify ways of contributing to knowledge. This survey includes aspects of literature related to:

- Recent manufacturing philosophies, strategies and solution technologies
- Process improvement techniques with emphasis on process mapping technologies
- Concepts and industrial application of cost and value engineering principles
- Enterprise modelling and integration
- System dynamics and simulation of manufacturing systems

2.2 Philosophies, Strategies and solution technologies deployed in MEs

Chapter 1 of this thesis outlined the various stages of development that the manufacturing industry has passed through. MEs have moved deploying only craftsman's technology to that of latest Computer Integrated Manufacturing technologies. Many researchers have indicated that, typically, today's MEs are in permanent change hence it behoves on many MEs to adopt strategies that allow them to become flexible to allow them to cope with the changes (Bernus and Nemes 1996; Weston 1999; Hitchins 2003). Also Weston (Weston, Rahimifard et al. 2007) observed that a Manufacturing Enterprise's ability to satisfy the above requirements often necessitates the realisation of both economies of scale and of scope. Being able to achieve this in an efficient, timely and cost effective manner depends upon the Manufacturing Enterprise's ability to break into and control a chain of causal effects. This means that MEs need to design and control systems such that they are easily reprogrammable, reconfigurable and recomposable through their life time often to satisfy yet to be determined demands the system will be subjected to (Weston, Rahimifard et al. 2007). To address ME requirements to handle complexity and change, many manufacturing paradigms have emerged.

Researchers at the MSI Institute, UK have reported that these paradigms can conveniently be categorized into philosophies, enabling strategies and solution technologies (Weston, Rahimifard et al. 2008). Figure 2 shows examples of these paradigms and their associated classifications.

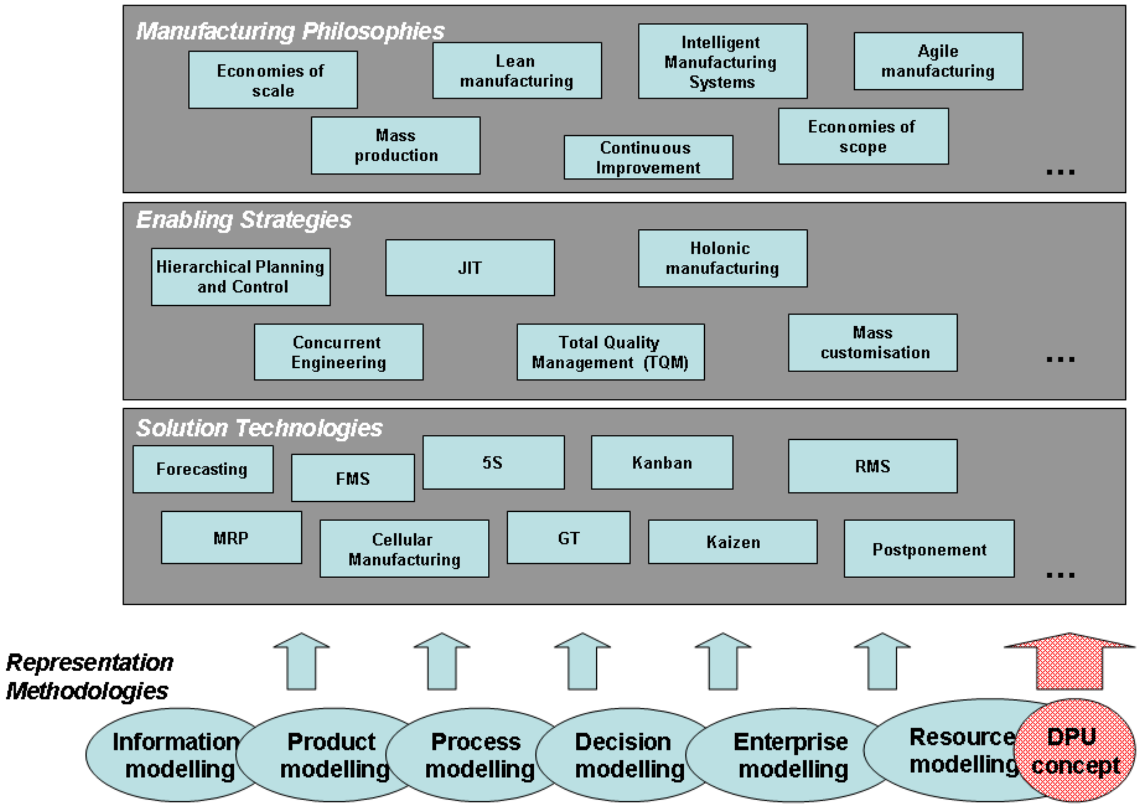


Figure 2: Example manufacturing philosophies, enabling strategies and solution technologies (Weston, Rahimifard et al. 2009)

These authors explained that manufacturing philosophies are based around a central concept that can be followed to derive some form of competitive advantage. This form of competitive advantage could be from improved product quality, timeliness of delivery or reduced cost. Enabling solutions on the other hand may correspond to the formalization of manufacturing rules, which ensure that manufacturing activities are performed according to objectives derived through the established manufacturing philosophy. They further explained that a ‘solution technology’ offers a means of implementing the rules established through the enabling strategy. Thus when these three functions are performed properly, it is expected that the ME will be able to meet the challenges which necessitated the formulation of the philosophy. It has however been reported that none of the philosophies is a panacea for all challenges in MEs (Ajaefobi 2004). It is the ability to flexibly switch from one manufacturing paradigm to another, as per the current requirement of the ME based on external and internal challenges, which will make the ME competitive. Achieving this requires ongoing management of manufacturing processes in view of deploying dynamic modelling techniques to enable smart decisions based on scientific verification.

Some commonly adopted manufacturing philosophies include: Lean Manufacturing (Womack, Jones et al. 1990); Agile manufacturing (Gunasekaran 1998); and Business Process Re-Engineering (Davenport 1993; Hammer and Champy 1993). Just in Time (JIT) is an example of a possible enabling strategy for implementing lean manufacturing philosophies whilst value stream mapping, 5S and cellular manufacturing are possible solution technologies. Similarly, mass customization defines an enabling strategy for realizing the philosophy of agile manufacturing. Possible solution technologies are Reconfigurable manufacturing systems and flexible manufacturing systems. The next section provides a review of some of these philosophies, strategies and solution technologies.

2.2.1 Lean Manufacturing

Lean has been associated with the production and delivery of products in time; at a lower cost, of high quality and on continuous basis (Womack, Jones et al. 1990; Pavnaskar, Gershenson et al. 2003). The central theme of lean is the elimination of waste (Bicheno 2000; Womack and Jones 2003; Chen, Li et al. 2008). Russel and Taylor (Russel and Taylor 1999) define waste as ‘anything other than the minimum amount of equipment, materials, parts, space, and time that are essential to add value to the product’. An alternative way of understanding waste (also known as muda) is defining it as any activity that the customer is not willing to pay (Womack and Jones 1996; Hines and Taylor 2000). Shingo (Shingo 1992) reported that waste (muda) can be divided into seven different types: overproduction, waiting, transportation, over processing, inventory, motion and defects. The different types of waste have been extended and renamed by other researchers (Hines and Nick 1997; Imai 1997; Liker 1998; Nicholas 1998; Boeing 2000; Womack and Jones 2003). Imai (Imai 1997) is of the view that there are nine different categories of waste. Waste observed in: rejects, design, WIP, first phase of production, motion, management, manpower, facilities, and in expenses. However other classifications by Nicholas and Boeing Engineers report waste as comprising of: complexity, labour (the unnecessary movement of people), overproduction, space, energy, defects, materials, time and transport (Nicholas 1998; Boeing 2000). In effect, different forms of waste and their classification schemes exist, but it is woefully inadequate to observe waste in manufacturing systems without knowing how to deal with it or eliminate it. Although identification of waste may be one of the foremost steps needed to improve manufacturing organizations.

Substantial contributions towards lean thinking have been made by many researchers, yet, Taiichi Ohno, father of the Toyota Production System, is known to be one of the main patriarchs of lean operations (Foner, Eric et al. 1991). Lean manufacturing was first implemented by the Toyota Cooperation, after engineers at Toyota observed that their mass production model of manufacturing was not optimally efficient in eliminating idle and changeover time and ultimately not cost effective (Chen, Li et al. 2008). However, the term 'lean thinking' got its name from a 1990's best seller called 'The Machine That Changed the World; The Story of Lean Production' (Womack, Jones et al. 1990). The benefits of lean manufacturing are evident in many factories throughout the world (Pavnaskar, Gershenson et al. 2003). Companies report improved product quality, reductions in cycle time, reduced work in progress (WIP), improved on-time deliveries, improved net income, decreased costs, improved utilization of labour, reduction in inventories, quicker return on inventory investment, higher levels of production, increased flexibility, improved space utilization, reduction in tool investment, a better utilization of machinery, stronger job focus and better skills enhancement (Zimmer 2000; CITEC 2008). Typical results reported (Zimmer 2000; Pavnaskar, Gershenson et al. 2003) after successful lean implementation indicates:

- Defects reduced by 20% per year, with zero defects performance possible.
- Delivery lead times reduced by more than 75%
- On time delivery improved to more than 99%
- Productivity (sales per employee) increases of 15–35% per year
- Inventory reductions of more than 75%
- Return on assets improvement of more than 100%
- Improvements of 10% or more on direct labour utilization
- Improvements of up to 50% in indirect labour utilization
- 50% or greater increases in capacity in current facilities
- 80% reduction in floor space
- 50% improvement in quality
- 95% machine availability
- 80–90% reduction in changeovers
- 60% reduction in cycle times

Typical characteristics of a lean factory include integrated single piece flow; defect prevention; production pull; continuous waste reduction; flexible team based work; active involvement and close integration with suppliers (Womack and Jones 2003). Womack and his colleagues (Womack, Jones et al. 1990) further report that in comparison with mass production, lean production utilizes about half of the: human effort; manufacturing space; investment tolls; engineering hours and production time.

To simplify the application of lean methods and also provide a road map for the instrumentation of lean, five (5) main principles were derived (Hines and Nick 1997; Bicheno 2000; Womack and Jones 2003). These are:

1. Specify value from the point of view of the customer.
2. Identify the 'value stream'. This is the sequence of processes from product concept to market launch
3. Make 'value flow'. Use the Stalk and Hout's Golden Rule-never to delay a value adding step by a non value adding step. Avoid or reduce interruptions, detours, backflows, waiting or scrap
4. Only make what is pulled by the customer
5. Strive for perfection by continually removing successive layers of waste as they are uncovered.

To support the application of lean strategies, a number of tools have been designed, experimented and utilized in many companies. On a regular basis new tools are introduced whilst existing tools continue to be modified to best suit the emerging challenges. Visual management techniques in the form of 5S (Hirano 1990; Osada 1991; Roll 2003), and mapping techniques (Womack, Jones et al. 1990; Rother and Shook 1996; Hines and Nick 1997) remain the outstanding tools for lean implementation. Essentially, these techniques are used to unravel the forms of waste described by Shingo (Shingo 1992). Hines and Nick (Hines and Nick 1997) and Bicheno (Bicheno 2000) have done extensive work in bringing together a set of mapping tools which are useful for preliminary analysis of processes before the implementation of lean. These mapping tools have been reviewed elsewhere in this Thesis. However, with such a plethora of tools, it is important to know which tool to apply in each circumstance because the misapplication of the tools may lead to wastage of resources and reduction in employee confidence in the lean philosophy (Pavnaskar, Gershenson et al. 2003). Therefore, Taylor and Brunt (Taylor and Brunt 2001) developed a technique for matching the seven different process mapping tools to the seven types of waste reported by Shingo.

2.2.2 Agile Manufacturing

The concept of agile manufacturing (AM) was deduced in 1991 through a government sponsored research work at Lehigh University (Gunasekaran 1998). The term was applied to an organization that has created its processes, tools, and training to enable it to respond quickly to customer needs and market changes; while still controlling costs (Goldman, Nagel et al. 1995). According to Gupta and Mittal (Gupta and Mittal 1996), AM is a business concept that integrates organizations, people and technology into a meaningful unit by deploying advanced information technologies and flexible and nimble organization structures to support highly skilled, knowledgeable and motivated people. Such an Organization should possess an ability to thrive in a competitive environment of continuous and unanticipated change; and to respond quickly to rapidly changing markets, driven by customer-based valuing of products and services (DeVor and Mills 1995). Agility was therefore used to describe the capability to thrive in competitive environments of continuous and unpredictable change by reacting quickly and effectively to changing markets (Cho, Jung et al. 1996). DeVor and Mills (DeVor and Mills 1995) further argue that technology alone does not provide agility. Instead it is the right combination of strategies, culture, business practices and technology in response to given market characteristics which matters.

It has been observed that agile manufacturing can be defined along four dimensions: (i) value-based pricing strategies that enrich customers; (ii) co-operation that enhances competitiveness; (iii) organizational mastery of change and uncertainty; and (iv) investments that leverage the impact of people and information (Gunasekaran 1998).

Literature exists about various aspects of the agile manufacturing philosophy. Typical useful examples are cited in: (Youssef 1992; Burgess 1994; Pandiarajan and Patun 1994; Cho, Jung et al. 1996; Spencer 1996; Gunasekaran and Yusuf 2002). A study of these materials show that agile manufacturers will basically have to respond to: (a) rapidly changing markets; (b) global competitive pressures; (c) decreasing new product time-to-market; (d) increasing inter-enterprise co-operation; (e) interactive value-chain relationships; (f) global sourcing/marketing/distribution; and (g) increasing value of information and services. To achieve this, agile manufacturers deploy a number of strategies and technologies. Some of these enablers of agile manufacturing are: (i) virtual enterprise formation tools or metrics; (ii) physically distributed manufacturing architecture and teams; (iii) rapid partnership formation tools/metrics; (iv) concurrent engineering; (v) integrated product/production/business information system; (vi) rapid prototyping; and (vii) electronic commerce (Gunasekaran 1998). A review of some of the strategies and tools for AM has been presented in the following sections with a view to identifying how the current authors work can be positioned relative to methods and tools already available to design and change responsive and easily reconfigurable systems by managing complexities and uncertainties that impact on businesses.

Proponents of agility argue that agile manufacturing is a natural extension of lean manufacturing. It is argued that lean concentrates on high productivity and quality without responsiveness Thus a manufacturer whose primary aim is to be lean compromises responsiveness by seeking cost-effectiveness (Yusuf, Sarhadi et al. 1999). However agility should not focus only on flexibility and responsiveness but should also consider the cost and quality of goods or services. A number of significant differences exist however between lean and agility although they also share a number of similarities. In an enabling work by (Naylor, Ben et al. 199) and (Barlow 1998) a useful differentiation made, is based on relative emphasis on metrics which define value from both perspectives. They indicated that Lean Manufacturing emphasizes the need to reduce lead time through the elimination of waste and also with a view to reducing cost and enhancing value while agile systems focus on lead time reduction with a view to becoming responsive. They indicated that one main difference observed is the ability to cope with uncertainty. Agile enterprises may be seen as more robust and flexible and hence possess the ability to respond to variations and disturbances, whilst lean enterprises uses market knowledge and other associated information to ensure long term planning to enable them to become stable.

2.2.2.1 Virtual Enterprise (VE) formation tools and metrics

VE is defined as ‘a temporary alliance of member enterprises that share the same business opportunities that can be achieved through integration of each member’s core competence (Camarinaha-Matos and Afsarmanesh 2001; Haung, Wong et al. 2004). Thus in effect each functional aspects of a supply or value chain may be performed by different organizations. To fulfil the Agile manufacturing concept of flexibility, responsiveness and reconfigurability, VEs need to posses capabilities to perform virtual designs, virtual manufacture and virtual assembly. To enable this, VEs must share the same business semantics to allow common understanding about the business goals (Kim, Son et al. 2008). A major challenge reported (Gou 2000; Haung, Wong et al. 2004) in the establishment and ongoing management of VEs is achieving effective synchronization and integration of business systems. Xinyu (Xinyu 2006) suggests however, that it may be appropriate to integrate cross-functional business processes without involving major changes in the existing private processes.

A number of tools have been proposed to support VE as a strategy. This includes use of web based facilities to support parametric CAD/CAM systems through use of a data integrator (Parks, Koonce et al. 1994). Many application tools like CAD/CAPP/CAM/CAA can be assisted with the internet to provide useful resources for VE. For example an integrated Central Network Server (CNS) can link local FMS or CNC machines by means of cable connections; such that product information from local user inputs may be used as a basis for the CNS to generate CAD/CAPP/CAM/CAA files for controlling FMS or CNC machines to accomplish production processes (Wang, Rajurkar et al. 1996; Gunasekaran 1998). Wang and Rajurkar (Wang, Rajurkar et al. 1996) further proposed a network of manufacturing databases to enhance the operation of given VEs. Performance metrics were identified for evaluating effectiveness of specific VE's related to: time to identify the core competencies of partner-firms; new product development time; technology levels; innovation; flexibility; delivery performance; quality; inventory; virtual enterprise development time; profitability and IT skills (Gunasekaran 1998).

Also reported is that current methods of production planning and control are inadequate for operations management in VEs and may require (Tu 1997):

1. modelling of evolutionary and concurrent product development and production under continuous customer's influence;
2. real-time monitoring and control of the production progress in a virtual company;
3. a flexible or dynamic company control structure to cope with uncertainties in the market;
4. an adaptive production scheduling structure and algorithms to cope with uncertainties of the production state in a virtual company;
5. modelling of production states and control systems in a virtual company and
6. reference architecture for a virtual company

2.2.2.2 Physically distributed manufacturing architecture and teams

A physically distributed enterprise has been defined as a temporary alliance of partner enterprises located in different parts of the world, where each contributes their core competencies to take advantage of a specific business opportunity; or alternatively to fend off a market threat (Vastag, Kasarda et al. 1994; Gunasekaran 1998). Some supportive technologies includes electronic mail systems and networks, multimedia and video conferencing as well as distributed artificial intelligence and intelligent manufacturing systems. These technologies are yet to be fully utilized in Industries at large.

2.2.2.3 Rapid partnership formation tools and metrics

Rapid formation of appropriate strategic partnerships is a major requirement in an agile manufacturing environment. Partnership formation within VEs can provide firms with new technologies and products, critical resources, new markets and core competencies (Gunasekaran 1998). It therefore involves aligning strategies and pooling of core competencies based on the competitive strategies of the firm. Although partnership formation is a sub-function of VE formation, some of the rapid partnership tools are information technology that includes Multimedia, Internet, database, Microsoft Project, Case Tools and Electronic Data Interchange (Gunasekaran and Kobu 2002). The following set of metrics are necessary for rapid partnership formation:

benchmarking, review of past performance and their core competencies (Gunasekaran 1998). Also, a set of metrics based on both financial (e.g. rate of return on investment, sales revenue, profit, increase in market share) and non-financial (time to develop new products, time to reach new market, manufacturing cycle time, time to complete the partnership formation process) are necessary (Gunasekaran 1998). Other factors which should be considered as critical criteria when forming partnerships are: consistency of culture, market intelligence, number of distribution channels, new technologies, product development time and costs, flexibility, inventory turnover, R&D costs, and market share for new products (Meadel, Liles et al. 1997).

2.2.2.4 Concurrent Engineering (CE)

CE as defined by the Institute for Defence Analysis (IDA) as the systematic approach to the integrated, concurrent design of products and related processes including manufacture and support (Dwivedi, Sharan et al.). It indicates that new products are designed with inputs from all concerned. The main idea is to get manufacturing involved at an early stage of the design process so that non-essential design attributes which will lead to non value adding activities down the manufacturing processes are eliminated in time. The key strategy is to combine the application of CAE/CAD/CIM methods and tools with methods and tools used for design for manufacture; by getting manufacturers involved in early stages of design decision making. By doing so, potentially, the enterprise can be responsive to the market they serve and produce at lower cost thereby having a competitive advantage on price. Dubensky (Dubensky 1992) report that through the application of CE, many companies have benefitted from:

- involvement of all functions and personnel
- better processing considerations.
- improved manufacturing launch considerations.
- fewer revisions to the product after manufacturing has started
- a better product.
- improved worker involvement and satisfaction.
- management involvement and acceptance.

CE has been known to support agility (Gunasekaran 1998) and an integration of partner business processes and practices used by partner enterprises can be viewed as an extension of CE methods (Vastag, Kasarda et al. 1994).

There are a number of tools which can facilitate product development process in a CE environment. They include: functional analysis; CAM tools; NC verification; solid modelling; finite element analysis; optimization; design for cost; value engineering; design for manufacture; design for assembly; design for ergonomics; design for reliability; Failure Mode and Effect Analysis (FMEA); robust engineering; and Taguchi methods (Hills 1992). Again CE can be applied with advantage in the selection of partnership, rapid prototyping, rapid partnership formation, organizational restructuring and process reengineering in a virtual enterprise.

2.2.2.5 Integrated product/production/business information system

To achieve configurability, economically, in an agile manufacturing environment, Duffie and Prabhu (1996) and Gunasekaran (Gunasekaran 1998) state that, a consistent IT (software) representation of manufacturing entities is required. Such an IT representation should support the following functional objectives (Cho, Jung et al. 1996; Gunasekaran 1998):

1. Openness- reliance on published and widely implemented interface protocols, so that anyone can use and offer services through an agile infrastructure for manufacturing systems, including services that enhance the structure itself.
2. Scalability- the ability to access services across the shop floor or around the world using the same protocols
3. Extendibility and graceful degradation - services can be added, removed or substituted at any time, with incremental changes in performance
4. Compatibility- with legacy systems through encapsulation.

A useful extension of these requirements is the application of the ‘Standard for The Exchange of Product model data (STEP), virtual manufacturing architecture, information and communication infrastructure for component-based hierarchical shop floor control systems (Cho, Jung et al. 1996).

2.2.3 Process Re-engineering, improvement methodologies and tools

Since the development of manufacturing technologies, there has been an observed need to improve the means by which work is performed and also how work moves from one station to other stations. In fulfilment of these objectives and also to satisfy the requirements of CIM projects, process engineering has been the focus of attention for many researchers (Hammer and Champy 1993; Davenport and Beers 1995; Vernadat 1996; Chatha and Weston 2005). For effective implementation of CIM and also to ensure that products generated from MEs are meeting customer requirements, it is important to understand the processes used to generate these products. Melan (Melan 1993) defines a process as a bounded group of interrelated work activities providing output of greater value than their inputs by means of one or more transformations. Although this is true to some extent, not all processes necessarily generate value added outputs; thus the need often to reengineer a process to achieve improved operational performance. In organizations, processes can typically exist in the form of policies, operating procedures, manufacturing processes, administrative processes and rules (Vernadat 1996). Many researchers have provided definitions for 'processes' but notably, these definitions were extended to introduce the term 'Business Processes' (BPs) (Davenport and Beers 1995; Vernadat 1996; Laudon and Laudon 2002). Davenport (Davenport 1993) indicates that BPs are structured measured set of activities designed to produce specified outcomes for a customer or a given market. But Vernadat (Vernadat 1996) extended the earlier definitions and explained that BPs consist of ordered sets of activities whose execution is triggered by some event and have the potential to generate observable or quantifiable outcomes. A study of these definitions show that the elemental constituent of a BP is activities.

Different strategic approaches to process engineering have been developed and deployed in many organizations. A suitable process engineering approach can enable improvements associated with processes to be achieved. Two main schools of thought about process engineering can be observed in the literature and have been reviewed in this thesis. These are: Business Process Re-engineering (BPR) (Hammer and Champy 1993; Harrison and Pratt 1993; Guha, Grover et al. 1997) and Enterprise Engineering with its associated modelling and Integration formalisms (Doumenigts, Chen et al. 1992; Scheer 1992; Lutherer, Ghroud et al. 1994; Zelm 1995; Bernus and Nemes 1996; Kosanke 1996; Vernadat 1996; Williams 1998; Weston 1999; Monfared 2000; Chatha, Weston et al. 2003; Ajaefobi 2004). .

2.2.3.1 Business Process Re-engineering

Business Process Reengineering (BPR) can be described as a process improvement methodology. In this Thesis, process improvement is distinguished from process optimization which tend to deploy some well established techniques like Simulated Annealing and Genetic Algorithms . Literature on process optimization using these techniques fall outside the scope of this research. Therefore the focus of this research is limited to process improvement.

Process improvement requires the rethinking of business processes to improve and accelerate the output of processes, materials and services (Curran and Keller 1998; Ajaefobi 2004). The BPR method is described by Hammer and Champy as the fundamental reconsideration and radical redesign of processes used by an Organizational, in order to achieve drastic performance improvement such as in cost, services and speed (Hammer and Champy 1993). It is typically centred on a simplification of enterprise processes to reduce excessive delays or cost in enterprise operations (Vernadat 1996). The proponents of BPR, Hammer and Champy, in a series of books including Reengineering the Cooperation (Hammer and Champy 1993) and Reengineering Management (Hammer and Champy 2003), argued that it is far more efficient to organize working teams around complete processes rather than organizing firms around functional specialities.

Because of the complexities and cross functional nature of business processes (Berztiss 1996), experts in Enterprise Engineering recommend that core business processes must be modelled first then analysed and finally reorganized (Bernus and Nemes 1996; Weston 1999). This is necessary since by adopting this approach Businesses can benefit from detail analysis of their processes and emerging information technologies (Schal 1998).

Four main keywords have been identified to be instrumental in the establishment of BPR (Hammer and Champy 1993). These are :

1. Fundamental: answering why a company does things a certain way
2. Radical: understanding the processes and making reinventions instead of minor enhancements
3. Dramatic: focussing on achieving quantum leaps
4. Processes: focussing on processes instead of tasks, jobs, people or structures

Chen and Tsai (Chen and Tsai 2008) observed that, literature on BPR shows three main streams of research related to BPR. These streams are:

1. Studies of implementation strategy (Earl, Sampler et al. 1995; Stoddard and Jarvenpaa 1995; Bititci and Muir 1997; Soliman 1998);
2. Studies of implementation models (Davenport and Beers 1995; Chan and Choi 1997; Kettinger, Teng et al. 1997); and
3. Studies of the critical success factors involved (Grover, Fiedler et al. 1999; Thong, Yap et al. 2000; Hengst and Vreede 2004).

In Earl's research on implementation strategies for BPR projects (Earl, Sampler et al. 1995) four main BPR strategies was reported - ecological, bureaucratic systems and engineering. Two other strategies have been recommended: evolutionary and revolutionary (Stoddard and Jarvenpaa 1995). The revolutionary approach was observed through their case study application to be appropriate at early stages of implementation than the latter stage (Chen and Tsai 2008).

Although it has been reported that BPR has been successfully implemented in some companies, 70% of BPR projects reviewed by Yogesh (Yogesh 1998) were found to be unsuccessful. The major attributing factor identified was the ignorance of human elements in process redesigns. Yogesh reported that major BPR projects resulted in massive layoffs. Furthermore:

1. BPR assumes that the factor that limits organization's performance is the ineffectiveness of its processes yet does not provide any means to scientifically validate this assumption.
2. BPR completely disregards the status quo and recommends a radical process improvement.
3. BPR does not provide any means to focus on the constraints of the organization.

As a result, Davenport (Davenport 1993) argued that a moderate approach towards BPR was essential. His approach centred on 'process innovation', where this involves continuous process improvement with clear overall business objectives (Davenport 1998). He further proposed a five-step approach to BPR as follows:

1. Develop the business vision and process objectives
2. Identify the business processes to be redesigned
3. Understand and measure the existing processes
4. Identify Information Technology levers
5. Design and build a prototype of the new process

For successful implementation of BPR, other methodologies and tools have been developed. Some of these implementation techniques were built upon well established manufacturing strategies. For example, based on already existing Group Technology (GT) approaches, Burbidge (Burbidge 1991) developed a BPR implementation technique for batch and job shop production systems. This technique involved: (i) company flow analysis (CFA); (ii) factory flow analysis (FFA); (iii) group analysis (GA); (iv) line analysis (LA); and (v) tooling analysis (TA). This work was extended by Macintosh (Macintosh 1997) into what was later to be termed 'information flow analysis' (IFA). This involved some degree of information modelling which is used as a basis to group products so as to form new groups. Other separate works by (Gunasekaran and Kobu 2002) and (Jang 2003) utilized IT to provide support for re-engineering business processes. Earlier on, Soliman (Soliman 1998) had recommended process mapping as an essential technique for BPR. He indicated that during the initial steps to BPR, process mapping techniques could be used to capture the existing process routings and based on the objective of the BPR, various types of analysis and evaluation can be done using the maps so generated. Typically non-value adding processes can be observed but the challenge is to identify which type of process mapping technology to deploy (Soliman 1998). Attempt has therefore been made in this Thesis to review some of the existing mapping technologies with a view of unearthing complementary mapping tools that can support the capture of key attributes of value streams and process costs.

2.2.3.2 Mapping of processes

Initially recorded mapping of work processes was conducted over the period 1890 to 1900 by the early Industrial Engineers (Lee 2005). Over this period, Frederick Taylor developed standardized work and time study concepts (Muhlemann, Oakland et al. 1992). Taylor's concepts have now been improved upon significantly. Other school of thoughts claim that in essence what Taylor's concepts achieved was the introduction of purpose, rationality and methodology for managing processes (Smith and Boyns 2005). Taylor postulated that there is only 'one best way' of doing any assigned task and it is the responsibility of Management to identify it (Taylor 1911; Muhlemann, Oakland et al. 1992). He explained that a failure to identify and recommend the best way of achieving results to the work force leads to inefficiencies. Theories propounded by Taylor in relation to processes and management requirements have currently been bound together and termed a 'scientific school of management' (Taylor 2003). Closely related to Taylor's development in the area of process management was the work of Frank Gilbreth who is often deemed to be the originator of the first mapping system; which later came to be known as 'process charting' (George 1968). A use of flow process chart was introduced to the American Society of Mechanical Engineers (ASME) by Gilbreth in 1921 in a presentation dubbed "Process Charts—First Steps in Finding the One Best Way" (Lee 2005). Gilbreth viewed work as a process and started developing symbols and conventions for work categorization. Allan H Mogesan, around 1930 to 1940, developed these ideas into the concept of work simplification, which essentially emphasizes Gilbreth's charting methodology (George 1968; Pluto and Hirshorn 2003; Lee 2005). Process charts were further simplified into 'flow charts' and popularised through work of Goldstine (Goldstine 1972). Recent work of Sterneckett (Sterneckert 2003) classified flow charts based on their application. Sterneckert (Sterneckert 2003) identified four main general types of flow chart:

1. Document flowcharts, which shows document flows through a system
2. Data flowcharts, which shows data flows in a system
3. System flowcharts, which shows controls at a physical or resource level and
4. Program flowcharts, which show the controls in a program within a system .

Historically, various types of maps have existed under different names, often based on their primary application domain. Although the term flow chart has dominated in many sectors, it is known also that in the 1950s, Shingeo Shingo deployed different process mapping techniques to physically depict flows of work and products and further used these maps as the basis for optimizing processes to achieve better efficiencies at Toyota (Foner, Eric et al. 1991; Shingo 1992). Shingo's mapping technique became an important facet of the Toyota Production System (TPS). This became widely known as 'Lean manufacturing', after Womack and Jones published their book 'The machine that changed the world' (Womack, Jones et al. 1990). Later on Rother and Shook in their book 'Learning to See' identified and popularised this kind of map referring to it as a 'Value Stream Map' (Rother and Shook 1996). The works of Hines and Nick (Hines and Nick 1997) brought together a set of seven mapping tools:

1. Process activity mapping
2. Supply chain response matrix
3. Logistics pipeline map
4. Production variety funnel
5. Quality filter mapping
6. Demand amplification mapping
7. Value adding time profile

They report that these tools have been adopted industrially for the preliminary analysis of processes depending on the variable which needs to be managed. In a related work by Hines and Taylor (Hines and Taylor 2000) a set of seven tools were collectively called value stream maps. They argued that although they exist independently, to ensure value addition to a given processes, there will be the need to simultaneously deploy some of the tools. Further research work by Bicheno (Bicheno 2000) introduced six sigma; kaizen; push-pull maps; cost time maps; business process maps; order fulfilment maps; overall lead time maps; physical structure and value stream maps into the public domain. A brief review of some of the mapping tools is reported in the following sections; but in view of the research interest of the present author, extreme focus and emphasis was placed on value stream mapping.

2.2.3.2.1 Process activity mapping

Process activity mapping is a technique derived from engineering schools and is normally used for charting the order fulfilment process of shop floors (Hines and Nick 1997). It has been widely used to identify lead time and productivity opportunities in respect of physical and information flows. The concept is to map out every activity step that occurs in the order fulfilment process. Such a process involves identifying the list of activities involved in the order fulfilment process and then in a tabular form, detailing the total 'distances' required to be travelled and time needed to complete the individual activities outlined. With the data gathered, analysis related to Operations (O), transport (T), Inspection (I), Delay/storage (D) can be conducted based on the time used for these functions.

2.2.3.2.2 Production variety funnel

This technique attempts to plot the number of product variants at each stage of the manufacturing process (Hines and Nick 1997). This provides logical reasons for product diversity and the need to maintain such complexity for the supply chain. It tends also to suggest the logical point at which buffer stocks can be held before customisation. The technique is therefore suitable for investigating the point of the manufacturing process at which postponement may be introduced. On this map the point where there is a sudden rise (which is considered to be the neck of the funnel), becomes a point of possible customization and postponements.

2.2.3.2.3 Logistics pipeline map

This map plots inventory levels against process time (Hines and Nick 1997; Hines and Taylor 2000). It therefore highlights the capacity to reduce process time in favour of inventory reduction.

2.2.3.2.4 Quality filter mapping

This map helps to identify quality problems in the order fulfilment process or the wider supply chain (Bicheno 2000; Hines and Taylor 2000). It further shows where three different types of quality defect: product, scrap and service occur in the value stream. The approach integrates quality and logistics performance measures. It is designed to establish both internal and external quality levels as well as levels of customer service.

2.2.3.2.5 Demand amplification mapping

This is a graph of quantity against time, showing the batch sizes of a product at various stages of the production process (Hines and Taylor 2000). An important result of the demand amplification map is to show the ‘bullwhip’ or ‘Forrester effect’. It is also useful for examining scheduling and batch sizing policies, and inventory decisions.

2.2.3.2.6 Value adding time profile

The value adding time profile plots the accumulation of both value adding and non value adding costs against time (Bicheno 2000; Hines and Taylor 2000). It is an excellent tool for looking at time compression or mapping out where money is being ‘wasted’. The difference between the total cost line and the value adding line represents the cost of the wastes. The area under the total cost line represents the amount of money tied up in a unit of inventory. Differences between various types of waste can also be seen.

2.2.3.2.7 Value Stream mapping

As explained in previous sections, the focus of this research is partly to investigate existing methods of modelling value streams and process cost and how they enable the design of manufacturing processes and instrument the optimization and efficiencies of processes. Based on this driving need, a review was conducted to understand the concept of value streams from socio-economic, engineering and business schools of thought.

2.2.3.3 The concept of Value streams

Modern day understandings about the economic 'essence of value' is born from old philosophical notions developed by classical and political economists (Rand 1993; Menger 1997; Moser 1997; Cox 1998). These form the basis of the objectivity and subjectivity theories of value (Rand 1993; Moser 1997) and the labour and intrinsic theories of value (Ricardo 1823; Marx 1865). These theories although very old, serve as the backbone for many current economic theories on national development, value and profit realization.

For purposes of Engineering applications, disciplines such as Industrial and Value Engineering have rendered alternative meanings to the concept of value (Ho 1995). Also Lean thinkers and Business schools have indicated other working definitions of value, for economic and process improvement reasons (Womack and Jones 1996). The major motivation in trying to provide a comprehensive understanding of the term is that, understanding the meaning of value will help in the design of appropriate value creation processes and the production of products and services of high values. With an appropriate working definition of value which ensures that values are quantified properly, MEs will be able to measure values created along process stages and be able to distinguish between processes that add or do not add value.

2.2.3.3.1 Sociological and Economic perspectives of value

One of the profound research findings, called 'objectivist theory of value', was proposed by Ayn Rand (Rand 1993). This theory tends to explain the worth of goods and services as a relationship between intrinsic, observable attributes in nature, human knowledge of these attributes, and how these attributes can satisfy the subjective needs of humans. The theory relies on five pillars as expressed below:

1. Reality exists independently of perception: Rand explained that if humans did not exist, reality would still have been. This implies that there are some intrinsic properties of reality which humans can observe, analyse, learn and benefit from them.
2. Humans have unique needs: He observed that there are universal needs and unique individual needs. For example basic necessities of life such as water, food and shelter can be

deemed as universal needs. whilst needs like sight glasses, mobile phones could be classified as unique individual needs. Hence needs are subjective.

3. Humans survive by reason: The third pillar of the objectivist theory states that humans, unlike animals, satisfy their needs through the accumulation and application of knowledge about facts and properties of reality.
4. Value is an objective relationship: Rand summarised and concluded his views by citing a notable story of the caveman in need of meat:
   - The caveman has a need for fresh meat
   - The caveman observes that a rock falling on an animal kills it
   - After many such observations, the fact that a rock has the property 'kills animals', becomes part of the caveman's knowledge of reality.
   - Because of this knowledge, rocks become **valuable** to the caveman as a tool for getting fresh meat.

He explained that the value of the rock as being able to kill animals is dependent on: 1) the intrinsic property of the rock as being hard and 2) the subjective need for meat by the caveman. Although this may be true, in the case of the vegetarian who has no use for meat, the value of rock will be something else.

One of the well established theories of value in economics is termed the labour theory. It proposes that the value of a product or service is related to the labour needed to produce the product or service (Junankar 1982; Peach 1993). Different forms of the labour theory was proposed earlier by Classical Economist like Smith (Smith 1776), Ricardo (Ricardo 1823) and later by Karl Marx (Marx 1865). However modern mainstream Economists consider the theory to have been superseded by the marginal utility approach (Sraffa and Maurice 1951; Ramsay 1992; Peach 1993).

Adam Smith explained that: 'the real price of everything, what everything really costs to the man who wants to acquire it, is the toil and trouble of acquiring it. What everything is really worth to the man who has acquired it, and who wants to dispose of it or exchange it for something else, is the toil and trouble which it can save to himself, and which it can impose upon other people' (Smith 1776).

By his definition, labour is in the form of pain, toil or a kind of difficulty. Hence labour which is pleasant is either partly labour or not labour at all (Peach 1993). However he classified highly skilled labour as capital, leading to the new concept of human capital. Once again in the words of Adam Smith: ‘the word **VALUE**, it is to be observed, has two different meanings, and sometimes expresses the utility of some particular object, and sometimes the power of purchasing other goods which the possession of that object conveys. The one may be called 'value in use’ ; the other, 'value in exchange.' The things which have the greatest value in use have frequently little or no value in exchange; and on the contrary, those which have the greatest value in exchange have frequently little or no value in use. Nothing is more useful than water: but it will purchase scarce anything; scarce anything can be had in exchange for it. A diamond, on the contrary, has scarce any value in use; but a very great quantity of other goods may frequently be had in exchange for it’ (Smith 1776).

Implicitly, value ‘in use’ means the usefulness of the commodity whilst value ‘in exchange’ means price. Smith further explained that value ‘in exchange’ is relative to labour. Thus ‘the value of any commodity, ... to the person who possesses it, and who means not to use or consume it himself, but to exchange it for other commodities, is equal to the quantity of labour which it enables him to purchase or command. Labour, therefore, is the real measure of the exchangeable value of all commodities’ (Smith 1776). This means the value of a product or service increases in proportion with the labour involved in the production of the product. Value ‘in use’ is similar to the objectivist theory proposed by Rand. An approach toward quantification of labour is therefore linked to value in exchange which is often the price of the commodity. This later explanation introduced several controversies.

Marx (Marx 1865) argued that if value is the same as price as proposed by Smith, then the unanswered question is the basis for deriving profits. Since most Companies are driven by the urge to obtain profit then value should be a measure of something else other than the labour cost. He further argued that the theory is vulnerable to the charge of tautology in that it explains prices by prices (Marx 1865). Ricardo (Ricardo 1823) responded to the paradox by arguing that Smith had confused labour with wages. He distinguished between labour and wages by explaining that ‘labour commanded’ is the value of the entire product created by labour, whilst ‘labour sustained’ is the wages paid for labour or services rendered. The former would always be higher than the latter and the difference becomes the profit related to the product or service.

Karl Marx later explained that the price of a commodity is different from its value although there exist a form of relationship influenced by demand and supply. He quoted Adam Smith and summed up as: ‘it suffices to say that if supply and demand equilibrate each other, the market prices of commodities will correspond with their natural prices, that is to say, with their values as determined by the respective quantities of labour required for their production' (Marx 1865). Most economist who held this view claimed that for products to be comparable, there must be a common element by which they can be measured and the commonest substance for almost all products and services is labour.

Subjectivity theory of value unlike the others, states that, to possess value, an object must be both useful and scarce and has the ability to satisfy the wants of individuals (Moser 1997). It contrasts with the labour theory of value that holds that there is an objectively correct value of an object that can be determined irrespective of individual value judgements, such as by analyzing the amount of labour incurred in producing the object. The foundation of this theory is that for anything to be valuable :

1) it must have a need and be desired
2) it must be scarce or just enough to satisfy demand.

It stands to reason that only needed items that are in limited supply can be valuable whilst the opposite could have no economic value and hence become free to society. A key view of this theory is that an individual purchases a product because he values it more than what he offers in exchange. On a similar note the seller agrees to trade only if he values the good less than the price being offered.

Menger in expanding this theory to form the marginal utility concept confirmed that: "the measure of value is entirely subjective in nature, and for this reason a product can have great value to one economizing individual, little value to another, and no value at all to a third, depending upon the differences in their requirements and available amounts. Hence not only the nature but also the measure of value is subjective. Therefore products or services always have value to certain economizing individuals and this value is also determined only by these individuals" (Menger 1997).

Quite differently, value is seen from sociological perspective as the abstract ideas about what a society believes to be good, right, and desirable (Wetherell 1996). They form the qualities of behaviour, thought and character that society regards as intrinsically good which are worthy of emulation by others. The sociological view is often regarded as subjective since it depends on humans interpretation of the world around them which could be based on environmental, cultural or societal influences on individuals.

2.2.3.3.2 Engineering and Business perspective of value

The origin of value analysis, also known as value engineering, is closely associated with the Industrial community in the United States who in the 1940s needed to identify alternatives to raw materials that were in short supply as a result of the devastating effects of the World War II (Miles and Erlicher 1947). It was traditionally applied to reduce cost of projects, processes and services, with the view of improving performances which will ensure competitiveness and profitability (Tantawy 2003). The basic goal over here was to improve value realization. Initial work in this area defined value as a ratio of output (function) to the input (cost) (Ho 1995). Thus mathematically,

Value = Functions/costs …. (i)

Based on this mathematical definition, Ho (Ho 1995) deduced that there are five main ways of improving the value of a product. These are:

1. reducing functions and cost at the same time
2. keeping functions at the same level and reducing cost
3. increasing functions and keeping cost at the same level
4. increasing functions and reducing cost
5. increasing functions more than cost

He further explained that due to the practical limitations in implementing the first four options, the only practical way to improve value is to increase functions more than cost (option 5). This means that value can be enhanced essentially by increasing functionalities of products, processes or services at the expense of cost, although it is practically difficult to achieve. A clear limitation with this approach was that it was difficult to quantify functionalities in financial terms hence making value a subjective measure. An alternative approach recommended by some researches is to define value as a ratio of importance to cost, where importance refers to fulfilment of product design specifications, product functionality and reliability, customer requirements, aesthetics etc (Partovi 1994). Hence

Value of business process = (Importance of business process) / (cost of business process) **…….. (ii)**

Over here, importance is derived by interviewing relevant personnel about the relative importance of one operation to the other (Rashid, Agyapong-Kodua et al. 2008). A graph of importance in percentages against that of cost is plotted to identify which operations have lower values so that they could be improved by employing Industrial Engineering tools and quality monitoring techniques. Analytical Hierarchical Process (AHP) has proven to be an effective technique for complex decision making and measuring relative importance of one process (decision) over the other (Saaty 1980). The outcome of AHP is a prioritized ranking or weighting of each decision alternative. Three steps often feature in the application of AHP. These are:

- constructing hierarchies,
- comparative judgment;
- synthesis of priorities.

‘Constructing hierarchies’ requires that complex decisions are structured into a hierarchy descending from the overall objective to various ‘criteria’, ‘sub-criteria’, and so on until the lowest level. During the comparative judgment stage, prioritization of elements at each level (‘elements’ means number of the hierarchy) is done. A set of comparison matrices of all elements in a level of the hierarchy with respect to an element of the immediately higher level are constructed so as to prioritize and convert individual comparative judgments into ration scale measurements.

Concepts related to value streams, developed by the MSI Research Institute of Loughborough University normally analyses historical selling prices of case study companies. Sales and market reports form the basis of estimating values generated by respective sections of the Company. To estimate values that have been or in theory could be, historical work patterns are also taken into consideration. In principle, value is considered as an intrinsic property of the product or service which is dependent on the resource inputs necessary for the derivation of their final states, but the marketability of the product or service is essentially dependent on how customers assume the value of the product or service in relation to its ability to solve their needs and its relative competitiveness in terms of prices of substitute products or services (Agyapong-Kodua and Weston 2007)

A commonly accepted view of value in the manufacturing industries is derived from the lean manufacturing philosophy. Lean thinkers associate value with waste (Womack, Jones et al. 1990; Shingo 1992; Bicheno 2000; Hines and Taylor 2000; Roll 2003) and thus define value as any activity that transforms a product in a way the customer is willing to pay (Womack and Jones 1996). A study of the lean value stream mapping concept depicts that value is perceived by lean thinkers as being related to the reduction or elimination of the seven forms of waste (Bicheno 2000). Based on the lean concept, Jones and Womack defined a value stream as the sequence of processes, including value adding and non value adding, identified from the raw material to the final customer (Jones and Womack 2003). Bicheno (Bicheno 2000) also view value streams as the set of activities needed to provide a particular product or service. To visually identify and best understand value streams, Lee (Lee 2005) promotes mapping as the best approach since it leads to consensus on systemic problems and remedies.

2.2.3.4 Mapping Value Streams

From previous definitions of value streams, Jones and Womack (Jones and Womack 2003) specified value stream mapping (VSM) as a simple process of directly observing the flows of information and materials as they now occur, summarizing them visually, and then envisioning a future state with much better performance. Lian and Van Landeghem (Lian and Van Landeghem 2007) notes that VSM is a mapping paradigm used to describe the configuration of value streams. However (McManus and Millard 2002) indicate that VSM is a method by which value stream analysis are illustrated. They defined value stream analysis (VSA) as a method by which managers and engineers seek to increase the understanding of their company's development efforts for the sake of improving such efforts. In response McDonald and his colleagues (McDonald, Aken Van et al. 2002) observed that a value stream comprises all the value-added and non-value-added actions required to bring a specific product, service, or combination of products and services, to a customer, including those in the overall supply chain as well as those in internal operations. By this definition they denoted that VSM is an enterprise improvement technique to visualise an entire production process, representing information and material flow, to improve the production process by identifying waste and its sources.

A significant body of literature has attempted to systematize the approach to mapping value streams. Notable among these are the works of the Lean Enterprise Research Centre, Cardiff Business School, UK (Hines and Taylor 2000), Rother and Shook (Rother and Shook 1996), Duggan (Duggan 2003), Womack and Jones (Jones and Womack 2003), Hines and Nick (Hines and Nick 1997) and the work of Lee of Strategos Inc, USA (Lee 2005).

The Lean Enterprise Research Centre in their research funded by Engineering and Physical Science Research Council identified five main steps to follow in an attempt to map value streams of an enterprise (Hines and Taylor 2000). This approach was to answer series of question related to shop floor issues. Whilst these answers are generated, mapping constructs are indicated systematically to finally generate the current state map by the fifth stage of the process. The stages identified were:

1. Customer requirements
2. Information flows
3. Physical flows
4. Linking physical and information flows

5. Completing the map

Guartema Lee in his latest book ‘Strategos guide to Value Stream and Process map’ did extensive work in recognizing some other steps required in the generation of current and future state value stream maps (Lee 2005). He indicated that although a completed map seems complex a sequential follow up of the sixteen steps in modelling current state maps is ideal for generating a concise map. He identified the steps as:

1. Draw customer, production and supplier icons
2. Enter customer requirements
3. Calculate daily production and container requirements
4. Draw outbound shipping icon
5. Draw inbound shipping icon
6. Draw boxes for each process sequentially
7. Add data boxes
8. Add communication arrows
9. Obtain process attributes
10. Add operator symbols and numbers
11. Add inventory locations and levels
12. Add push, pull and FIFO symbols
13. Add any information that might prove relevant
14. Add working hours
15. Calculate lead times
16. Calculate total cycle time and overall lead time’.

Lee further identified that creating the future state map requires in-depth understanding of lean principles. He therefore categorized the development of the future state maps into nine main steps. These are:

1. Review the present state map
2. Calculate takt time
3. Identify bottleneck processes
4. Identify lot sizes and setup opportunities
5. Identify potential work cells
6. Determine kanban locations
7. Establish scheduling methods
8. Calculate cycle time and lead time

9. Add kaizen Bursts

He iterated that when these steps are carefully followed, a good value stream map can be achieved.

It has been well accepted within the lean circles that VSM has great potential to improve production systems: Pavnaskar (Pavnaskar, Gershenson et al. 2003) argues that:

- The analysis of the initial situation is based on the acquisition and treatment of numerical data and uses a graphical interface that makes it easier to see the relationship between material and information flows
- The systemic vision provided for each product family reflects manufacturing system inefficiencies. This is also highlighted by (Jones and Womack 2003)
- A common language is provided for the team to unify lean concepts and techniques in a single body. This is also highlighted by (Baker 2003)
- There is the possibility of it being the starting point of strategic plan improvement (Gregory 2003).

One clear issue about VSM worth investigating is the possibility of it being a useful tool for manufacturing systems redesign especially in a complex multi-product environment. A number of researchers have provided insight on this aspect of manufacturing process engineering. Typically they have indicated some limitations with the VSM technique. Some of the limitations highlighted include:

- Because it is a ‘paper-and-pencil-based’ technique, the accuracy level is limited, and the number of versions that can be handled is low (Braglia, Carmignani et al. 2006; Lian and Van Landeghem 2007);
- In complex manufacturing environments with multiproduct flows, it is extremely difficult to map all the process routes (Duggan 2003; Braglia, Carmignani et al. 2006; Agyapong-Kodua, Ajaefobi et al. 2009)
- It is not also suitable for dynamic analysis (McDonald, Aken Van et al. 2002; Agyapong-Kodua, Ajaefobi et al. 2009).

Based on a review of existing literature on methodologies and tools for the redesign of manufacturing systems, Serrano (Serrano, Ochoa et al. 2008) noted that there are three other sets of schemes which researchers are applying to achieve enhanced results as compared to the the results provided by the VSM technique. His assertion was based on Wu’s (Wu 1996) argument that a manufacturing system could be structured as the aggregation of three subsystems:

1. a physical or operational subsystem, referring to material flow
2. an informational or auditory subsystem, referring to information flow and
3. a decisional or managerial subsystem, referring to the process of decision-making.

From this perspective, VSM is viewed to partially represent aspects of the material and informational subsystems. Serrano (Serrano, Ochoa et al. 2008) after evaluating the performance of VSM in manufacturing systems design indicated that in broad terms: flow diagram charts; structured systems; Architectural systems; modelling and simulation software are the four main tools currently deployed for manufacturing systems redesign and engineering. He classified VSM and all the process mapping tools as flow diagram charts. The set of methodologies classified as structured systems were:

- IDEF0 (Icam DEFinition Zero) (Roboam 1993)
- SADT (Structured Analysis and Design Technique) (Marca and McGowan 1988)
- SSADM (Structure System Analysis and Design Method) (Ashworth 1988)

He identified:

- GRAI (Graphes a` Resultats et Activite´ s Interrelie´ s) (Doumenigts, Chen et al. 1992)
- CIMOSA (Open System Architecture for CIM) (Kosanke 1996; Vernadat 1999; CEN/ISO 19440)
- PERA (Purdue Enterprise Reference Architecture) (Williams 2002)

as Architectural systems suitable for manufacturing systems redesign. Also he noted that material and information flow modelling and simulation software programmes are also good tools for redesigning manufacturing systems (Wu 1996). Different software packages in this area can be divided into two groups: discrete event simulation and dynamic systems software. In spite of their dynamic character, level of accuracy and quantitative nature, their having a focus similar to the VSM framework, acquiring the required software, providing training and investing the amount of time necessary could be important reasons why the software is not so useful in many companies (Baines, Harrison et al. 1998; Oyarbide 2003; Aguilar-Save´n 2004; Serrano, Ochoa et al. 2008)

In broad terms, the present author has classified these manufacturing systems redesign tools, with capabilities to support value stream mapping, into 1. Enterprise modelling and 2. simulation tools. The next sections review existing tools and techniques under these categories. Their relative strengths and weaknesses have been highlighted with the view to identify how these techniques can complement each other on the value stream mapping vision.

2.2.4 Enterprise modelling and applications

Basically, modelling is a technique for deriving a simplified or idealized description of a system, situation or process (Askin 1993). They are often supported by underlining set of mathematical equations or logical relationships (Batur, Srinivasan et al. 1991). Physical models provide visual aids for checking and verifying the desirability of designs. Mathematical models however use decision variables to create models which are capable of mimicking the real-time conditions of systems (Carrie 1988). This could be descriptive or prescriptive in nature. The goals of enterprise and simulation modelling, however go beyond this (Carrie 1988; Rahimifard and Weston 2006; CEN/ISO 19440). The extended objective is to model relevant business processes and enterprise objects concerned by business integration (Vernadat 1996).

Enterprise modelling is a generic term which covers the set of activities, methods, and tools related to developing models for various aspects of an enterprise (AMICE 1993; CEN 1994). Basically, it is the art of externalising and formalising structural and behavioural knowledge about how an organisation is organised, how it works and to some extent how it performs (Bernus and Nemes 1996). The aim is to build models to represent, analyse, design and simulate various facets of an organisation (for example, functional, information, resource or decisional aspects) as well as various flows (for example. control, information or material flows) (AMICE 1993). Depending on their level of details and precision, these models can serve as the basis for enterprise/business reengineering. They can be shared among users as a means of communication and support systems interoperability, as well as controlling enterprise operations (Scheer 1992).

Some common modelling capabilities attributed to enterprise modelling include (Rahimifard and Weston 2006):

- It enables attribution of multi-perspective model views to models of process segments.
- It can represent (and help communicate/visualise) unified views of multiple stake holder
- Generates common representation of ME processes and systems that can inform/support/unify various forms of decision making
- Has abstraction and generalisation concepts which facilitate the generalisation reuse of models, such as in creating reference models of processes and resource systems
- Plays a major role in enterprise engineering and enterprise integration

It has also been reported that by (Rolstadås 2000), that Enterprise Modelling provides a number of benefits which include:

- Saves time and money by analyzing how change affect businesses, then can help determine the best solution, and can help map the solution onto existing systems.
- Assists organizations with altering business strategies, allowing them to take a picture of where the business is today and to map the solution to existing information systems.
- Generates models that provide framework for understanding business processes determining the impact of business events and defining how the processes interact with the data flowing through the organisation.
- Supports multiple modelling techniques in one tool integrating three key business perspectives to serve the needs of business and technology users.
- Helps verify that information architectures support the business processes
- Helps provide workgroup and enterprise wide model collaboration..

Despite these observed benefits, Rahimifard and Weston (Rahimifard and Weston 2006) have reported that enterprise models do not have sufficient semantics suitable for representing process changes and instances where process mixes and volumes are or could in the future be affected. Also alternative manufacturing, logistic and business policies cannot be suitably tested without any enhancement of ‘current state’ of enterprise models. They affirm that, in principle, enterprise models represent static states of business operations and hence requires other complementary techniques to make them dynamic.

2.2.4.1 Enterprise modelling techniques and methodologies

A number of public domain Enterprise modelling architectures, methodologies and techniques have been conceived to facilitate key aspects of process oriented organisational design and change. Currently there are many independently developed techniques for designing and implementing phases of an organization. One of the most important results derived from the ESPRIT projects is the Computer Integrated Manufacturing Open System Architecture (CIMOSA), its supporting modelling tools and validation in industrial environments (AMICE 1993; CEN/ISO 19440). Other key researchers have demonstrated how the application of CIMOSA methodologies and framework can help capture salient process oriented elements in organizations (Lutherer, Ghroud et al. 1994; Zelm 1995; Kosanke 1996; Vernadat 1996; Weston 1999; Monfared 2000; Chatha, Weston et al. 2003; Ajaefobi 2004; Weston 2005). Many other enterprise modelling architectures are currently in use. This includes Purdue Enterprise Reference Architecture which was published by Williams (Williams 1992), to provide a generic enterprise model reflecting the full life cycle of enterprises. It is claimed that PERA uniquely provides a formal way to identify optimum levels of automation and addresses continuous processes and discrete parts manufacturing (Williams 1998). Some known enterprise modelling tools are Architecture for Integrated Information Systems (Scheer 1992); Generic Enterprise Reference Architecture and methodology (Bermus and Nemes 1996) and GRAI-GIM, a framework and modelling tool developed by the University of Bordeaux (Doumenigts, Chen et al. 1992).

2.2.4.1.1 CIMOSA

CIMOSA (AMICE 1993; Vernadat 1996) was developed by AMICE (a consortium of 30 major European vendors and users of Computer Integrated Manufacturing systems including IBM, HP, DEC, Siemens, Fiat, and Daimler-Benz for European Strategic Program for Research and Development in Information Technology (ESPRIT) project. The project was started in 1985 and completed in 1996.

Characteristic of the CIMOSA is the CIMOSA Cube, which is a representation of the modeling framework (see figure 2).

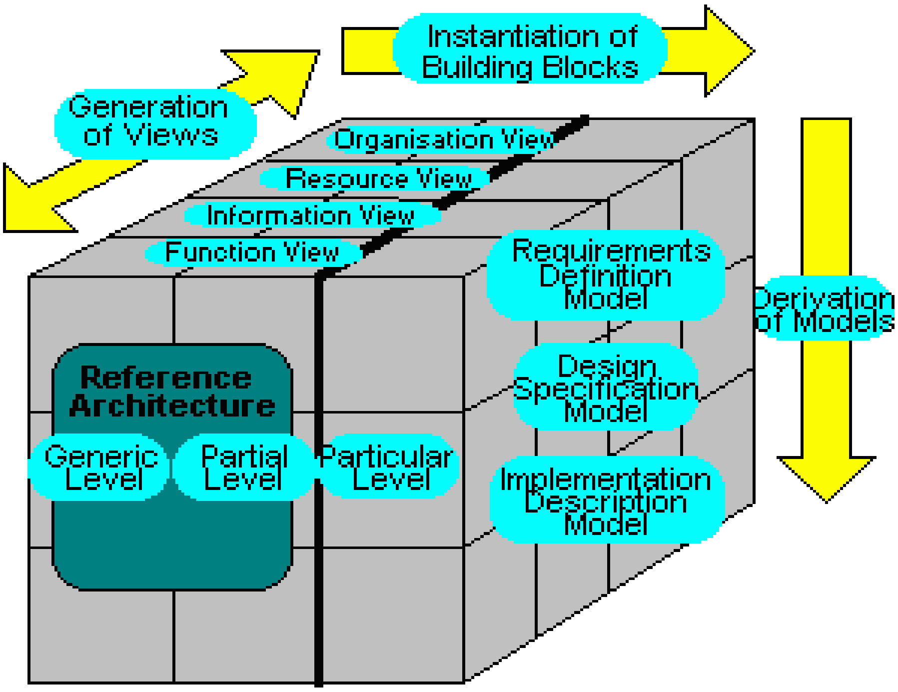


Figure 3 CIMOSA cube (AMICE 1993; Vernadat 1996)

From the cube it can be observed that each face of the cube specifically represents a relevant aspect of modelling. For example, the reference architecture is divided into generic, partial and particular levels, each supporting different views of the enterprise model. This attribute allows one to work in a subset of the model instead of looking at the complete model. This thus reduces the level of complexity that would have otherwise been involved. The modeling views are also divided into function, behaviour, information, organization and resource. These sets of views may be extended as per the intent of the model.

The life cycle dimension of CIMOSA encompasses 'Requirements Definition', 'Design Specification' and 'Implementation Description'. This again may be extended or started at any of the life cycle phases depending on the purpose of the model. The Requirement Definition level decomposes the goal of the enterprise for gathering business requirements whilst the Design Specification Level gives alternative technical choices and designs which are evaluated in order to select the best available technical solution and specify optimised system-oriented representation of the business requirements. The Implementation Description Level ensures an implementation of a complete CIM system and all its component representations, objects, processes, activities, resources and organisational units of the enterprise. Figures 3 and 4 demonstrates the CIMOSA decomposition technique.

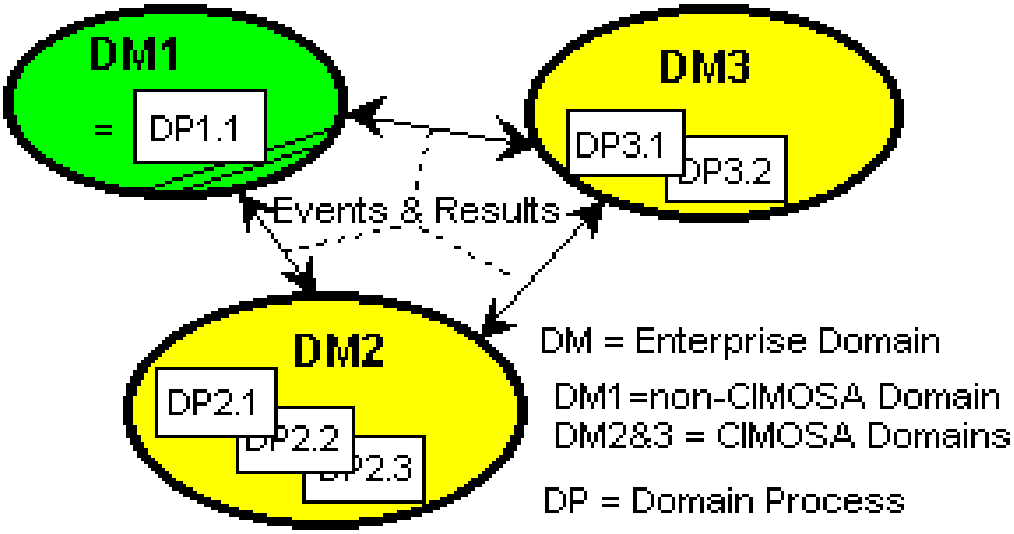


Figure 4 Decomposition to domain processes (AMICE 1993; Vernadat 1996)

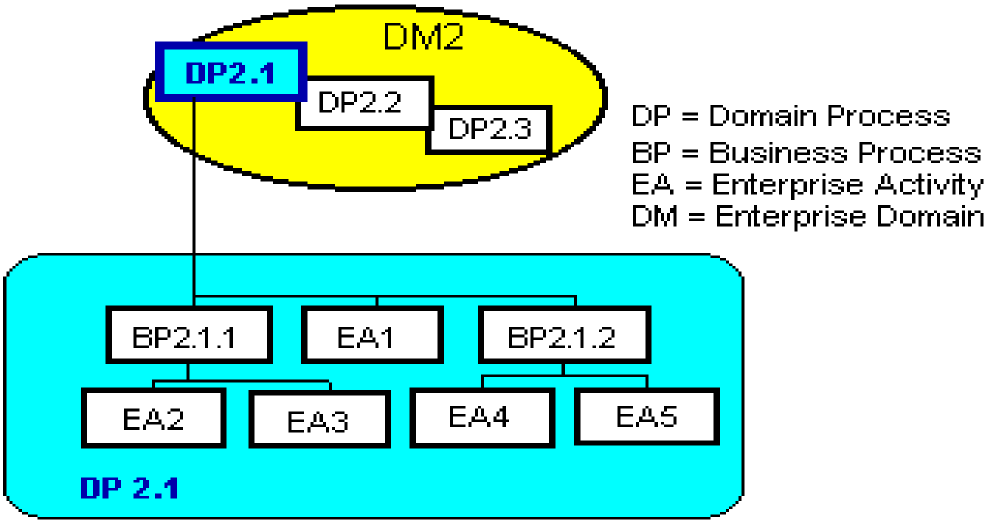


Figure 5 Further decomposition to BPs (AMICE 1993; Vernadat 1996)

It is claimed that the CIMOSA methodology provides decomposition and re-integration formalism and generates basis for analytical modelling (AMICE 1993; Vernadat 1996). Essentially, it also enables process and system design to be documented and communicated, providing a common base for the comparison of old and new processes (Vernadat 1996; Chatha and Weston 2005; Rahimifard and Weston 2006). Also claimed is that CIMOSA enables processes to be standardized and may lead to systematic design of software and human systems (Zelm 1995). Chapter 3 further reviews available EM techniques relative to each other.

2.4.5 Complex dynamic business process modelling

The enterprise modelling methodologies described above have the capability to represent enterprises in a 'static' manner. However if decisions are to be made in real MEs a more informed approach, based on the dynamics of the real world enterprise, has to be taken into consideration. Especially if the end goal of a project is to quantify business benefits that can arise from making manageable ME changes (to process structures, product and material flows, resource assignments and the like). Therefore, there arises the need to a) create models that replicate process behaviours in the context of use; so that assumptions, parameters and data incorporated into those models can be verified, and b) use verified models to predict better ways of optimising process designs and/or of deploying those designs. This is necessary such that by visualizing the whole process within a given period of time, better understandings about 'as is' system behaviours can be realized leading to more effective 'to be' design alternatives prior to ME change (Rahimifard and Weston 2006).

Various literature related to current trends when managing operations in MEs have explained that there are significant complexities and dynamics associated with the control, optimization, and organization of resources, so as to to realize enterprise objectives (Askin 1993; Bernus and Nemes 1996; Vernadat 1996; Weston 1999; Sterman 2000). On the other hand, traditional approaches as well as enterprise modelling techniques adopted in solving problems in MEs have not fully accommodated the complexities and causal relationships associated with processes in MEs. For example classical production planning and control methods have not fully consider MEs as dynamic systems (Goldhar and Jelinek 1983; Scholz-Reiter, Freitag et al. 2004) hence when there are changes along the 'bottom line' of manufacturing processes, it becomes difficult to manage the complexities and dynamics that emanate out of these changes. This is part of the reasons for the failure of many management strategies. Ad hoc methods of solving complexities in MEs have been ineffective because research has shown that most MEs are composed of complex process networks which are inter related in a way that changes made to one process thread induce dynamics in the ME by having causal and temporal effects on other process threads (Rahimifard and Weston 2006).

In an attempt to render scientific support in solving problems of 'complexities and dynamics' in MEs various methods have emerged. This includes fuzzy logic (Batur, Srinivasan et al. 1991; Wang 1992; Yester, Sun et al. 1993), neural networks (Minsky and Papert 1969; Gardner and Derrida 1988; Spooner, Maggiore et al. 2002), Bayesian networks (Pearl 1985), non-linear control dynamics, enterprise modelling (Bernus and Nemes 1996; Vernadat 1996; Weston 2005), systems dynamics (Forrester 1961; Burns and Ulgen 2002), statistical and other parametric modelling techniques. The literature analysis presented in Chapter 3 have attempted to compare the application, strengths and weaknesses of these complex systems modelling technique.

Recently there is the strong drive towards a collective use of non-linear control and system dynamics theories in manufacturing enterprises. This is because it has been proven that complex dynamic behaviours can occur even in the simplest manufacturing system (Scholz-Reiter, Freitag et al. 2004). In view of this, a review of example system dynamic modelling techniques are presented in the next section.

2.4.5.1 System Dynamics Modelling methodology

System dynamics (SD) modelling evolved from research in control engineering and non-linear dynamics (Forrester 1961; Coyle 1983). 'It is a rigorous method of system description, which facilitates feedback analysis, usually through a continuous simulation model, of the effects of alternative system structures and control policies on system behaviour' (Wolstenholme 1982). System dynamics modelling is characterized by two major modelling frameworks: causal loops and stock and flow diagrams (Randers 1980; Sterman 2000) which are usually supported by strong non-linear complex mathematical theories (Forrester 1961; Sterman 2000; Scholz-Reiter, Freitag et al. 2004).

2.4.5.1.1 Causal loop and 'stock and flow' modelling methodology

In general terms, causal loop models (CLMs) are known to depict the causal links between cause and effects. They are deduced from verbal or historic reference behaviour of systems (Richardson 1999). It could also be developed from observed trend of system reaction over time. It also forms a connection between structure and decisions that generate system behaviour (Binder, Vox et al. 2004). Basically, it contains variables, and arrows which show the causal relationships between the variables.

A body of literature in the domain of system dynamics have shown that CLMs are good for:

- depicting relationships between cause and possible effects (Homer and Oliva 2001; Binder, Vox et al. 2004)
- creating dynamic models of businesses for alternative policy verification (Wolstenholme 1999; Homer and Oliva 2001)
- capturing mental models of individuals and teams during start of projects and also during project dissemination (Ford and Sterman 1998)
- depicting the effect of dynamics on supply chains (Akkermans 1995)
- indicating the dynamics of public policy making and implementation (Morecroft and Sterman 1994)
- systemizing in part the transformation from static modelling to dynamic modelling (Chatha, Weston et al. 2003; Weston 2005).

CLM starts with a variable (cause) followed by an arrow which shows the causal links with the 'effect' associated with the variable. Each causal link is denoted by a positive or negative polarity to represent how the variables change in respect to the other. For example the loop shown in figure 5 will be read as 'if X increases, Y will also increase correspondently and if there is a decrease in X there will also be a decrease in Y'. The converse is a negative link which indicates that when X increases Y will decrease and vice-versa.

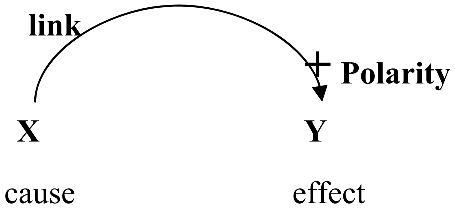
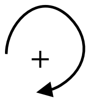


Figure 6: Causal loop model notation

Mathematically, a positive link of **X** to **Y** implies that the rate of change of Y with respect to X will be greater than 0. Therefore $dy/dx > 0$. Similarly in the case of accumulations, X adds to Y hence Y=$\int_{to}^{t}(X+...)ds+Yto$. A negative link of X to Y means $dy/dx < 0$ hence Y=$\int_{to}^{t}(-X+...)ds+Yto$.

The determination of loop polarity is like calculating the sign of the open loop 'gain' of the loop as pertains in control theory. The term 'gain' refers to the strength of the signal returned by the loop whilst open loop means that the gain is calculated for just one feedback cycle by breaking the loop at some point. Further literature on the mathematics of loop polarity can be obtained from Sterman (Sterman 2000).

A loop is called positive, regenerating or reinforcing if it has no negative polarized links or if the sum of the negative links is even. Otherwise it is a negative or balancing loop. These notations are described in figure 6.

Positive or reinforcing:  or **R**

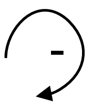
Negative or balancing:  or **B**

Figure 7: Loop notation

Burns (Burns 2001) noted that since it is fairly easy to create CLMs, there is the high tendency of creating models which are difficult to be translated into simulation models. This is often the case since there are always many connection 'possibilities' between variables involved in the model.

However it is possible to limit some of these possibilities without any loss of robustness in the models that are developed (Burns 2001). Sterman (Sterman 2000) observed that to maximize the clarity and impact of causal loop models:

1. causality must be distinguished from correlation
2. links polarities must be clearly assigned without any level of ambiguity
3. important delays must be indicated in the causal links
4. curved lines should be used for information feedbacks whilst important loops follow circular or oval paths.
5. models should be organized to minimize crossed lines and models could be drawn iteratively until the best layout is achieved.
6. The goals of negative loops should be explicit.

Although CLMs have featured well in the domain of system dynamics (Binder, Vox et al. 2004), most often they have illustrated qualitatively the influences observed or predicted to exist between system variables (Richardson 1999; Sterman 2000). Hence CLMs in themselves are not parametric and may be limited for the application of quantifiable system analysis. In light of this need, system thinkers recommend the incremental translation of CLMs to ‘stock and flow’ models (SFMs) which can be used for simulation purposes (Burns 2001).

Some key notations in SFMs are stocks, flows and auxiliaries. Stocks are accumulations. They characterize the state of the system and generally the information upon which decisions and actions are based (Sterman 2000; Burns 2001; Binder, Vox et al. 2004). It creates delays by accumulating the difference between the inflows and outflows (Burns 2001). By decoupling the rates of flow, stocks are the source of disequilibrium dynamics in systems (ISEE 2007). Flows are responsible for filling and draining stocks. For example a firm’s inventory (stock) is increased by increase in production and reduced by increase in shipment, spoilage, theft, etc. An inflow is represented by a pipe (arrow) pointing into the stock whilst an outflow is represented by a pipe pointing out of the stock. Valves are used to designate the control of the flows whilst clouds denote the sources and sinks of the flows. Converters on the other hand serve as the repository for algebraic and graphical functions, holds constants and defines external inputs to the model hence converting inputs to outputs. All these modelling elements are linked together by connectors. Basically there are two types of connectors, action and information connectors. Action connectors are signified by a solid, directed wire whilst information connectors are signified by a dashed wire.

2.4.6 Application of simulation modelling techniques in MEs

Carrie (Carrie 1988) defines simulation as a technique for imitating the behaviour of some situation or system (economic, military, mechanical, etc) by means of an analogous situation, model or apparatus, either to gain information more conveniently or help make well informed decisions. In Manufacturing Enterprises, it is usually very costive to make prototypes of designs and processes, especially when the outcome of the process is not clear (Askin 1993). However a reasonable level of understanding can be derived from already existing systems by considering the logic of activities. If the behaviour of a system is studied over a sufficiently long period, fair conclusions can be drawn about the system's response to actions (Askin 1993). In principle simulation models in Manufacturing Enterprises can help solve problems of parameter optimization; design of control policies; system operation checking; performance evaluation; system dimensioning and the test of design alternatives (Vernadat 1996).

Simulation modelling tools often deployed in modelling manufacturing processes are broadly classified into discrete event and continuous simulation. Examples of discrete event simulation tools available include Simul8 (Shalliker, Rickets et al. 2005), Arena, Plant Simulate, Lean Modeller (Nielsen 2005). Examples of continuous simulation packages are iThink (ISEE 2007), Powersim and Vensim. Table 1 draws out some observations on the difference in these types of simulation tools. This comparison reveals that the simulation tools studied provide overlapping functionality which can usefully be deployed when seeking to model the workload effects of products flowing through ME process segments and the related requirements of (and impacts on) the human and technical resource systems needed to resource specified workflows through process segments (Weston, Rahimifard et al. 2007).

Table 1: Differences in simulation applications (Weston, Rahimifard et al. 2007)

During the past few years there has been the strong desire to support value stream mapping with simulation modelling tools. Initial attempts but with limited success have been provided by (McDonald, Aken Van et al. 2002; Braglia, Carmignani et al. 2006).

2.5 Cost Engineering methods

2.5.1 Introduction

Concepts of costing related to manufacturing were developed during the late 19th to 20th centuries to help meet the growth which was experienced in the manufacturing industries (Maskell 1991). Literature shows that since 1930, traditional cost accounting principles have been the main tools for measuring manufacturing cost and profit performance, product pricing, evaluating inventory and capital investment (Drury 1991). The major challenge specified by Maskell (Maskell 1991) is that processes and management of manufacturing industries have advanced beyond methods specified by traditional accounting principles. As a result, it has been claimed that traditional cost accounting methods are trailing behind manufacturing technologies. Observing these limitations, Son (Son 1991), and Johnson (Johnson and Kaplan 1987) have developed cost estimation methods currently adopted by some MEs. A study of current cost accounting methods and their application in advanced MEs operating in dynamic business environments show that the actual 'step by step' processes involved in the manufacture of products are often neglected (Son 1991; Agyapong-Kodua, Wahid et al. 2007). This is partially as a result of lack of detailed understanding of processes and unavailability of cost data associated with complex manufacturing processes. Five major limitations observed in traditional accounting systems are (Maskell 1991):

1. they lack relevance
2. cost are distorted
3. they are inflexible
4. they offer practical hindrances to dynamic manufacturing systems
5. they are subject to the needs of financial accounting.

These limitations are real in MEs because due to the inherent complexities and dynamics associated with MEs, it is fairly difficult to estimate, control and monitor cost consumption appropriately and instantaneousness without incurring errors (Son 1991). The above limitations led to the birth of a discipline called Cost Engineering (Samid 1990) .

Humphreys (Humphreys 1987) defines a cost engineer as 'an engineer whose judgement and experience is utilized in the application of scientific principles and techniques to problems of cost estimation; cost control; business planning and management science; profitability analysis; project management; planning and scheduling. An older definition provided by Bauman (Bauman 1968) was ‘a relatively new designation for any graduate or professional engineer or equivalent, employing his technical skills in the practice of process cost estimation, cost control, profitability, or the general engineering economics of capital investment. In most environments today, Business Administrators and Economists take hold of the overall business planning and management, pushing the cost engineer into his core elements of cost estimation, scheduling and cost control (Samid 1990).

2.5.2 Accounting and process classes

An enterprise’s accounting system serves many purposes. Drury (Drury 1991) indicated that the purpose of accounting systems include:

- providing information to external parties such as stockholders, creditors and various regulatory bodies, for investment and credit decisions;
- estimating cost of products produced and services provided by the organization; and
- providing information useful for making decisions and controlling operations.

Generally, there are three broad areas of accounting which collectively provide quantitative data for decision making, strategy formulation, planning and control, performance measurement and financial reporting (Barfield, Raiborn et al. 1994). These three areas are::

- Financial accounting;
- Management accounting
- Cost accounting

Financial accounting is designed to meet external information needs and to comply with generally accepted accounting principles (Drury 1991). Financial accounting must comply with the generally accepted accounting principles established by the Financial Accounting Standards Board. The information used in establishing financial accounting is typically historical, verifiable, quantifiable and monetary. It is necessary for obtaining loans, preparing tax returns, and understanding how well or poorly the business is performing (Barfield, Raiborn et al. 1994). Management accounting however attempts to satisfy internal information needs and to provide product costing information for external financial statements (Drury 1991; Barfield, Raiborn et al. 1994). This information is targeted at assisting managers to organisational financial goals. Cost accounting on the other hand is defined by the Institute of Management Accountants as a technique for determining the cost of a project, process or a thing (Drury 1991; Barfield, Raiborn et al. 1994). The cost in this sense is determined by direct measurement , arbitrary assignment or systematic and rational allocation.

Chatha (Chatha, Weston et al. 2003) suggests a hierarchy of enterprise processes based on strategic, tactical, and operational classes. This approach supports the hierarchy evident between financial, management, and cost accounting (see Figure 8).

Elaborating further on activities typical of each process class, the strategic class of processes have mid to long term outlook, formulating plans in support of enterprise objectives. The tactical process class develops and implements means of realising strategic objectives. The operational process class consists of ordered sets of activities carrying out operations using capabilities, methods and techniques developed by tactical processes.

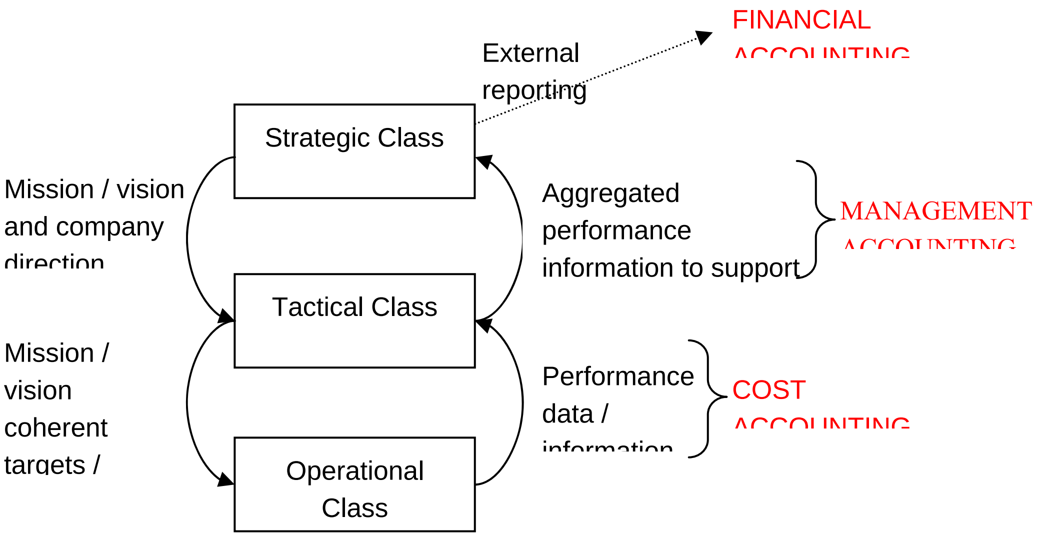


Figure 8 Accounting and process classes (Chatha, Weston et al. 2003)

2.5.3 Methods of product costing

The two determinants of product cost are the product costing system and the valuation method used (Drury 1991). Product costing systems differ and the system used indicates the cost object and the method of assigning costs to production. The valuation method specifies how product cost will be measured.

2.5.3.1 Costing Systems

Many researchers in the domain of cost accounting have specified that basically there are two costing systems: Job order and Process costing (Drury 1991; Stewart 1991; Cooper and Kaplan 1992; Barfield, Raiborn et al. 1994; Koonce, Judd et al. 2003). They indicated that normally Job order costing is used by entities that make or perform relatively small quantities or distinct batches of identifiable, unique products or services while process costing is suitable for entities that produce large quantities of homogeneous goods.

Process costing captures the cost of raw material and the total cost of converting the raw material into finished goods (Son 1991). Traditional cost accounting indicates that a simple way of estimating process cost is to determine the unit cost per period as a ratio of the sum of production costs to the quantity of production (Barfield, Raiborn et al. 1994). Also production cost is obtained by accumulating all cost incurred in the process of production or across all departments. Equivalent units of production are an approximation of the number of whole units of output that could have been produced during a period from the actual effort expended during that period. Based on best practice accounting methods, a simplistic way of mathematically representing process cost per unit item is (Drury 1991; Barfield, Raiborn et al. 1994):

$$\text{Process cost/unit item} = \frac{\sum \text{direct cost} + \sum \text{Indirect cost}}{\text{Total units of production}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

When equation (ii) is modified to include work-in-progress it is expressed as:

$$\text{Process cost/unit item} = \left[\frac{\sum \text{direct cost} + \sum \text{Indirect cost}}{\text{Total units of production}}\right] - \text{WIP} \ldots\ldots\ \ldots\ldots\ldots (2)$$

Equation (iii) can further be simplified to read:

$$\text{Process cost/unit item} = \left[\frac{\sum \text{direct cost} + \sum \text{Indirect cost}}{\text{Total units of production}}\right] - [\text{WIP}_{\text{open}} - \text{WIP}_{\text{close}}] \ldots (3)$$

These accounting methods have been used extensively in many industries but for most current MEs, what is required is to be able to provide cost estimates and control the cost required for production (Otswald 1992). Four main estimation methods have been observed to be dominant in manufacturing cost estimation exercises. These methods are intuitive, analogous, parametric and analytical (Duverlie and Castelain 1999; Cavalieria and Maccarrone 2004).

The intuitive method mainly depends on the experience of the estimator. This is commonly applied in industries where cost estimates are required at short notices and also where no standard cost data exist. There are high possibilities of providing inaccurate estimates when this approach is adopted but other researchers have argued that considering specific markets, the intuitive method of cost estimation might be the best approach to win customers (Layer, Ten Brinke et al. 2002).

Analogous cost estimation methods are based on extrapolations from previous cost estimates of similar parts. In some instances cost ratios are determined based on properties such as length, weight and material type, etc and are used as basis for determining the cost of similar components (H’mida, Martin et al. 2006).

Parametric cost estimation methods link cost of products to technical parameters and define product cost based on mathematical relationships between product characteristics (Duverlie and Castelain 1999; H’mida, Martin et al. 2006). It is contended that although parametric cost estimation methods are fast and accurate for well-defined part families, they have no physical relationship to manufacturing processes (Qian and Ben-Arieh 2008). However, previous work by Son (Son 1991) on ‘cost estimation model for advanced manufacturing systems’ show that aspects of processes and product parameters can be integrated to derive equations capable of being used to estimate production cost for advanced manufacturing systems. Son (Son 1991) showed that for a labour intensive activity, the actual manual labour which transforms material piece, m, is defined by, Ld,:

$$Ld = n_o tr\alpha \ \ldots.. (4)$$

where n_o is the number of operators; t is the time spent; r is the existing rate of pay or wages per time and α is a percentage availability factor. Also if ‘y’ different numbers of jobs use indirect labour of salary s, then for z numbers of indirect labour units, the total indirect labour cost, Li is given by:

$$Li = \sum_{y=1}^{y} syzy \ \ldots.. (5)$$

Similarly, for a machine intensive work centre with, m_r, usage cost of N numbers of machines, if t is the total machine usage time then the total usage cost is Mu:

$$Mu = \sum_{N=1}^{N} m_r NtN \ \ldots.. (6)$$

Adding up the necessary cost elements associated with machine utilization provides a total machine cost, Mt, estimated in the form:

$$Mt = \text{usage cost} + \text{maintenance cost} + \text{repair cost} + \text{insurance cost} + \text{property tax} \ \ldots.. (7)$$

Mathematically, for a process involving N numbers of machines operating over a period T, the total machine cost, Mt is:

$$\mathbf{M}_t = \sum_{N=1}^{N} \{\mathbf{m}_{rN}\mathbf{t}_N + \mathbf{m}_N\mathbf{v}_N + \mathbf{b}_N\mathbf{u}_N) + \mathbf{af} + \mathbf{W}\} \ \ldots.. (8)$$

Where **m** is the maintenance cost per unit, whilst **v** is the total maintenance time; **b** is the repair cost per unit time whilst **u** is the total repair time; **a** is the insurance premium rate whilst **f** is the cost of machine and **W** is the property tax of machine **N.**

Son (Son 1991) further showed that, if a floor square metre cost is fs and the manufacturing floor space is Ms, then the floor space cost, Cfs = fs x Ms ….. (9)

The storage cost, Sc is expressed in terms of the floor space cost and the cost of keeping materials in storage over a given time. Thus for n_m number of materials or components in storage with Cs unit cost, stored over t length of time, the inventory cost, Ci, is expressed as:

$$Ci = n_m Cst \;\ldots\ldots (10)$$

Therefore for N different types of machines with p number of storage points, the total storage cost is expressed as:

$$Sc = \sum_{N=1}^{N} CfsN + \sum_{p=1}^{p} Cip \ldots\ldots (11)$$

In estimating tool cost, Tc, assuming a tool has a useful life n, then the total tool cost can be expressed as:

$$Tc = Ct\,Nt \;\ldots. (12)$$

Where Ct is the unit cost per tool and Nt, the total number of different tools changed.. Other costs such as depreciation was defined as the cost of recovering manufacturing equipment and other fixed assets whose benefits spanned over one accounting period. Material cost on the other hand was defined as the sum of the cost of making materials available for production. This therefore included the actual cost of direct and indirect materials and transportation. These expressions provided by Son (Son 1991) gives pragmatic solution to modelling cost in manufacturing environments.

Also application of parametric models vary in complexity from simple material models and 'cost-size' model to complex parametric equations (Creese, Adithan et al. 1992). Duverlie and Castelain (Duverlie and Castelain 1999) have specified that there are three forms of parametric cost estimations: method of scales, statistical models, and cost-estimation formulae (CEF). Extensive literature and application of parametric cost estimation methods can be found in (Feng, Kusiak et al. 1996; Ou-yang and Lin 1997; Jung 2002; Cavalieria and Maccarrone 2004; H'mida, Martin et al. 2006; Qian and Ben-Arieh 2008).

Conventionally, analytical cost estimation methods have been used for summing cost related to activities involved in production processes (H'mida, Martin et al. 2006). One of the major contributions in the area of analytical cost estimation methods is Activity-Based Costing (ABC) (Brimson 1991; Cooper and Kaplan 1992; Özbayrak, Akgü et al. 2004). Activity Based Costing (ABC) uses causally related drivers, attributing overhead to the activities that create or drive them.

The basic premise of ABC is that activities consume resources and products consume activities. As with previous approaches to costing, direct costs are traced and indirect costs are allocated. However, indirect costs are assigned to activity cost centres (costs that are relevant to a specific activity). Cost drivers guide the assigning of indirect costs to products.

Figure 9 illustrates an ABC system. Overhead costs are pooled and a rate per unit of cost driver is established.

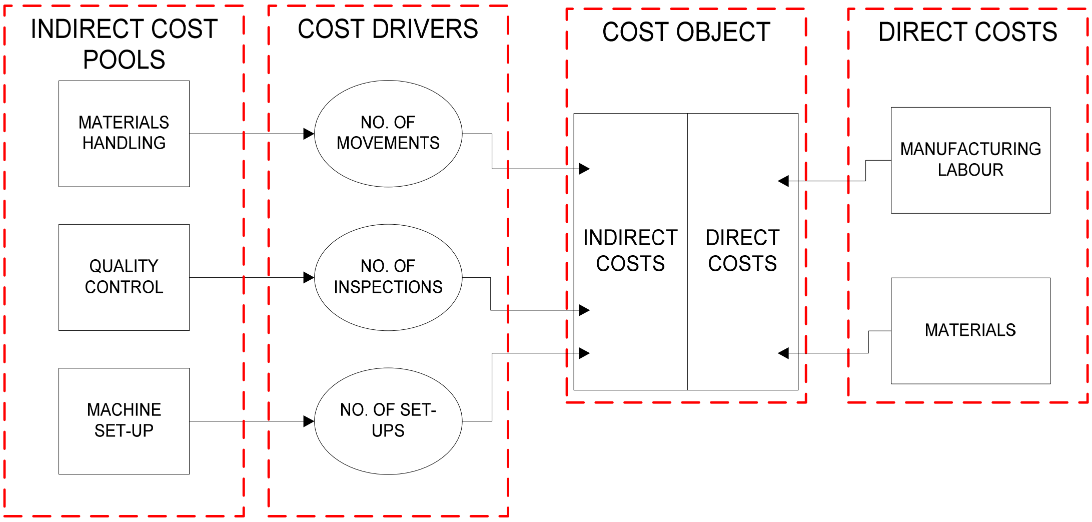


Figure 9 Activity Based Costing (ABC) illustrated

This costing method focuses on attaching costs to products and services based on the activities used to produce, perform, distribute or support those products and services. It has been reported to be suitable for companies with the following characteristics (Barfield, Raiborn et al. 1994):

- High overhead costs that are not proportional to the unit volume of individual products;
- Profit margins that are difficult to explain
- Significant automation that has made it difficult to assign overhead to products using the traditional direct labour or machine hour bases and
- The production or performance of a wide variety of products or services. Some of the criticisms of this method are the fact that the development of cost pools and identification of cost drivers are time consuming tasks. Also arbitrary apportionments are still necessary at the pooling stage in order to derive the cost of each activity (Son and Park 1987).

2.5.3.2 Target Costing

To provide a basis for the utilization of the concept of 'value' in this research, further review on target costing was conducted. It has been reported that some MEs are using target costing as a cost management tool for reducing the overall cost of a product (Barfield, Raiborn et al. 1994). Also indicated is that target costing is particularly popular among Japanese firms such as Toyota, Nissan, Toshiba and Daihatsu Motor in various industries such as automobile manufacturing, electronics, machine tooling, and precision machine manufacturing (Maskell 1991). Compared to traditional standard costing approaches in which an estimate of product, general administrative, marketing, and distribution costs are taken into consideration, target costing takes on a more proactive approach to pricing (Drury 1991). Traditional costing determines cost based on the design of goods, adds a markup and establishes a price. In comparison, the marketplace directs target costing by first setting a selling price, then subtracting target income and finally reaching a cost (Barfield, Raiborn et al. 1994) . A comparison of target costing and value estimation is given in Chapter 3.

2.5.3.3 IT-based costing systems

An extensive analysis of existing commercial software and proprietary tools which support manufacturing cost estimations have been published in (DoD 1999). Other tools such as FIPER, developed at NIST for design cost estimations has been reported in (Koonce, Judd et al. 2003); TIMCES, a cost estimation tool which integrates CAD and CAPP systems is shown in (Wong, Imam et al. 1992) and neural network-based approaches is described in (Shtub and Zimerman 1993).

2.6 Summary of Literature Survey

The literature survey presented in this chapter describes current manufacturing philosophies, strategies and solutions. The survey showed that these methods have been applied to solve specific problems in manufacturing environments. The survey was extended to capture best reported tools and techniques for mapping manufacturing processes with the view to improve value generation and reduce cost consumption. This led to several process mapping techniques and Enterprise Modelling tools. To help manage complexities and dynamics in manufacturing processes which impact on cost and values, system dynamics, simulation modelling and cost engineering techniques were also reviewed.

Detailed literature and gap analysis centred on potential knowledge addition in the area of modelling cost and value generation in dynamic multiproduct flow dynamic manufacturing environments is shown in Chapter 3. This formed the basis of the research design and focus.

As a result of the observed limitations and defined research objectives, a new modelling methodology is proposed in Chapter 4.

3. Research Focus and Design

3.1 Introduction

The literature survey in Chapter 2 has demonstrated various paradigms and methodologies which exist for designing, controlling and managing processes in MEs. The survey was conducted with the view to understand existing practices which support the realization of multiple products with enhanced value generation at minimal cost in MEs. Throughout the study, it was observed that Lean and Agile Manufacturing philosophies and their related strategies and solution technologies are the major deciders of industrial operations, support and management of businesses with the quest to remain competitive and meet market requirements.

Because most MEs are subject to ongoing change, to remain competitive and maintain large market shares, MEs will at specific points in time, fundamentally have to organize their processes and associated resource elements in a way that value can be added to 'inputs' at acceptable cost such that the 'outputs' obtained through manufacturing processes of MEs can compete based on availability, price and/or quality. How Industries achieve this objective will depend initially on their ability to effectively define key performance indicators which include value and cost generated along process segments. After the derivation of definitions for cost and value, scientific tools need to be deployed to help measure, analyse, control and manage processes so that cost and value information can be used to support decision making in MEs. This is necessary because current phenomena of 'business fluidity' coupled with inherent complexities in MEs require MEs to adopt cost effective and responsive business processes with capability to realise multiple value streams specified by changes in customer needs.

To help establish a research focus, this chapter commences by analysing the various research and applied views on value and cost generation in multiproduct manufacturing environments. The analysis on the views was done to help identify gaps in existing knowledge related to value and cost realization in manufacturing processes, so that needed knowledge can be added to help MEs perform better. In addition to the value and cost analysis, various tools and technologies emanating from the manufacturing philosophies surveyed and presented in Chapter 2, have been analysed to establish their capabilities and help derive current requirements for modelling multiproduct flow dynamic value and cost streams for effective process design, business analysis and management of processes. As a result of the established requirements for modelling multiproduct flow dynamic value and cost streams, a set of research objectives was established. A brief survey of research philosophies and methodologies are also presented to help design the research around the identified aims and objectives.

3.2 Analysis of research views on value and cost generation

The objectivist theory of value propounded by Rand (Rand 1993) emphasized the need for products to posses intrinsic attributes that can be translated to equivalent monetary values. Rand concluded that value is not a quality contained only in a product. Neither is it based on the perception of individuals, but it is a relationship between the intrinsic facts of reality and the subjective needs of individuals. This implies that for one person under a given condition, the value of a product will remain the same. This is, however, not so in all cases, because new products with superior properties are often introduced to the market and they have the tendency to satisfy human needs in a better fashion than previously manufactured products. Also the objectivist theory of value fails to define a means of identifying and measuring intrinsic attributes of products. Products are therefore considered to be single entities and their values need to be worked out separately. Thus a margin of product values will need to be established and depending on how customers view the products in relation to their subjective needs, a price can be established.

Unlike the objectivist theory, the labour theory attempts to quantify value as an expression of the sum of constant capital and labour. Constant capital is related to the value of the raw material, whilst labour is used to describe the average skill and productivity required to complete a process.
The major limitation with the labour theory is the theoretical view of labour as painful and 'sorrowful' activities needed to achieve a process. On the contrary, labour in modern MEs may not necessarily be painful or sorrowful. This is because manual labour, repetitive, boring and hazardous activities are gradually being taken over by robots and other automated machines. Human beings on the other hand are increasingly being used for designing, planning, selection, controlling and managing of operations. Thus when total labour in a manufacturing process is defined in terms of man hours, it becomes deficient in semi or fully automated manufacturing environments. In addition cost related to administration, supervision and other indirect tasks in MEs cannot readily be estimated and used for value analysis.

An alternative to the classical economic opinion of value is the sociological view which tends to express value as abstract ideas about what is believed to be good in a society. The sociological view provides explanations to why societies will prefer one thing over the other but in general terms, the sociological view is subjective and difficult to measure. Value Engineering provides further insight on how value can be measured based on functionalities of products, processes and services, or the identification of the relative importance of one process over the other. Measurement of importance can be derived through use of the Analytical Hierarchical Process (AHP) which allows individuals to decide the relative importance of one process over the other. The influence of people's decision on 'importance' cannot be controlled. Therefore the approach is also subjective and not based on customers perspectives.

Lean thinking demonstrates that value is generated when a product is transformed in a way that the customer is willing to pay. Thus in mapping value streams, efforts are made to capture cycle times, delays and process-related parameters so that process efficiencies and lead times can be measured. Lean does not extend the process metrics measured to reflect the economic relevance of lead times, cycle times, delays, inventories, etc. It is therefore difficult to ascertain value and cost in mapping value streams.

In analysing the gaps in concepts related to value generation, it was observed that basically:

1. In relative terms, every product or service has value. The degree of value realized through a process is dependent on resources associated with the realization of the process. Resources, here, refer to humans, machines and computers necessary to realize the product or service. However, how this value is perceived is dependent on the market view of the product. This is based on the prices of other substitute products. In that case, a product has the tendency to dominate in value if it is scarce and without intense competition from other substitute products. Invariably market forces push products to compete among themselves to adjust their values. When a market equilibrium is achieved, prices of products may represent their experimental values. Market equilibrium is achieved only when demand is balanced by supply.
2. A key point also is that the value of a product is dependent on the view of the individual and the economic entity the individual is prepared to offer in exchange of it. This results in a mental bargain to decide the wealth of the product or service. Given the same economic environment, values of groups of products will have marginal differences. This is because although values are dependent on individuals they are inherently possessed by the product or service itself as a result of the processes involved in their preparation.
3. Value in use is the extra economic gain associated with the use of a product or service. An individual values a product if it is able to satisfy a need. The degree of valuation is dependent on how satisfied the individual becomes upon satisfaction of the need and often times the level of desperation which gets solved after obtaining the solution.

4. The author is of the view that for on-going businesses, an average of the selling price of the product or service over a statistically observed period of time could be considered as the initial value of the product or service, unless it is thriving badly in the economic market, in which case a review of pricing should be conducted before decisions are taken. For newly introduced products or services, the value the customer will be willing to pay will be equivalent to similar goods or services already on the market, unless there is a clear innovative difference in the new product. Hence 'best' products may not sell well if they are outside customers 'acceptable valuation limits'
5. At each process stage, process efficiency can be derived by working out the ratio of value generated by the process to the process cost. To provide a simplistic view on estimating value, two approaches can be adopted. The first approach requires the estimation of process variables which impact on value generation as predicted by the Lean School of thought and the next stage is to express these parameters in relative economic terms such that the financial implication of process variables can be observed.

Analysis of existing literature on cost estimation shows that despite the long standing industrial adoption of cost models, current generation cost models are commonly limited in the sense that existing cost modelling applications have their data embedded within the application program. These data are then operated upon by internal mathematical formulae which the user might not be aware or conversant with. This close coupling of functionalities with the information makes it difficult to modify the costs methods deployed.

Also the literature revealed that there is no consistency in how industries cost their products. The general notion has been the application of profit margins to cost of production to derive the selling price of the product. The current understanding is that prices are determined by dynamic market forces and the duty of the enterprise is therefore to reduce the cost of production by realizing and eliminating non-value adding activities. Also the output of existing cost models are usually meant for analysis by specific end users. It becomes limited when the output has to be used by other potential users in the enterprise. With regards to existing cost modelling methods, data has to be extracted manually from the information repositories within the enterprise and physically put into the models. This results in data duplication and creates problems of data verification and consistency. Consequently current generation cost models perform less well when they are used by MEs operating in dynamic environments.

Attempts to solve problems related to the design of cost effective products have led to the adoption of target costing schemes in many MEs. A critical study of how MEs apply target costing shows that:

1. Target costing is focussed on product design. Thus alternative cost is generated for different design concepts and a selection based on the concept which generates less cost is chosen. This is different for 'value' which is used as the basis for process improvement. Although target costing and value both have market price as the underpinning factor, value stream analysis uses perceived market price to influence the design of processes.
2. Also target costing establishes the cost of alternative means of realizing products but does not reflect on the value contribution of each business process in the ME. In the case of target costing, value or cost ratios are not used to distinguish the impact of process realization on the overall market value. Therefore since the objective of the research is to partly establish the impact of process realization on cost and value generation, it was conceived that a better means of defining value and using it as the basis for process improvement was necessary.
3. Also a number of definitions of 'value' have been provided in literature within the broad domains of Manufacturing, Value Engineering, Economics and Business, which need to be streamlined to support actual value realization in MEs. Additional benefits can be observed when there is the need to established whether to buy or make a part.

3.3 Requirements for multiproduct flow, dynamic value and cost streams in MEs

Reviewing techniques related to current manufacturing philosophies, it was observed that many researchers have continuously attempted to introduce and improve existing process improvement tools to cater for the current needs of MEs. Unfortunately, the tools developed are uniquely strong only in their respective domains of either business process engineering, enterprise integration, systems thinking and value and cost engineering. Observing the strengths of these tools, it was noted that to effectively model multiproduct value and cost streams for decision making in a dynamic manufacturing environment the following modelling attributes will be required:

- The required methodology and technique must suitably capture all different product types in MEs with the view of linking products to respective process routes. This is because unlike single flow manufacturing systems, literature shows that there are many MEs which need to realize multiple products to remain competitive and survive within their lifetimes. Also many MEs are characterised by significant product mixes, shared resources with unsteady changes in information or material flow, as well as control, and there is the need to deploy techniques which will be able to mimic to a larger extent these multiproduct flow properties.

- Because of the varying range of products a given ME needs to realize, coupled with the external factors which invariably impact on the ME, process changes may be required over a short time. The literature showed that most MEs would have to realise networks of processes comprising the following process types: (1) processes that realise products and services for customers and values for stakeholders; (2) processes that ensure that product and service realisation is well managed, such that it remains aligned to established business and manufacturing policies, and strategic goals of the ME, and 3) processes that structure and enable ongoing change as the ME systematically renews and reconfigures itself, developing and implementing new strategies, policies and processes in response to external change (Weston 1999). These processes will typically be resourced by combinations of human and technical resources and normally would have been designed and trained to achieve given targets. Changes made to any part of the process will trigger correspondent causal and temporal effects in other parts of the process. For most MEs the dynamics due to these changes can be enormous. A technique capable of identifying the causal impacts of changes in MEs which induce dynamics and hence complexities will help MEs manage their businesses well. The technique must enable accurate and timely feedback schemes such that changes made to any segment of an enterprise process can be captured and its impact measured.
- Generally in MEs, decisions related to process designs and change impact on cost and value. Cost and values are important performance indicators because they partly determine the effectiveness of the ME. Companies that make the best decisions with regards to value creation and cost reduction normally win larger market shares. It is however not easy to make such decisions, because it is difficult to quantify accurately the expected values and costs to be derived from a manufacturing process. Also literature has shown that when considering irregular market patterns and varying customer demands, it is relatively difficult to plan and operate manufacturing systems in such a way that optimisation of values and costs can be achieved over relatively short intervals. This is because most often factors which influence cost and value realization are at the operational level and it is sometimes difficult to capture information related to them at the point in which they occur. It is therefore necessary to be able to fairly estimate, control and monitor the generation of cost and values with reasonable level of accuracy, especially at the process points where they occur. The development of a technique to help measure cost and values simultaneously at an operational level will support decisions related to process efficiencies and the design of alternative processes to realize enterprise objectives. The technique must possess the capability to quantify ‘value’ based on financial measurable parameters in the ME, so that

efficiency in financial terms can be derived when the values so realized are compared with the cost involved in the process. The process costing aspect of the technique should enable enhanced traceability of costs to specific products and processes to enable improved management of cost distortions whilst supporting the accurate estimation of process cost due to the deployment of alternative business process configurations.

- Because of the cost implications and risks involved, a virtual experimentation tool which enables business ideas and process improvement suggestions to be tested before their implementation will be useful. This will save MEs from implementing decisions which in actual fact will not yield needed results. Predictions and future ME projections can be tested and used as a basis for improving current operations in the ME. This will facilitate process design and ME change specifications and impacts of process dynamics on performance indicators.
- Literature has also shown that decomposition of enterprise requirements ensures that complex problems are characterised and modelled in modular forms, so that analysis and understanding becomes easier. The consistent utilization of appropriate modelling or mapping constructs will enable the reuse of models or maps. Thus the required technique should inherently possess decomposition formalisms and display uniform set of constructs for model reusability in MEs.
- Current manufacturing systems require the support of IT systems, and principles related to Computer Integrated Manufacturing (CIM) to manage aspects of complexities. The proposed technique should therefore support CIM and IT principles.

3.4 Current approaches for solving multiproduct dynamic cost and value streams

The literature survey presented in Chapter 2 showed how many ’researchers’ and ‘industrialists’ have attempted to meet aspects of the requirements specified in Section 3.3. Tools and techniques developed in the area of process design and improvement also concentrated on the reorganization of processes in MEs, making cost and value stream important measurable parameters. Tools available in literature with potential to define, measure and utilize aspects of value and cost information in manufacturing processes can be classified into:

1. Process mapping tools
2. Enterprise Modelling (EM) tools
3. System Dynamics (SD) modelling tools
4. Business process simulation modelling (SM) tools and

A process mapping tool is a generic term used in this thesis to refer to the broad range of business process re-engineering tools which have been commonly applied for process improvements especially in scientific management and industrial engineering projects. When considering the intended purpose of process maps and also the needed requirements to satisfy value generation at minimal cost in dynamic multiproduct flow environments, a criteria was developed to serve as a benchmark for assessing each of the mapping techniques. The objective was to determine if any of the existing mapping tools could conveniently satisfy the requirements detailed in Section 3.3.

Reviewing literature, 14 different process mapping tools were identified. These maps had been developed and used by several researchers and industrialists in many process improvement projects especially related to the manufacturing industry. Each of the maps was applied for different purposes but the maps have been collated together and assessed on a common platform to observe the possibility of complimenting each other with the strengths of other tools.

To simplify the requirements specified in Section 3.3, the criteria for assessing the various mapping tools was based on the following:

- Ability to analyse multiproduct flows and their associated product dynamics;
- The possibility to identify and capture aspects of complexities and dynamics in MEs;
- The suitability of the mapping tool to assist in complex manufacturing systems and process redesigns;
- The ability to reflect causal impacts of activities in MEs especially on financial terms;
- The possibility to measure process cost without distortion;

- The ability to quantify value added through a given process;
- Availability of suitable constructs for value and cost modelling;
- The ability of the tool to support business analysis especially in a virtual environment;
- The capability to decompose processes into elemental activities to enhance understanding and process analysis;
- The suitability of the tool to support CIM and IT principles.

Table 2 shows how the various identified mapping tools have been assessed along this criterion.

Process modelling tools	**Analysis of multiproduct flows and product dynamics**	**Identification and capturing of aspects of complexities and dynamics in MEs**	**Suitability for complex manufacturing systems and process redesign**	**Reflection of causal impacts of activities on financial indicators**	**Ability to measure process cost without distortions**	**Ability to quantify value added through a process**	**Availability of suitable constructs for value and cost modelling**	**Supporting business analysis in a virtual environment**	**Capability to decompose processes for easier analysis and understanding**	**Support of CIM principles and IT techniques**
1. Process mapping tools										
a. Overall lead time map (Hines and Nick 1997; Bicheno 2000)	It maps lead time for general processes without linking them to specific products. Not suitable for in-depth multiproduct analysis	It is a linear mapping tool and does not capture any feedback. Complexities and most especially dynamics is not the focus of this mapping tool	It supports process redesign in the area of lead time reduction but not helpful in complex manufacturing systems design	This process design tool has no capability to capture the causal impact of processes on each other	The tool does not extend to measuring cost of processes	The tool does not provide any means to quantify value addition in manufacturing processes	There are no constructs for modelling cost and value	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios	Processes are not decomposed into elemental components	Although could support CIM principles, in its present state there is no evidence for its support. It is simply a 'pencil and paper' mapping technique
b. Order maps (Bicheno 2000; Hines and Taylor 2000)	Essentially for mapping customer orders with the view to improve customer service. Not suitable for in-depth multiproduct manufacturing systems analysis	The technique attempts to capture aspects of complexities due to varying customer orders but does not extend this complex view of orders on production systems	This is not a manufacturing process redesign tool. It is suitable for front end business analysis and most especially in support of customer services	It attempts to analyse some causal impacts but with limitation application on customer orders. It does not support analysis of economic implication of manufacturing activities	It is not a suitable technique for measuring process cost hence distortion of cost information cannot be observed	No observed approach exist for quantifying value addition through processes	There are no constructs for modelling cost and value	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios especially in a virtual environment	Decomposition of processes is not an aspect of this mapping technique	Although it could support CIM principles, in its present state there is no evidence for its application in the area of CIM. It is simply a 'pencil and paper' mapping technique

c. Customer map (Hines and Nick 1997; Bicheno 2000)	It is mainly for identifying market shares of customers and does not match results unto product types and their associated processes	Similar to the order maps, various customer types are identified but not extended to analysing the complexities and dynamics in MEs	Customer identification can be enhanced by this technique but it does not offer great support for manufacturing systems design	A certain level of causal impacts of customer behaviour is observed but not extended to the actual manufacturing processes.	It has no capability for measuring process cost	The technique has no means for quantifying process values	There are no constructs for modelling cost and value	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios	Not suitable for decomposition of processes	Not suitable in CIM applications in its present state
d. Process activity map (Hines and Nick 1997; Bicheno 2000)	The technique does not distinguish between product types. Processes are mapped with the intention of improving the general production processes. This method is useful for mostly single flow manufacturing systems.	It is related to process design but because of its simplified approach, it is not able to capture multiproduct dynamics	Although a manufacturing process design tool, because of its limitation in the area of multiproduct flow, it cannot support process re-design in a complex manufacturing environment	This tool has no indicators for the effect of activities on each other. It expresses relationships between activities in a linear manner	There is no in-built approach for measuring process cost. It can however be extended to support activity based costing	Cycle times and queue times are used to depict value and non value added times in manufacturing processes.	There are no constructs for modelling cost and value	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios especially in a virtual environment	It enables decomposition of processes to some extend but there is no formalized approach to achieve this	Quite limited in its application in CIM systems. It could however be used as the initial mapping tool in single flow manufacturing systems

e. Product variety funnel (Bicheno 2000; Hines and Taylor 2000)	It possess the ability to identify multiproduct flows and map it as such. The objective however is different from process redesign and optimization. It is purely used to support design of products so that variety in designs can be minimized to enhance flexibility.	It attempts to identify dynamics of multiproduct flows but it does not extend to the provision of solution for solving product dynamics	This technique is more inclined towards product redesign in support of mass customization.	In a linear way, this technique shows how multiple flows merge in a production system but does not give any indication of capability to capture the effect of feedbacks	This technique is not for process costing	The measurement of 'value' is not the focus of this technique	There are no constructs for modelling cost and value	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios	Process decomposition is outside the scope of this technique	It could be used to understand effect of multi products on product design and process lines but not very useful in the complete design and analysis of CIM systems. Also not supported by IT
f. Quality filter map (Bicheno 2000; Hines and Taylor 2000)	This maps only quality issues and does not link quality to product types. It identifies product defects, scrap defects and service defects	It does not capture dynamics of processes but impacts of quality issues on overall production are quantified.	This identifies quality issues in MEs and does not indicate dynamics which are often associated with multi products	This technique does not reflect the effect of causal impacts on manufacturing systems design	It can be extended to quantify cost of defects but not for estimating process cost	Value added on materials are not captured by this technique	There are no constructs for modelling cost and value	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios	Process decomposition is outside the scope of this technique	It could be used to understand quality issues in CIM environments. It is not supported by IT

g. Demand amplification map (Bicheno 2000; Hines and Taylor 2000)	It focuses on customers and their orders. It does not segregate orders according to product type. Hence does not match products to processes. Useful for sales and supply chain analysis	It is capable of identifying some complexities and dynamics based on the 'Forrester effect' but dynamics of demand are not matched unto manufacturing processes	Results from these techniques are not often mapped unto production systems hence makes it difficult to use it as a manufacturing process redesign tool.	The tool does not reflect causal impact of activities. No financial indicators are expressed in this technique	The technique is suitable for demand analysis but does not support process cost estimation	It does not indicate measurement of values	There are no constructs for modelling cost and value	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios especially in a virtual environment	Process decomposition is outside the scope of this technique	It could be used to help understand front end demand issues but it will require translation of demand unto manufacturing systems design and operation
h. Push pull map (Bicheno 2000; Hines and Taylor 2000)	It is suitable for single flow production systems. It is an effective lean implementation tool but limited in multiproduct flow scenarios	Push pull maps are not capable of identifying dynamics and complexities in MEs.	This is a process design tool but not capable to support complex manufacturing systems design	It does not reflect causal impact of activities. No financial indicators are expressed in this technique	The tool does not relent itself to process cost estimation	Value indictors are viewed from the lean aspects of cycle time, queue times and overall lead time	There are no constructs for modelling cost and value	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios	Process decomposition is outside the scope of this technique	It is most suitable for CIM applications in single flow manufacturing environments. It is not supported by IT

i. Physical structure map (Bicheno 2000; Hines and Taylor 2000)	It is useful for rationalization of policies on suppliers and customers. It does not lead to product classifications and their inherent complexities	It is a linear mapping process and does not capture any feedback. Complexities and most especially dynamics is not the focus of this mapping tool	This is not necessarily a manufacturing systems design tool. It forms the basis for analysing supplier requirements and how these matches with customer requirements. It is not a tool for manufacturing process design	This does not involve analysing the causal impact of activities. Since no analysis of causal impacts are achieved it does not also reflect the impact of activities in financial terms	It is not useful in area of process costing	It does not offer any means of quantifying value	There are no constructs for modelling cost and value	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios especially in a virtual environment	Process decomposition is outside the scope of this technique	It is not a CIM design tool but could help define policies on suppliers and customers
j. Capacity map (Hines and Nick 1997; Bicheno 2000)	It is useful for 'static' resource analysis. Not capable to depict product variances and their effect on resources.	Although suitable for matching resources to processes, there is no room for alternative business scenario analysis and thus cannot capture possible dynamics in the ME	This is a process design tool but with extreme focus on resource utilization. However the resource analysis is based on 'static' data (point in time).	Causal relations are not observed by this technique	The technique has no extensions to process cost estimation	The technique does not show any means of measuring value	There are no constructs for modelling cost and value	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios especially in a virtual environment	An understanding of process elements can be obtained from this technique but it is not suitable for thorough process decomposition	It could support CIM design and analysis to some extend but will require IT support for further analysis

k. Cost time profile (Hines and Nick 1997; Bicheno 2000; Hines and Taylor 2000)	It shows accumulated cost over a given time. It is a static cost analysis tool which does not predict multiproduct impacts on processes and cost	It absorbs and underestimates the realities of complexities and dynamics in MEs.	This technique is capable of analysing cost implication of activities in a manufacturing enterprise but with limited application in complex environments	This a linear approach to mapping without reflecting the impact of other processes. It depicts financial indicators in a linear form	A level of process cost estimation can be achieved with this technique.	The focus is on cost and not value generated.	There are no constructs for modelling cost and value	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios especially in a virtual environment	No decomposition approach has been recommended in this technique	It is not very much applied in CIM projects and also not supported by IT
l. Logistics pipeline map (Bicheno 2000)	It does not map product differences. It is essentially utilized in supply chain analysis where inventory accumulation is the focus	It is not suitable for analysing and managing complexities and dynamics in MEs	the tool is focussed on supply chain analysis especially identifying points where inventories are accumulated and it is not a major process design tool	There are no schemes for depicting causal effect of activities on subsequent activities. Financial considerations are only given at the inventory accumulation points	The technique is suitable for estimating inventory cost but does not extend itself to the entire process network	It is not a tool for measuring value addition	There are no constructs for modelling cost and value	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios especially in a virtual environment	This is not a suitable technique for process decomposition	May be suitable for supply chain issues in CIM. It is not yet supported by IT

m. Value adding time profile (Bicheno 2000; Hines and Taylor 2000)	It is not suitable for multiproduct flow analysis. It essentially maps cost of value adding and non-value adding activities without differentiating product types.	Complexities and dynamics are beyond the scope of this technique	It is a useful manufacturing process redesign tool but most suitable for single product flow systems	This technique is not suitable for depicting causal impact of processes on each other. It however attempts to quantify process metrics in financial terms. For example, value adding cost	The technique has the capability to support activity based costing in MEs	The tool measures the cost of 'value added processes and the non-value added processes'. The definition of value is based on the lean metrics of cycle and lead times	Cost and values are not necessarily modelled. They are viewed in terms of process lead times, value added times.	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios especially in a virtual environment	This is not a suitable technique for process decomposition	Only suitable for cost analysis of single flow manufacturing systems

n. Value stream map (Womack, Jones et al. 1990; Hines and Taylor 2000; Duggan 2003; Womack and Jones 2003; Lee 2005)	Identifies product types but simplifies analysis based on product families. It is unable to recognize the effect of multiple flows on resource utilization and hence its impact on values and costs	Complexities and dynamics are beyond the scope of this technique.	This is mainly a manufacturing process redesign tool with emphasis on the realization and elimination of waste through the identification of process and queue times. It is however limited when applied to MEs of high product complexities and dynamic market environments.	There are no indications of feedback schemes on processes. Also no financial indicators are expressed in this technique. Indicators are focussed on production lead time, queue time and inventory sizes	The technique in its current state is not capable of estimating process cost but has capability for supporting activity based costing.	Value addition is measured from the lean approach and can be used as the basis of identifying areas of potential improvement in manufacturing processes especially in a less complex manufacturing environment	Cost and values are not necessarily modelled. They are viewed in terms of process lead times, value added times. They are not depicted as a 'flow'	This a 'static' mapping tool and limited in its capability to observe and analyse alternative business scenarios especially in a virtual environment	The technique possesses the capability to enact the decomposition of processes but will need some support from other techniques. The present state does not show how processes can be thoroughly decomposed with the view to separate problems from solutions	This technique renders itself for the application of CIM techniques. This has lead to the development of software like 'Lean Modeller'

Although subjective, based on the author's knowledge in the application of these mapping tools and from the literature analysis described in Table 2, a score range of 0-5, with 5 being the highest, was assigned to each of the mapping tools in terms of how they match up with the requirements described in section 3.3. Table 3 shows quantitatively how the author viewed the performance of the reviewed mapping tools, in relation to the requirements for multiproduct flow cost and value analysis.

From the analysis performed in Tables 2 and 3, it was evident that:

1. None of the mapping techniques was best suited for multiproduct flow analysis. At best, enhanced versions of the value stream mapping technique recognize the need for product classification to simplify or annex the effect of some of the challenges associated with multiproduct flow dynamics. Most of the mapping techniques assume in a simplified manner, single flow manufacturing systems. The maps uniquely possessed their capabilities to map what they had been designed for. This was especially so in the case of the 'product variety funnel, customer maps, order maps and lead time maps'. But in relation to this research, they are not suitable for in-depth analysis on multiple product flows in dynamic manufacturing environments.
2. Also observed from the strengths and weaknesses of the mapping tools was the fact that none of the tools was really good for capturing aspects of complexities and dynamics in MEs. This is because most of the tools were designed for mapping processes of linear orientation and do not reflect real-time dynamic instances of the ME. Hence none of them was found suitable to adequately support complex manufacturing systems designs. An observed reason is that none of the tools possessed the ability to reflect causal impacts of activities on processes. This latter part is necessary in order to indicate feedbacks that are often present in real life manufacturing systems. Multiple 'what if' scenarios cannot be effectively assessed because of the static nature of the results derived through these tools. Also results derived from the mapping tools are not extended to indicate the effect of processes on cost and value, which are part of the key economic indicators in every industry. Notwithstanding the process-based tools like value stream mapping, cost time profile and value adding time profile can be enhanced to support activity based costing. In the area of value estimation, no tool was observed to effectively quantify value. The value stream mapping approach quantifies value in terms of operation times and production lead times. No constructs really exist for identifying cost and value as flows from one activity unto the other, but in reality the reflection of cost and values as sequential flows is a good way to improve processes in MEs.

Process maps	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**Total**
a. Overall lead time map	0	1	2	0	0	0	0	0	0	1	**4**
b. Order maps	0	1	0	1	0	0	0	0	0	1	**3**
c. Customer map	0	1	1	1	0	0	0	0	0	0	**3**
d. Process activity map	0	1	2	0	1	1	0	0	1	0	**6**
e. Product variety funnel	0	2	1	1	0	0	0	0	0	1	**5**
f. Quality filter map	0	1	1	0	2	0	0	0	0	1	**5**
g. Demand amplification map	0	2	1	0	1	0	0	0	0	1	**5**
h. Push pull map	0	0	2	0	1	2	0	0	0	0	**5**
i. Physical structure map	0	0	1	0	0	0	0	0	0	0	**1**
j. Capacity map	0	1	2	0	0	0	0	0	1	0	**4**
k. Cost time profile	0	1	2	2	2	0	0	0	0	0	**7**
l. Logistics pipeline map	0	0	2	1	2	0	0	0	0	0	**5**
m. Value adding time profile	0	0	3	2	2	2	1	0	0	1	**11**

Key:

A= Ability to analyse multiproduct flows and their associated product dynamics;
B= The possibility to identify and capture aspects of complexities and dynamics in MEs;
C= The suitability of the mapping tool to assist in complex manufacturing systems and process redesigns;
D= The ability to reflect causal impacts of activities in MEs especially on financial terms;
E= The possibility to measure process cost without distortion;
F= The ability to quantify value added through a given process;
G= Availability of suitable constructs for value and cost modelling;
H= The ability of the tool to support business analysis especially in a virtual environment;
I= The capability to decompose processes into elemental activities to enhance understanding
J= The suitability of the tool to support CIM and IT principles.

Table 3: Performance of process mapping tools against modelling requirements

3. None of the tools rendered itself for alternative business analysis through a virtual means. This is necessary because of the capital intensity of manufacturing assets and the need to be able to visualize in perspective the likely effect of the implementation of business ideas. However in recent times some of these mapping tools have been supported by simulation modelling tools for business analysis. Without the support of IT, these tools provide a static view of the enterprise.
4. Analysing the various mapping tools, it was observed that none of the tools had formalisms which supported detailed decomposition of processes. Decomposition of processes enable enterprise systems to be grouped into elemental bits for easier management. Also there are no clear methodologies for defining processes and their associated activities. Specifically, the approach for identifying waste in the value stream mapping technique was considered not exhaustive. This is because it lacked the appropriate understanding of decomposition of processes, thus important cost and waste sensitive areas may be omitted at the elemental level when processes are not well decomposed. In addition, there is no clear distinction between information, resource and material flows and this makes it difficult to distinguish between flows, causing management of flow elements to be distorted. Generally, behavioural rules are not explicit for both structured and unstructured processes. Because of the limited formalisms, enterprise knowledge cannot be fully capitalized and the associated benefits of enterprise integration as a requirement in CIM cannot be enabled. Thus on a more critical note the process mapping tools do not render adequate support for the design and implementation of CIM systems. The idea of open systems architecture and standardized CIM modules which support the ‘plug and play’ approach is not harnessed in any of the methodologies. Furthermore, the tools do not support the design and management of CIM systems life cycles.
5. Through a study of the capabilities of the mapping tools and from the foregoing discussions, it is evident that value stream mapping has proven effective in many manufacturing organizations engaged in single product flow manufacture and concepts of value streams have successfully been used in organizations deploying lean manufacturing techniques. However value stream mapping was observed not to be an effective process redesign and improvement tool for manufacturing systems that need to realise multi-product flows. Apparently current best practice approach to value steam mapping is not capable of mapping complexities and dynamics inherent in MEs. Also existing literature on the lean approach to

value stream mapping does not clearly show how values are quantified along process segments. The closest idea towards quantification of values is based on cycle and lead times. None of the other mapping tools could be used complementarily with the value stream mapping tool to help overcome these limitations. There is therefore the need to enhance the value stream mapping tool with other tools which will support:

- multiproduct flow analysis
- complexities and dynamic system analysis
- complex systems design
- business decision analysis in a virtual environment
- decomposition of processes
- support for CIM and IT applications, engineering.

In view of the expressed limitations of the VSM technique in meeting the above requirements, Enterprise Modelling (EM) tools were reviewed to establish the possibility of arriving at an EM tool which could possibly replace or support the VSM technique to overcome the limitations expressed. Enterprise Modelling (EM) tools are used to refer to architectures, methodologies and techniques in the enterprise engineering domain used for modelling various aspects of enterprises. Five (5) of the tools considered in the review were:

- Purdue Enterprise Reference Architecture (PERA)
- Architecture for Integrated Information Systems (ARIS)
- The Computer Integrated Manufacturing Open System Architecture (CIMOSA)
- Integrated Enterprise Modelling (IEM)
- Integrated Definition (IDEF modelling suites)

Based on the same criteria used to assess the process mapping tools, Table 3 describes the strengths and weaknesses of the various EM tools.

Modelling tools	Analysis of multiproduct flows and product dynamics	Identification and capturing of aspects of complexities and dynamics in MEs	Suitability for complex manufacturing systems and process redesign	Reflection of causal impacts of activities on financial indicators	Ability to measure process cost without distortions	Ability to quantify value added through a process	Availability of suitable constructs for value and cost modelling	Supporting business analysis in a virtual environment	Capability to decompose processes for easier analysis and understanding	Support of CIM principles and IT techniques
2. Enterprise modelling tools										
a. PERA (Williams 2002)	PERA identifies products requirement as an enterprise mission. No well refined means of analysing different product types and their process characteristics have been developed. It does not include product family characteristics.	PERA does not define any modelling constructs for enterprise dynamics and complexities	PERA is a CIM system design methodology. The application of PERA does not provide rigid constructs for modelling manufacturing systems. When complex systems modelling is required, PERA is open to the application of any suitable modelling technique.	There are no elements in the PERA methodology to depict causal impacts in the manufacturing system. The implication of causal effects on financial and economic indicators are implied but not explicit.	Process costing is outside the scope of PERA	Value is not quantified in PERA. It is purely a CIM implementation methodology	There exist generic constructs for inputs, outputs, processes and control parameters. Where necessary, enterprises can be structured in a way to indicate process parameters as cost and value.	PERA provides the necessary basis for transforming aspects of the CIM business into virtual models for alternative business analysis.	More detailed decomposition skills may be required in support of PERA as PERA itself does not provide a methodology for decomposing processes	PERA supports CIM principles and it is at the moment the most complete methodology for business users in developing CIM implementation

b. ARIS (Scheer 1992)	ARIS as an open architecture in the sense of its formalisms. Thus processes can be modelled around products classes but this is definitely dependent on the ARIS user's skills and capabilities	ARIS provides a means to address complexities and perform frontline analysis before their implementation	ARIS structures the enterprise into four views and three modelling levels. The ability to segregate the enterprise into these levels make it helpful to conjugate problems.	ARIS possess a data view which is used to define semantic data models which is then translated into relational schemata before implementation. But this does not take into consideration causal impacts of processes	Since ARIS is a process based tool, there is the possibility to introduce cost elements	There are no means to indicate value additions along processes	Cost and value modelling are not captured in ARIS although there is the potential to develop constructs to support that. Elements of cost are captured in ARIS Toolset	ARIS Toolset supports alternative business analysis. It is currently extensively used in business process re-engineering of managerial information	ARIS is able to decompose processes to some extent but it deals more with traditional business-oriented issues such as production planning and inventory control	ARIS is essentially focussed on software engineering and organizational aspects of CIM. It is therefore an enabling technique for CIM systems

c.

c. CIMOSA (AMICE 1993; Vernadat 1996)	CIMOSA models processes in greater detail as compared to the other enterprise modelling techniques. Although this is the case, models generated through CIMOSA are	CIMOSA models support modularity of design and hence complex systems can be decomposed into elemental levels to explicit understanding such that detailed analysis can be performed. It	CIMOSA supports manufacturing systems design and implementation description issues. Its decomposition capabilities tends to simplify enterprises such that enterprise can	There are no clear means of reflecting causal impacts of activities on financial and economic indicators. It may require some enhancements to achieve this	The process modelling approach in CIMOSA can be instrumented to support activity based costing	Value is not quantified in the CIMOSA technique	There are no observed constructs for value and cost in CIMOSA modelling	Aspects of business analysis can be achieved through the utilization of CIMOSA modelling techniques but models cannot be simulation	CIMOSA supports the functional and thorough decomposition of processes. Well defined formalisms exist in showing how CIM systems can be decomposed into levels suitable for	CIMOSA properly covers the functional and behavioural aspects of CIM systems and it is in line with emerging international standards for CIM (e.g. STEP, ENV12 2004). CIMOSA methodology is

not product specific. It may require further development or modifications of modelling steps to include product specific enterprise models	may however require enhancements from the system dynamics techniques to effectively capture aspects of dynamics in MEs	be designed and managed in modular forms leading to an improved way of managing system complexities						analysis.	however complex in nature and lacks the support of computer tools

d. IEM	IEM is a process improvement tool which models the functional and informational aspects of an enterprise. The functional aspects are represented in terms of activity models. Additional work may be required to design IEM models along multiproduct flows	Aspects of complexities and dynamics can be understood from the IEM models	Because of its decomposition technique, aspects of complexities can be managed	Detailed analysis of causal impacts are not captured by IEM	Cost is not a functional aspect of IEM	value is not quantified in IEM	There are no constructs for cost and value	IEM models cannot be simulated thus placing a major limitation in its application in virtual environments.	Activities are modelled together to form an activity-chain which is used to form processes. The decomposition principles in IEM do not allow modelling of systems to levels of granularity	Although can be processed by a computer, IEM models cannot be simulated. The models are not time dependent and alternative resource attributions are not included

e. IDEFx (Roboam 1993)	Literally, any kind of process flow can be modelled in IDEF3. the current state does not map product flows unto	Complexities and dynamics can be understood from IDEF models but they do not really capture these complex	IDEF models are not quantitative but literally any kind of process flow and logics can be modelled in IDEF3. An outstanding attribute of the IDEF3 models is	IDEF models do not show any explicit concept of triggering events and the causal	IDEF2 has graphical formalisms for modelling time dependent aspects of activities. Based on these time	Value is not carefully quantified in any of the IDEF modelling tools. However there is the possibility of including	The current state of IDEF models do not include cost and value constructs	Although IDEF3 has significantly enhanced aspects of IDEF0 and IDEF2, time and resources are still not aThey need to	IDEF0 models lack formalisms and activity diagrams do not indicate precedence sequences and the approach is prone to subjectivity.	IDEF models are appropriate for initial CIM systems design but may need to be enhanced before suitably benefitting from ITs. In their current states,

processes. Multiproduct are not linked to processes. Processes are analysed separately	factors. It is an element which have to be implied from an understanding of the process models	the description of synchronization mechanisms between process and processes or processes and their environment. It does not show exception handling mechanisms	impacts of process elements are not captured although they may indirectly influence the logic of process flow	measurements, activity based costing can be supported by this modelling method	mathematical methods of modelling value into IDEF models especially if there is a well defined means of estimating value		be enriched and translated into Petri net models before they can be simulated	This limitation was overcome by IDEF2 and IDEF3 through the application of queuing networks in IDEF2	they are descriptive and not suitable for simulation applications

Table 4: Review of existing EM tools in relation to requirements for multiproduct flow value and cost dynamics

Reflecting on the strengths and weaknesses of the EM tools as described by Table 4, the author observed that in general terms:

1. The Enterprise Modelling (EM) tools, relative to process mapping tools, offered additional modelling concepts that enable the capture of semantically enriched models of various aspects of enterprises. Enterprise elements are separated and distinguished such that it is easy to identify processes and their execution agents. The models provide a multi perspective view of enterprises and thus is more suitable for analysing various and complex aspects of businesses. Because of the unified approach towards CIM systems, they provide a uniform representation of enterprises which cause users to understand their operations in depth. In theory enterprise modelling approaches facilitate the design and development of better processes and systems, and can improve the timeliness and cost effectiveness of change projects in MEs, but full and industry wide benefit in practice is yet to be realised.
2. In relating the strength of the reviewed enterprise modelling tools, to previously analysed tools for modelling value streams and cost, it was observed that extensive enterprise modelling tools have not been designed and used with a view to capturing multi value and cost flows, which is the main focus of this research. It is however fair to note that most enterprise modelling tools have embedded structures and formalisms for capturing many aspects of processes; such that value and cost analysis can be performed on them. In as much as there is no stand alone EM tool for cost and value analysis, it was observed that some of the model viewpoints provided by EM tools can be structured and combined with principles derived from value stream mapping; to provide a holistic approach for modelling values and cost.
3. The CIMOSA modelling approach was observed to offer an extensive set of modelling constructs and well experimented decomposition formalisms for modelling enterprises at multiple levels of granularity. Via enterprise modelling, networks of processes are generated such that connections between process elements Can explicitly be described and graphically represented. This is an essential way to help analyse causal impact of activities on each other. Because of the detailed decomposition attributes made available with EM tools, this means that operational activities can be captured in detail and modelled at suitable abstraction levels, such that value addition and cost generation can be estimated at an acceptable degree of accuracy. The models generated can be used to , analyse bottlenecks and other process improvement factors which are within the scope of the mapping tools. The CIMOSA modelling tool does not however provide constructs for depicting cost and value flow; nor does it actually computer execute the EMs developed so that enterprise behaviour can be modelled as a function of time varying system states.

4. In analysing the possibility of using EM tools to depict multi product flows in MEs, it was noted that most of the EM tools are ‘process oriented’ and they generate models from understandings of generic processes in companies. For example, the CIMOSA approach to systems requirement modelling commences by developing one or more top level business contexts that link stakeholders (domains). The enterprise domains are then decomposed into their respective domain processes. Further decomposition of domain processes naturally fleshes out the various business processes in the enterprise without necessarily matching them to respective products. Additional work is therefore required to configure business processes around product classes.
5. Although EM tools are useful for CIM systems design and development and enable better understand of enterprise operations, most of them are not computer executable and as a standalone tool cannot be simulated for alternative business analyses. But EM tools have widely been used to support database design and engineering and therefore IT systems design, development and integration.

In meeting the requirements of CIM implementation and the fulfilment of international regulations such as ENV40003, the CIMOSA modelling methodology was observed to be the most complete and able to handle time, exceptions and non-determisms in model generation. As a result, there exist the potential to combine ‘best in class’ aspects of the value stream mapping technique in terms of product classification, cycle and lead time determinations, definition of waste and value, etc, to ‘best in class’ model generation capabilities of the CIMOSA technique to support enhanced modelling of values in multiproduct manufacturing environments. However, generally, EM tools are limited in their provision of adequate constructs for capturing essential dynamic attributes in enterprises. Because of these limitations, system dynamics tools which do possess capabilities to model aspects of dynamics and complexities were reviewed to observe how they can support VSM and CIMOSA modelling techniques in the area of complex systems modelling. To provide a full understanding of some commonly used system dynamics tools, analysis and comparison was made, based on the same requirements specified for modelling multi product dynamic value and cost streams as detailed in Section 3.3. Table 5 shows the relative strengths and weaknesses of six (6) system dynamics modelling tools.

Modelling tools	Analysis of multiproduct flows and product dynamics	Identification and capturing of aspects of complexities and dynamics in MEs	Suitability for complex manufacturing systems and process redesign	Reflection of causal impacts of activities on financial indicators	Ability to measure process cost without distortions	Ability to quantify value added through a process	Availability of suitable constructs for value and cost modelling	Supporting business analysis in a virtual environment	Capability to decompose processes for easier analysis	Support of CIM principles and IT techniques
3. System dynamics tools										
a. Causal Loops (CL) (Forrester 1961; Sterman 2000; Burns 2001; Burns and Ulgen 2002)	Causal loop models are not product specific. They represent the causal effects of activities. Specific product -based causal loop models can however be generated.	The identification of aspects of complexities and dynamics can be model through CL modelling technique	CL as a standalone technique is not useful for complex manufacturing systems design. It may be suitable for strategic decision analysis. When combined with a suitable process modelling technique, it provides a suitable platform for complex systems design	CL models can be made to depict the causal impacts of activities on financial and economic indicators in MEs. This depiction is however qualitative and cannot accurately be quantified in the CL technique.	There are no measurable parameters in CL modelling	Values are not quantified in CL. They can at best depict the factors which influence value generation	There are no established constructs in CL modelling. They basically represent cause and effects interlinked by arrows and sign polarities.	Because of its ability to capture dynamics in MEs, it is a useful tool for qualitative analysis of businesses. CL models by themselves cannot be simulated but they can be transformed into equivalent iThink models for simulation purposes	Processes are not decomposed in the CL modelling technique. It aggregates processes for top-level business analysis	Research literature has not yet shown CL models being used in support of CIM implementation.

b. Stock and Flows (SF) (Sterman 2000) (Randers 1980; Binder, Vox et al. 2004)	With some rigour 'Stock and Flow' models can be created to represent different groups of products but they have not been used for such applications	Aspects of complexities and dynamics can be captured through the application of SF models	SF model to a lighter degree support complex manufacturing systems design. They will require further drilling down before their full benefit in process redesign can be realized	Causal impacts are captured in SF models and could be made to reflect financial and economic indicators especially when these indicators are modelled as stocks, flows or convertors	They possess the ability to quantify cost through the parametric cost estimation process	SF models posses the capability to quantify value based on the definition of value established by the modeller	There are no constructs for value and cost modelling. It is possible to express cost and values as 'stock, flows, auxiliaries' etc for the purposes of analysis	SF models may support alternative decision analysis but it may need the support of a continuous event simulation tool like iThink.	They posses no decomposition formalisms	There is no evidence of SF models used for CIM applications but there exist the potential of its suitability in CIM and IT applications
c. Petri Net (PN) (Peterson 1981; Zhou and Venkatesh 1999)	PNs can accommodate levels of product complexities but will require a formalized approach for doing so	PNs are suitable for capturing aspects of system dynamics. Process models can be can be extracted from CIMOSA or IDEF3 models	Together with queuing networks, computer simulation and perturbation analysis, PNs are able to support complex and dynamic manufacturing systems design.	PNs are able to analyse qualitative causal effects of activities of dynamic systems	Because of the mathematical support in PNs, they can be useful in measuring costs	PNs will be able to quantify value based on the definition of the modeller.	There are no well established constructs for cost and value modelling	They support alternative business decision making and PNs make simulation explicit on graphical tools	Petri nets inherently support the end to end modelling of processes without consideration of organizational boundaries.	PNs can be used in CIM systems design especially at the functional design level. They are computer executable

d. Bayesian networks (BNs) (Pearl 2000)	BNs is a statistical modelling tool and could help classify products but not model products with their process. It is not a process modelling tool	BNs are capable of representing aspects of dynamics and complexities in MEs in the form of variables and their probabilistic independencies	BNs in the form of their influence diagrams can be a helpful to for complex systems designs but will require some rigour to fit into the ME designs	Causal relations can be captured and represented as conditional dependences and used for onward analysis	Efficient algorithms exist which can be designed to identify process costs without distortions	BNs can be designed to help quantify value	There are no existing constructs for cost and value modelling	BNs support decisions of alternatives but will require rigour to exemplified in the virtual world of MEs	There are no decomposition techniques associated with BNs	There are no proven use of BNs in CIM applications
e. Fuzzy logic (FL) (Batur, Srinivasan et al. 1991) (Wang 1992)	FL feeds on the fuzzy set theory to support reasoning but it does not explicitly model processes.	Complexities can be expressed but in a statistical manner	It is not an ME design tool but could help in various stages of decision making during the ME design	Causal relations could be depicted but limited to variables and not processes	Process cost can be estimated with FL	Value can be expressed especially when there are conditional effects	No value and cost constructs exist	it is a probabilistic tool which supports programming languages which can be instrumented to support decision making	No decomposition required	In Engineering applications, FL is mostly used for product design instead of CIM designs

f. Neural networks (NNs) (Minsky and Papert 1969; Gardner and Derrida 1988; Spooner, Maggiore et al. 2002)	Factors influencing multiproduct flow can be developed and modelled through the application of NNs but not as a process. For example, NNs can be used to group products into their respective classes based on a mathematical or relational algorithms. it cannot match graphically products to their processes	The application of NNs in real life is suitable for modelling complexities especially the complexity of data and not ME design	This is a design support tool but not a design tool itself. It is a non-linear statistical data modelling tool	It is capable of reflecting causal impacts through the expression of algorithms	NNs possess the ability to measure process cost through the formulation of algorithms	NNs can be able to achieve value estimation through mathematical functions and algorithms	No constructs really exist	It is a useful decision modelling tool which support computer applications	Processes are not decomposed. It is not a process modelling tool	Could support CIM applications but only as a data modelling tool and for analysis of complex relationships.

Table 5: Review of system dynamic tools in relation to requirements for multiproduct flow value and cost dynamics

Summarizing the analysis shown in Table 5 and based on further investigation on the application of system dynamics (SD) modelling techniques, it was noted that:

1. SD techniques offer a unique approach towards the modelling of complexities and dynamics in systems. Literature has shown how SD models are able to capture factors or elements which induce dynamics in many social, health, political and economic systems. Later attempts have been made to use these techniques in support of the design of manufacturing systems. Little successes have been reported though and this may be due to the inability of these techniques to critically model processes at the elementary level. In essence, they are useful tools for capturing and analysing factors which impact on processes and their executing agents, but in reality, without a process model, it is difficult to make full use of SD models in manufacturing environments and most importantly in CIM design and application. This is because in CIM environments, enterprise or process models are key and arguably should be the base line for enacting process improvements.
2. The strong mathematical base of these modelling techniques discourage lots of manufacturing experts from deploying them. This is particularly so in the case of BNs, FL, NNs and PN technologies. Training will be required to enable manufacturing experts to understand and benefit fully from these techniques. The CL technique however does not involve any complex mathematical expressions and it is good in illustrating, qualitatively, the cause and effects evident in a system. Also observed was that the CL modelling technique could be used together with process modelling techniques to capture and analyse the causal impact of activities on various business performance indicators. This will lend support for complex manufacturing systems design. Also factors which influence value generation and cost can be captured and expressed on process-based models for effective economic analysis of manufacturing processes.
3. None of the system dynamics tools on its own was capable of modelling multiproduct flows in manufacturing environments. However they are able to capture factors which influence or impact on ME processes due to multiproduct flow phenomena. This is because they are not essentially process modelling tools and can only support by providing understanding about complexities and dynamics along process segments.

For simplicity and first stage qualitative analysis, it was considered that CL would prove to be the most suitable. However CL models cannot be simulated in their natural state and needs to be transformed into equivalent simulation models before in-depth process and business analysis can be performed. Generating simulation models can help save cost, generate best results, promote enterprise integration, improve value generation and support the derivation of methods for improving processes in MEs. Based on these additional needs, further analysis and comparison of some of the commercially available simulation modelling tools was done. The choice of tool reviewed was limited because of study constraints, but the three tools chosen as the subject of review covers different classes of simulators. The outcome of this analysis is shown in Table 6.

From Table 6, it can be deduced that:

1. The Lean Modeller software provided modelling constructs and measurable parameters similar to the constructs deployed when using the conventional value stream map technique. It is easier therefore to translate value stream maps into equivalent simulation models in Lean modeller. A primary limitation however is the fact that Lean Modeller can handle only single flow process models. When complexities increase, it becomes difficult to mimic the real life situation in Lean Modeller. The software is not able to model multiproduct flows and the fundamental assumption in Lean Modeller is that, individual products follow a single process route. This may be so in a well established lean manufacturing enterprise but in most industries where there are multiple flows, resource sharing, and other dynamic instances, Lean modeller becomes inadequate. A later enhanced version of the software, Lean Modeller Enterprise, is capable of depicting some aspects of multi product flow and complexities in MEs but its capability is still limited to applications in lean enterprises. Its counterpart, Simul8, offers a more extensive approach towards complex multiproduct flow modelling. On the other hand, the iThink software is a continuous event simulation tool and does not segregate products flowing in the enterprise. iThink is able to generate graphs and based on the mathematical formulae underlining the model, different aspects of complexities can be captured and used to define possible effects on the enterprise. iThink is not a process modelling tool and therefore lacks formalisms for detailed modelling of process logics and controls
2. On the other hand, to measure cumulative cost and values associated with complex systems, iThink provides a better approach than the discrete event simulation tools. This is because of the flexibility iThink software provides in defining mathematical relationships between process parameters. Once mathematical expressions are derived, iThink is able to generate futuristic values based on the intended use of the model. The limitation in this approach is that the cumulative results continuous event simulation provides are not helpful in achieving product differentiations which could support decisions on products which add more value to the ME or cost less to produce. Simul8 however, is able to differentiate product types and their associated cost implications on production systems.

3. Causal effects which are shown by causal loop models can best be illustrated and quantified by the iThink modelling technique. In effect, causal relationships can best be described in iThink than in Simul8 or Lean Model but because iThink is not a process modelling tool it is difficult to match these causal impacts on processes. Although SIMUL8 and Lean Modeller can be used to provide more precise models, iThink requires less effort and it is good at depicting overall business behaviour.
4. It is therefore envisaged that different continuous and discrete event simulation modelling tools of relative strengths could be used coherently to model aspects of processes like queues, product flows, process routes, causal effects, stochastic events, resource utilization, process times, material and information flows, breakdowns, etc depending on the intended use of the models.
5. When a simulation model of a process is created, it will be difficult to interpret fully. This is especially so until it is presented in the context of the overall enterprise model. However attempts to present simulation models in the context of the broad enterprise may render it complex and inappropriate to support decision making. Therefore EMs will be required to provide (1) the needed backbone of modelling concept for SMs and (2) to explicitly describe the key properties context on which any simulated process segment needs to operate.

The above discussion and analysis has shown that VSM has been reported as one of the most effective mapping methodologies for designing and creating efficient manufacturing systems capable of adding value to inputs that flow though various aspects of manufacturing processes. A critical review has however exposed its practical limitations in the areas of multiproduct flows, causal impacts and dynamics, cost realization, decomposition formalisms, CIM systems design and IT applications. It has also been observed that there are number of EM, SD and SM tools with complementary strengths to address the limitations observed in the VSM technique. Literature however has not shown how to integrate these modelling techniques for optimal modelling performance in Industries. The author is of the view that the appropriate integration of the strength of these modelling tools and the establishment of verified transformation schemes from one stage of modelling to the other will provide an alternative modelling technique of higher capabilities to solve multiproduct value streams and cost dynamics.

Modelling tools	**Analysis of multiproduct flows and product dynamics**	**Identification and capturing of aspects of complexities and dynamics in MEs**	**Suitability for complex manufacturing systems and process redesign**	**Reflection of causal impacts of activities on financial indicators**	**Ability to measure process cost without distortions**	**Ability to quantify value added through a process**	**Availability of suitable constructs for value and cost modelling**	**Supporting business analysis in a virtual environment**	**Capability to decompose processes for easier analysis**	**Support of CIM principles and IT techniques**
4. Simulation tools										
a. Simul8 (Shalliker, Rickets et al. 2005)	Multiproduct flow and product dynamics can be expressed in Simul8. It makes use of visual logics and spreadsheets to assign different product properties to operation centres. This approach obviously depends on the experience of the Simul8 modeller	Aspects of complexities and dynamics can be expressed but with careful understanding of the process control logics	It can support redesign of complex manufacturing systems to some degree of approximation. It is useful for measuring, analysing, improving and controlling manufacturing processes	Not directly expressed but can be deduced from process variables	Process cost estimation can be achieved to some extent especially with activity based costing	Value quantification is not achieved in Simul8	Value and cost constructs are not included in Simul8	Suitable for alternative business analysis in a virtual world. It is able to develop multiple 'what if' scenarios and support animated simulations. It can communicate the effect of planned changes before their implementation	Decomposition can be supported thoroughly modular process mapping/modelling tools like CIMOSA or IDEF	A useful tool for CIM system analysis and implementation.

b. Lean Modeller (Visual8Co. 2006)	Lean Modeller standard' is not suitable for multiproduct flow modelling	Lean Modeller is not excellent for modelling complexities and dynamics.	Complex and dynamic manufacturing systems cannot be measured, designed or controlled through the application of lean modeller.	There is no reflection of causal impacts in this modelling technique	For a single process flow, Lean modeller is able to measure process cost	Value is expressed in lead times and cycle times.	There are no available constructs for cost and value but they can be deduced from in-built metrics	Business analysis in single flow MEs can be tested and verified.	No decomposition facilities are included	Has potential to support CIM design and analysis but with limited application in complex MEs
c. iThink/ Stella (ISEE 2007)	iThink/Stella as a system dynamics simulation tool does not depict different product flows. It aggregates elements of product flows and generate graphs to depict their effects	It is good for capturing aspects of complexities and dynamics.	There is room to depict how complex manufacturing systems can be supported through the application of iThink simulations	It is an excellent tool for illustrating the impacts of activities on financial indicators	iThink is not a process modelling tool	iThink models can be designed to show how values can be estimated along a process thread	There are no constructs for modelling cost and value. But estimating cost and values are possible	It is an effective tool for strategic decision making without detailed segregation of product elements	Processes are not decomposed	iThink could support CIM applications but only as a decision support tool

Table 6: Review of simulation modelling tools in relation to requirements for multiproduct flow value and cost dynamics

3.5 Research aims and objectives

Based on the foregoing analysis and previously reviewed established Industrial needs, this research study aims to develop an enhanced approach for modelling multi product flow value and cost stream dynamics, to support business analysis related to manufacturing systems design, operation, control, process improvement and management. To achieve this the following are the underlining objectives:

1. To evaluate 14 different process mapping techniques;
2. To evaluate 5 EM and 3 SM techniques;
3. To specify next generation cost and value streams modelling requirements for dynamic manufacturing enterprises based on 1) and 2);
4. To synthesize 1) and 2) and based on 3), develop an integrated cost and value streams modelling technique;
5. To test the applicability of the modelling methodology in four case study companies
6. To verify and validate 'as-is' models and experiment 'what-if' scenarios through the application of the derived methodology.
7. To identify the limitations of the developed methodology and recommend further work and improvements.

3.6 Design of Research

From the above description of research aims and objectives and in view of the research gaps identified in sections 3.3, it was necessary to explore existing methods of research, to see which of them best support the research objectives and will also help achieve the required results within the available research time frame. This was deemed important because research objectives differ and the selection of the appropriate methodology is necessary for the timely and accurate delivery of results.

3.6.1 Review and selection of Research Styles

Two main research styles have been identified to be useful in the identification and utilization of information. The two research styles are identified as quantitative and qualitative. Quantitative style of research represents information in numerical form. This could take the form of tables, graphs, charts and other statistical indicators which could help show trends, changes, comparisons and similarity of patterns. A clear advantage of the quantitative styles of research is that in dealing with quantitative data there can be a realistic and measurable scientific evidence to support or disprove an idea or contention. The limitation however is that the use of the data and hence inferences derived from the data might be accurate only in the context in which it was collected and hence generalising observations might not be accurate. Qualitative styles of research are deployed when there is the need to analyse how certain actions occur not just how often they occur. Information gathered through qualitative research styles is usually presented in a textual form. The usefulness of qualitative research is that it exposes the thought processes or reasoning behind a particular behaviour.

Reasoning about the needs of the research and with the background understanding of research styles, it was considered that both qualitative and quantitative styles were required to capture essential aspects of data required for the research. The research style determines the type of data required which is obviously derived from an understanding of the research objectives. The type of data collected determines the research method required to analyse them in order to develop an answer to the research problem.

3.6.2 Review of Research Methodologies

Available literature (Walliman 2001) classifies various types of research into categories such as historical; comparative, descriptive, correlation; experimental; creative; action; ethnogenic; feminist and cultural. Detailed explanation of these broad classifications have been provided by several authors. A good reference for further reading and understanding of the individual research types are provided by Melville and Wayne (Melville and Wayne 1996), Kumar (Kumar 1999) and Walliman (Walliman 2001). Four of the research approaches which have won popularity over the years due to the driving need of the Sciences are: descriptive, experimental, creative and action research types.
Descriptive research type relies on observation as a means of collecting data (Walliman 2001). In an explanation given by Melville and Wayne (Melville and Wayne 1996), no distinction was given between descriptive research types and case studies. The main idea here is to examine situations as a case study and establish what is the practice and based on the practice deduce what can be predicted to happen under the same circumstances. However Yin (Yin 1994) is of the view that descriptive research could be an aspect of a 'case study' together with 'explanatory' and 'exploratory' researches. Walliman (Walliman 2001) also noted that since descriptive research depends on human observations and responses, there is a higher tendency of distortion of data and inaccuracies which could occur through deliberate attempts to design questions to favour a certain cause or through selective observation of events.

Creative research on the other hand seeks to identify knowledge and hence potentially leads to discovery, design and development of new physical things (artefacts) as well as creation of new models, algorithms, theorems, etc. (Melville and Wayne 1996). This obviously have a wide range of application in academia and innovative researches.

Experimental research however differs in many respect from the other types of research. In this approach the research strives to isolate and control every relevant condition which determines the events investigated, so as to observe the effects when the conditions are manipulated. A example is a chemical experiment. It is however important to note that not all experimental researches take place in a laboratory.

Action research is related to experimental research. Cohen and Manion (Cohen and Manion 1994) defines action research as a small-scale intervention in the functioning of the real world and a close examination of the effects of such an intervention.

3.6.3 Selection of Research Methodology

The basis for the description of the research types provided in section 3.6.2 was to provide understanding about existing research types and to also establish the relevance of each of the research methods to the author. Table 7 provides a summary of the research types and their relevance to the scope of the research.

Research type	Types of activities involved	Relevance to author's scope of work
Descriptive	Testing of hypothesis of theories in a case study environment	Highly relevant
Experimental	Scientific testing of cause and effects	Relevant
Creative	Fact finding without a specified destination	Partially relevant
Action	Introduction of change factors into real life systems	Partially relevant

Table 7: Summary of research types and relevance to research scope

3.6.4 Research Resources

Thietrart (Thietrart 2001) and other researchers noted the use of primary and secondary sources of data for research purposes . This was found relevant to the research. The primary sources of data used include:

- ‘Business processes’ of collaborating companies based on CIMOSA modelling templates
- Observations on production floors of case companies
- Formal interviews with relevant actors

- Consultations with Research supervisor

Other secondary sources of data include:

- Existing data from collaborating companies (e.g. organization charts, flow charts, company profiles, sales records, manufacturing performance indicators, etc)
- Process maps and cost data of case study companies
- Journal papers and other publications
- Previous works by MSI Research staff
- Text books
- Internet

3.6.5 Research Plan

Based on the research requirements, aims and research resources available, a stepwise approach to the research was conceived. This was to help the author arrive at assessable recommendations. Although the stages were not followed strictly in the order presented in Table 8, it served as a guide to put structure around the research. It was also observed that some of the stages overlapped and others were achieved in parallel.

Steps	**Activity**
Step 1	Conduct literature review on key contributing areas to the research: • Manufacturing philosophies, strategies and solution technologies • Process mapping and enterprise modelling techniques • Cost and value engineering • System dynamics • Simulation modelling techniques
Step 2	Identify gaps in knowledge and specify next generation modelling requirements for dynamic manufacturing enterprises
Step 3	Compare best practice methods with modelling requirements and derive integrated multi product flow cost and value stream modelling technique
Step 4	Test the applicability of proposed modelling technique in case study companies
Step 5	Observe strengths and limitations of modelling technique and specify application domains of technique
Step 6	Generate general recommendations with respect to area of research

Step 7	Generate specific recommendation for case study companies

Table 8: Research plan

The above research plan formed the basis for the structure of this Thesis. Table 9 gives an overview of the various chapters in the Thesis.

Chapter number	**Chapter description**
Chapter 1	Background to research, problem identification, Research hypothesis and scope
Chapter 2	Literature survey
Chapter 3	Research scope and design
Chapter 4	Specifications and development of proposed modelling schemes and methods
Chapter 5	Case application 1: Application of initial proposed method
Chapter 6	Case application 2: Further application of initial proposed method
Chapter 7	Case application 3a: Static application of developed modelling method
Chapter 8	Case application 3b: Dynamic application of developed modelling method
Chapter 9	Case application 4: Further developments and application of modelling method
Chapter 10	Research analysis, contribution to knowledge and conclusions

Table 9: Structure of Thesis

4. Design of the multiproduct flow dynamic cost and value stream modelling technique

4.1 Introduction

The literature review in the area of multiple product realization in Manufacturing Enterprises (MEs) was presented in Chapter 2. To help satisfy the requirements for cost and value generation in MEs engaged in multiproduct flow systems, a set of tools belonging to the domains of process mapping, enterprise modelling, systems dynamics and simulation modelling were reviewed with the aim to establish a suitable method which will help capture cost and values associated with processes. This was to form a base for developing a technique to support the management of manufacturing processes through the observation of key performance indicators such as costs and values. The individual tools reviewed were observed to possess unique strengths in their respective application areas but what was required to help meet multiproduct flow systems requirements was observed to be the integration of the strengths of some of the tools reviewed. Whilst perceiving these benefits arising from application in this area of an integrated modelling approach, also observed was a need to develop transformation mechanisms to help streamline the various modelling stages to be established. Based on these observations and related assumptions, this Chapter describes a proposed integrated method for modelling multiproduct flow dynamic cost and value streams. The proposed method is designed with the view to help address the requirements specified in Section 3.3 for multiproduct flow systems. The subsections of this Chapter explain how aspects of the proposed methodology have been designed to help meet the requirements specified in Section 3.3. Chapters 5 – 9 show how the derived method was applied in four case study companies and further refined based on the understandings obtained through case study application.

4.2 Decomposition of processes

The proposed methodology starts off with the quest to comprehensively understand processes, associated flows and resources which transform inputs into ‘useful units’ that meet the goals of the company under consideration. This naturally leads to the generation of a ‘big picture’ which informs the modeller and user about functional requirements in the Organization. In deriving the big picture, care is taken to underline the internal and external stakeholders of the ME and special emphasis in terms of further decomposition is realized by detailing out requirements which are relevant to the current study. From the literature survey it was observed that CIMOSA modelling templates provided suitable decomposition formalisms to help achieve this objective. The initial CIMOSA modelling templates were created by Monfarad (Monfared 2000). The defined stakeholders represent subsets of the enterprise. In conformity with CIMOSA terminology, these subsets of the enterprise are called Enterprise Domains. Thus in essence, Enterprise Domains represent functional areas of the enterprise which are decoupled from each other with clearly identified objectives which enable them to be composed of well defined processes for achieving the objectives defined for the domain. These are represented as DMs (for example DM1, DM2, DM3, etc). Essentially, DMs are a realistic decomposition of a given enterprise which have clearly identified goals, objectives and roles in the enterprise such that explicitly defined interfaces exist between them. DMs should not have hidden or unknown implicit interactions between selected domains otherwise they will not be decoupled effectively. DMs are normally captured through a study of Organizational charts and other company documents or through interviews with relevant personnel. Deriving DMs by this approach may be inadequate in complex large-sized multifunctional manufacturing environments, because of the complications that are likely to emanate, hence the author introduced a more structured approach which requires a study of operations in the organization. This approach starts by enumerating the goals of the existing departments and individual processes observed to exist in the company. Based on the observed goals and associated processes, stand alone processes, called Domain Processes (DP) are grouped to reflect the distinctions in goals and deliverables. Further refinements of DMs and DPs are done until a suitable representation of DMs and DPs can be obtained. This improvement in approach leads to the creation of ‘CIMOSA decomposition tables’ as shown in Tables 9 and 10.

Derivation of Enterprise Domains (DMs)				
Enterprise overall objective:				
No.	**Enterprise Domains (DM)**	**Domain objectives**	**Business processes (BPs)**	**BPs goal expansion (check for similarity and process links)**
1	**Domain 1**	**Clear domain 1 objective**	BP1.1	1
			BP1.2	1
			BP1.3	1
			BP1.4	1
2	**Domain 2**	**Clear domain 2 objective**	BP2.1	2
			BP2.2	1 (links up with DP1 objectives)
			BP2.3	2
			BP2.4	1 (links up with DP1 objectives)
3	**Domain 3**	**Clear domain 3 objective**	BP3.1	3
			BP3.2	3
			BP3.3	2 (links up with DP2 objectives)
			BP3.4	2 (links up with DP2 objectives)

Table 9: Derivation of Enterprise Domains (DMs)

Derived Enterprise Domains (DMs)

Enterprise overall objective:

No.	Enterprise Domains (DM)	Domain Processes (DPs)	Business processes (BPs)
1	**Domain 1**	**DP1**	BP1.1 BP1.2 BP1.3 BP1.4 BP1.5 BP1.6
2	**Domain 2**	**DP2**	BP2.1 BP2.2 BP2.3 BP2.4
3	**Domain 3**	**DP3**	BP3.1 BP3.2

Table 10: Final stage domains derivation

In a graphical form, the achieved goal of a collection of DMs is modelled using suitable templates and this is termed a 'context diagram'. In detailing out the elements of the context diagram, the goal of the modelling exercise is clearly stated and used as a basis to define which of the DMs to focus on for further decomposition. These selected DMs become the CIMOSA domains: DMs which are external to the modelling objectives, and hence for which further decompositions will not be carried out, are treated as 'Non-CIMOSA' domains. Distinguishing the non-CIMOSA domains from the CIMOSA domains ensures that detailed analyses and further decompositions are carried out only on the selected domains to limit the extent of complexity which otherwise would develop. The context diagram therefore provides a snapshot of all the stakeholders of the ME under consideration. An example is shown in figure 10.

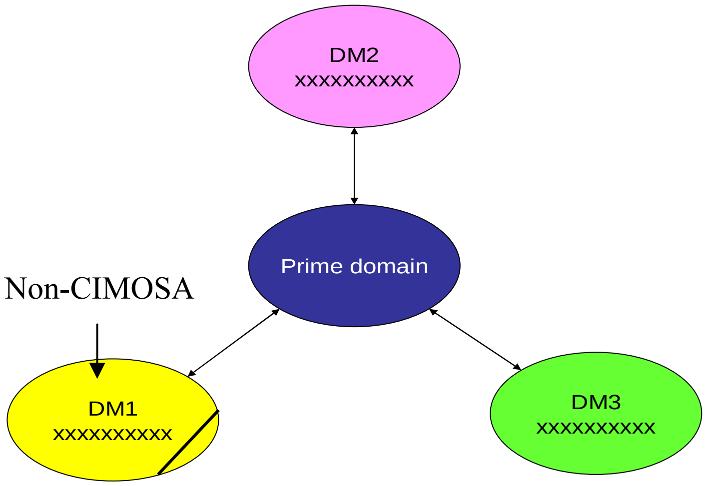


Figure 10: An example context diagram formalism

At the next stage of the process decomposition, interactions between respective domains in terms of information and material flow are modelled. The outcomes of this modelling stage are captured using a so called 'Top level Interaction diagram'. The interaction diagram therefore shows relationships that exist between the domain processes. Textual descriptions can be expressed but for the sake of simplicity a graphical representation of the interactive processes and their resultant elements of interaction is normally developed. Already existing constructs from within the original CIMOSA modelling scope, for information and physical materials were selected and subsequently used to explicitly define interactions that exist between processes. Figure 11 shows a graphical representation of a top level interaction diagram. The author revised the Monfarad (Monfared 2000) approach to CIMOSA modelling by introducing the creation of structure diagrams as the next stage of modelling. In the structure diagram, DPs belonging to CIMOSA conformant DMs are further decomposed into lower-level processes called Business Processes (BPs). In the structure diagram, relationship entities are not shown between BPs. They only represent the decomposition of the various DPs observed in the top level interaction diagram.

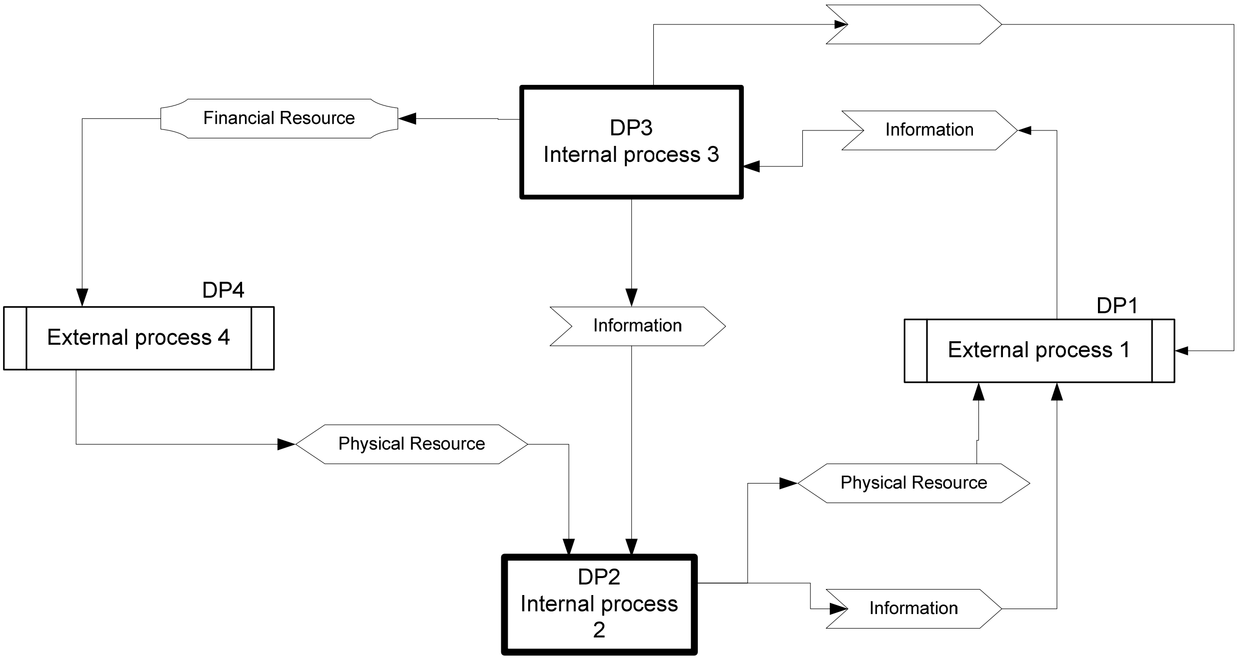


Figure 11: An example representation of Top level interaction diagram

The structure diagram gives the basis for the derivation of further sub-interaction diagrams which are used to describe how BPs interact.

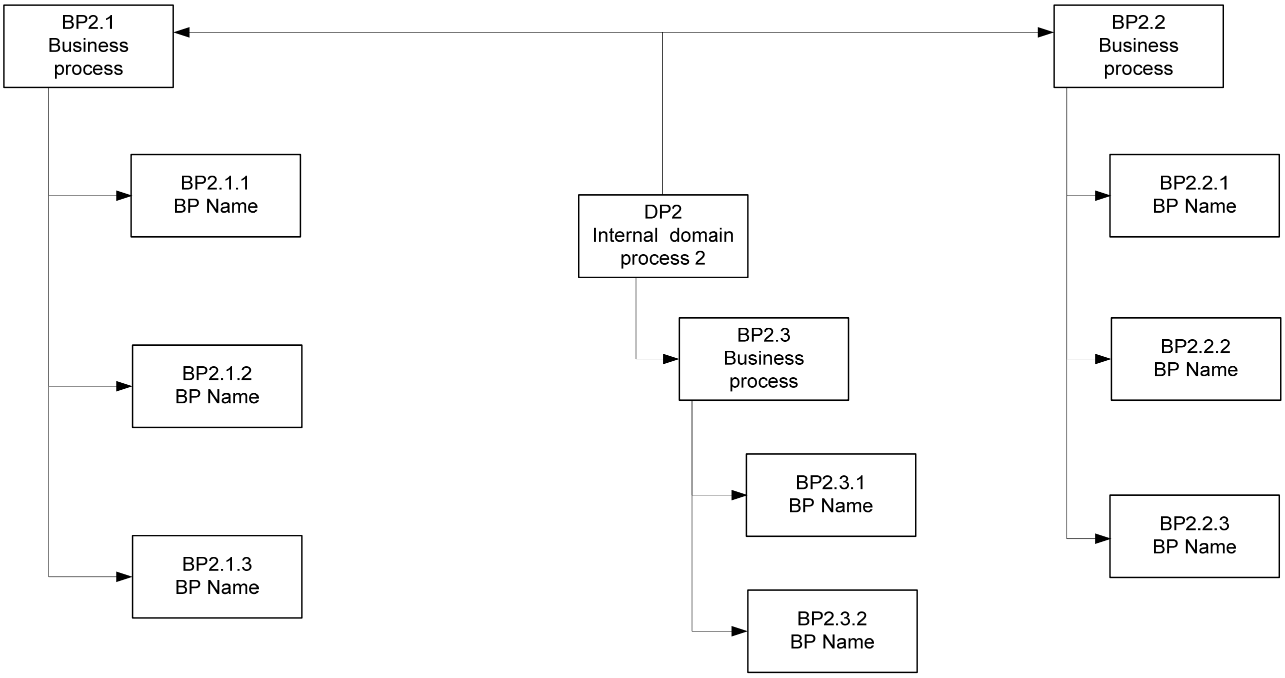


Figure 12: An example structure diagram

An illustration of a sub-interaction diagram is shown in figure 13.

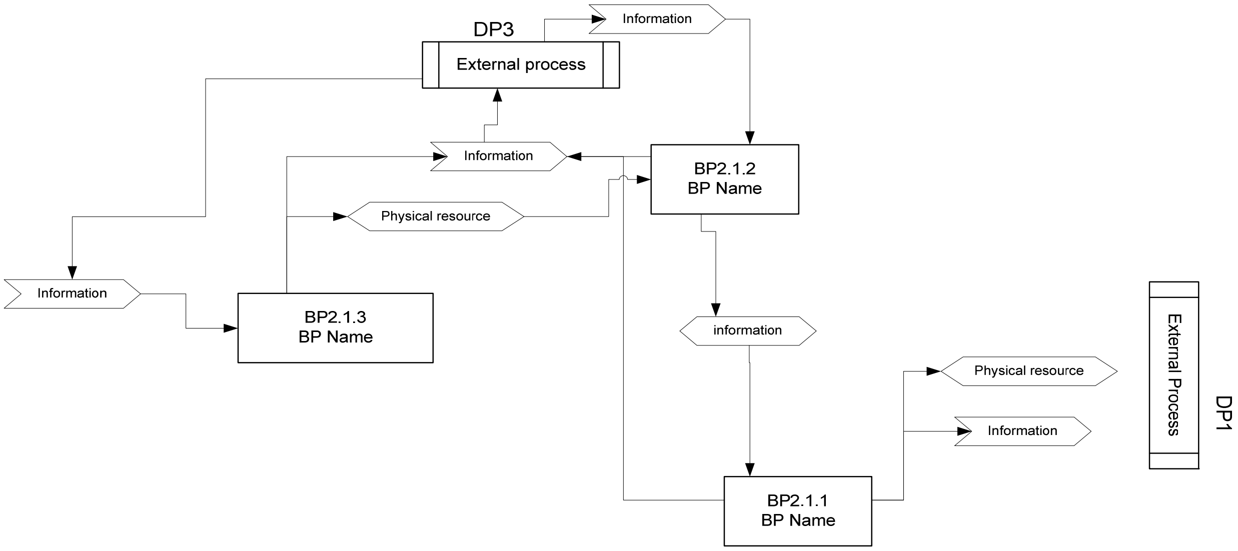


Figure 13: An example sub interaction diagram

The final stage of the process decomposition stage shows how BPs are decomposed into sets of Enterprise Activities (EAs) which represent the processing steps involved in the transformation of objects through the application of Enterprise Resources (ERs) as shown in figure 14.

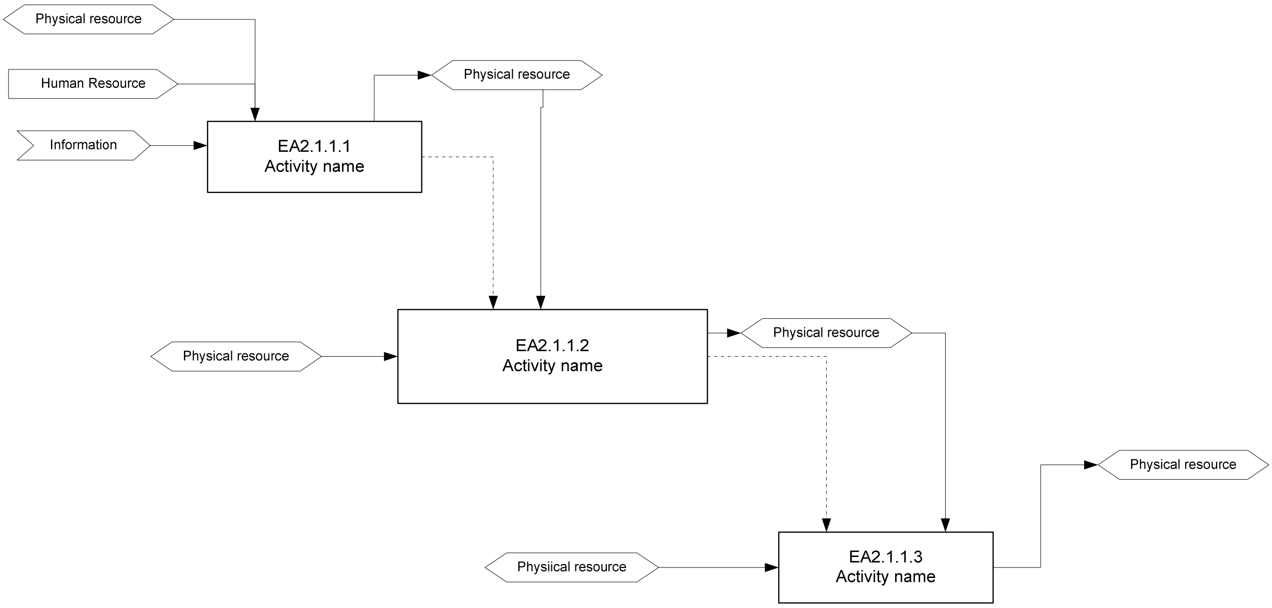


Figure 14: An example Activity diagram

In principle, the decomposition of processes in the manner described above, will help capture almost (if not all) processes within domains of interest and also promote understanding about these processes, thus enabling the management of processes of interest to be possible. Because of the explicit description of interactions that exist in processes, when changes are made to process segments, their resultant effects on other processes can readily be understood and analysed and if needed, can be modified.

4.3 Product classification

Many approaches exist for classifying products, but fundamentally, any approach adopted will be guided by the underlining reason for the classification. Depending on the intended use of a set of classified products, products can be classified based on their functions. Thus functional parameters such as power rating, size, volumetric flow rates and density can be used as one basis for classification. From a business point of view, products can be classified based on the value they generate for the Organization. Further analysis from a sales perspective can be developed which could lead to classifying products based on customers and revenue generation. Another means of product classification from a design perspective can be developed by analysing the design complications involved in the different products under consideration. Similarly, depending on the intended use of the classification, products can be defined based on their demand patterns.

From the explanations given above, it can be deduced that there exist many ways of classifying products. But since part of the research outcome relates to managing complexities emanating from product and process dynamics, it is anticipated that classifying products based on process similarities can help limit some of the impacts of multiple products on processes. To further refine the approach, a second stage classification based on ‘work-content’ at each process stage is defined with the view to limit variations in processing times for products belonging to the same product family. Details of these classification methods have been explained in proceeding sections.

4.3.1 Process-based product classification

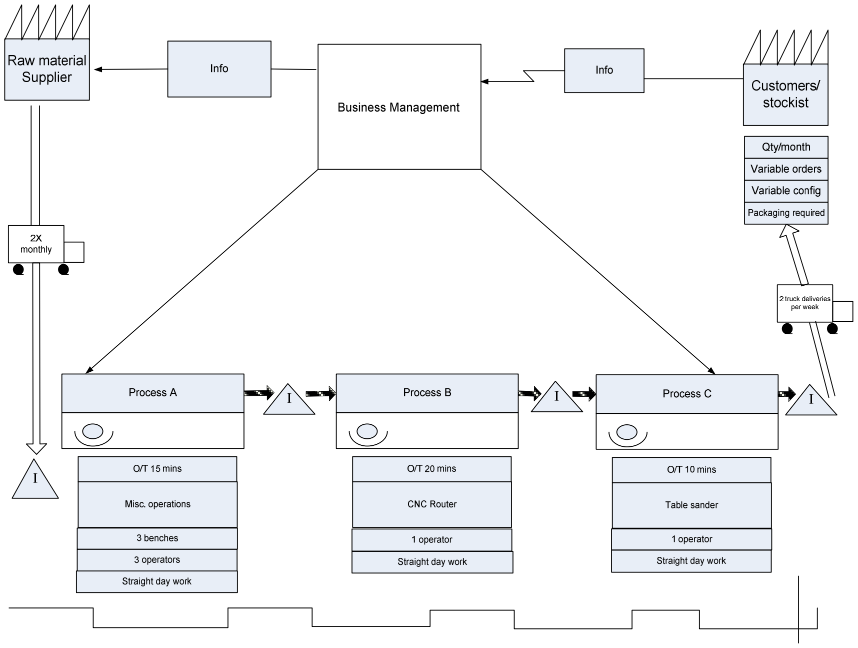
In Section 4.2, a method for decomposing and describing processes was presented. The objective at that point was to describe the ME in terms of a ‘collection of activities or processes’ conducted over a time frame. Literature has shown existing methods for classifying processes based on product routes, but the contribution offered by the author involves routing material through networks of CIMOSA based BPs to form a ‘business process-oriented configuration’ (BOC) for the product under consideration. In terms of the process-based classification method proposed, different products realized by the ME are routed through an identified list of BPs making particular emphasis on material flow routes. This is because the operating idea of value stream modelling in this research is based on the fact that value is added to materials (information and knowledge) to convert them in a way customers are willing to pay. The products that share a similar process route are grouped together to form one product family. A product family matrix is generated by forming a grid that contains a list of processes in the columns and a list of products in the rows. Matching the different products to their BPs will explicitly represent the end-to-end processes required to produce the various products. In complex organizations that realize multiproduct flows, this can be a tedious exercise but the objective still remains that products will need to be classified based on the similarities in their BOCs.

4.3.2 Refined process-based product classification

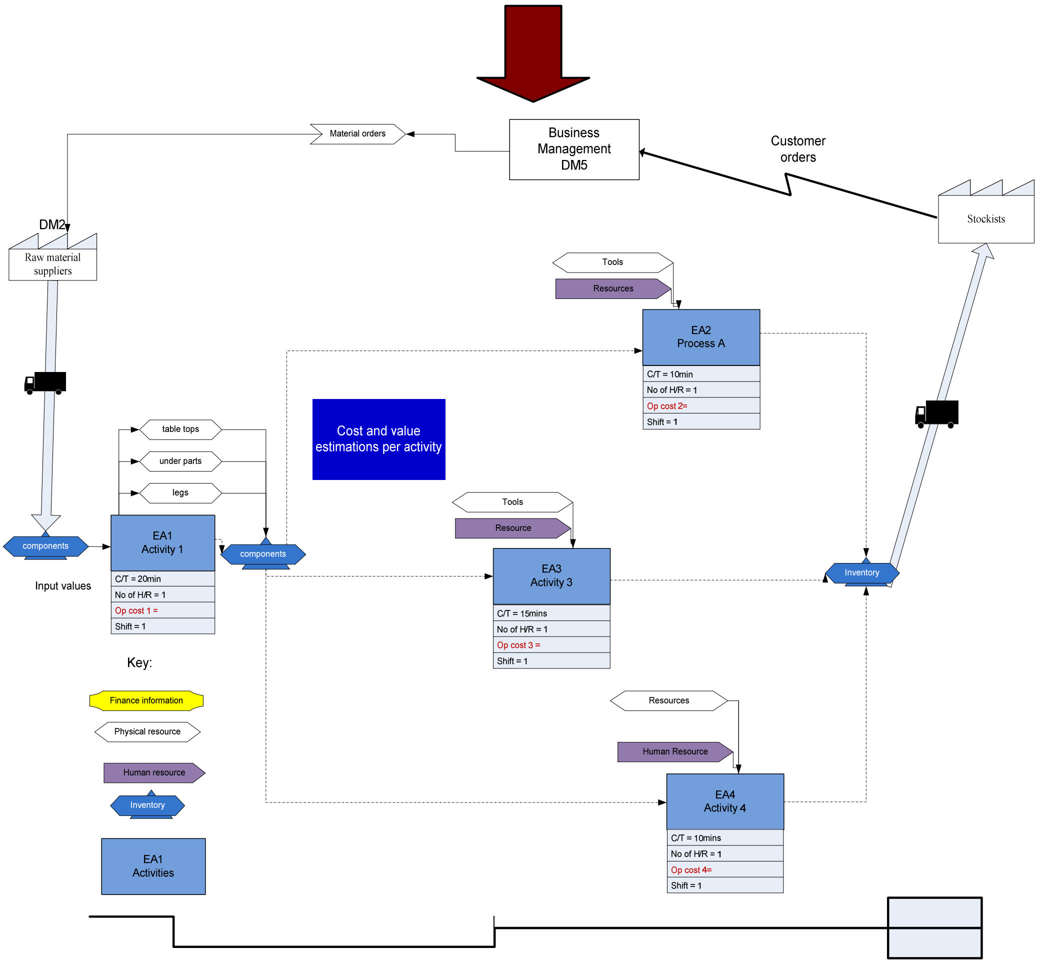
Grouping products based on similarity of process routes is a useful initial way to classify products. The author is of the view that further refinements will be required so that in approximate terms products with similar processing costs can be grouped. This is achieved by refining the product families based on the times required to process them at each process centre. To limit product variety, a ‘work content’ for each operation is defined based on earlier works by Duggan (Duggan 2003), to be the total time required for one operator to perform all the needed operations from start to end. A work content range is therefore defined to be the percentage difference between the highest work content and lowest work content. The work content range is then used as means to distinguish ‘high and low work content products’ within the same family. This observation leads to a breaking down of the initial developed product families into sub product families distinguishing high and low work content products. This approach is shown in the third and fourth case study applications.

4.4 Derivation of static cost and value streams

In response to the need to improve upon the capabilities of existing value stream mapping techniques, (in support of value and cost modelling, such that process cost distortion is minimized and values can be quantified along process segments) the VSM method was reviewed critically and additional modelling constructs proposed. Based on the limitations in the current VSM method, an alternative modelling method was proposed. In the proposed method, resources are further classified into human beings, machines, IT (software and technology) and materials. During initial modelling stages the approach is designed to focus on BP levels, but because a collection of activity diagrams are explicitly linked during CIMOSA decomposition to respective BPs, detailed analysis can naturally follow. Thus for every work station, cycle times, resource types and number, information, uptime or efficiency, shift pattern and process cost are noted. Additional data in terms of related monetary values are assigned to individual processes. The cost of realizing respective BPs can then be generated by estimating the total cost of executing the set of activities that make up the BP. Further static analysis can be performed on the developed VSM. Key process improvements parameters, such as production lead times, waiting or queuing times, queue size, process cost and throughput, can be used as the basis for deriving future state value stream models. Another perceived advantage is that by the adoption of this approach, value and cost generated at every process stage can be demonstrated as a ‘flow’. In reality this is achieved through the combination of the strength of the conventional value stream technique and the CIMOSA decomposition capabilities. Because of the likely complications in demonstrating this approach for long and large value chains, decomposition and product flow are maintained at the BP level and decomposed to activity levels only when further analysis is needed. In real life situations hyper links can be readily developed for easy access to sub processes. A diagram representing the new approach to static cost and value stream modelling is shown in figure 15. The diagram shows how constructs representing physical resource, information, monetary parameters and queues are introduced in the new modelling approach. Also process cost and value estimates are shown in the new modelling approach described by figure 15.



Lean based VSM



Static cost and value stream model

Figure 15: Proposed static cost and value stream modelling constructs

4.5 Derivation of virtual simulation cost and value stream models

The derived static value and cost stream models can be used as the basis for a number of types of static analysis. Various estimates on the total cost consumed when running the process can be derived. Another possibility is to compare the values generated through running respective processes with the selling price of components or materials and deciding on options whether to buy or make. However all these estimates are limited to the current state and it will be difficult to predict likely occurrences and hence design or organize the manufacturing systems to meet unpredicted challenges. It is therefore viewed necessary to transform the static value stream models into dynamic value streams models. This is to satisfy the quest for alternative business analysis in a virtual environment and also to support human systems, IT system and CIM system developments. An extension of the static cost and value stream models into equivalent dynamic models also has potential to quantify benefits that can be derived from making manageable ME changes to process structures, products and material flows, resource assignments and the like. Additional information such as actual processing times, resource and task allocation, product or process routings, machine sharing mechanisms, setup times and history of machine failures can be incorporated into models when using some existing commercial simulation tools. Also the adoption of any process improvement scheme such as push, pull, postponement and the other solution technologies may require investments which will need to be justified before their implementation. Benefits from the adoption of any of these solution technologies can be verified through the deployment of virtual simulation models: specifying values and the associated process improvement indicators such as lead time, inventory, queue times and cost. Most critically, many businesses are often concerned primarily with short term profit margins and hence virtual models of value and cost streams will be helpful in quantifying potential benefits of change in the long and short term.

In line with these assumptions, and because of the general ongoing need for change in MEs, use of a system dynamics modelling tool in the form of causal loops was incorporated into the proposed new VSM approach. This was considered important to help identify causal relationships between factors which induce dynamic impacts into ME value streams. Causal loop models enable qualitative representation of process elements and their implicated changes on each other. As such causal loop models can provide a basis of understanding for designing and experimenting with quantifiable simulation models. There are essentially two major objectives which are expected to be obtained through the application of virtual simulation models. The first aspect relates to the economic or business representation of the factors which affect the ME. This will naturally lead to the estimation of cumulative cost and values generated through running the processes of the ME. A business model is therefore generated to represent the economic effect in terms of cost and values generated through process segments. These results are achieved through the transformation of causal loop models into system dynamics stock and flow models. Models generated through system dynamics techniques have been generally accepted to provide excellent support in the understanding of complexities and dynamics, however, there is still no clear procedure in the public domain which shows how causal loop models are systematically translated to simulation models. Where a solution has been provided to the transformation process, the language of communication and mathematics involved has been limited to expert system dynamics modellers making it difficult for Manufacturing and Operations Managers or Industrialists to benefit fully. Hence most Management Scientists tend to either stick to the use of causal loop models or adopt separate simulation techniques without necessarily linking these two elements of systems dynamics. However the ability to transform industrially based CLMs to simulation models (SMs) is considered essential by this author if qualitative decisions are to be measured and used as a basis for accurate and scientific prediction of systems behaviour. To help overcome this challenge of translating CLMs to SMs, it was planned as part of this study that a systematic translation procedure would be introduced. The challenge is real because in general terms, CLMs, are known to depict the causal links between cause and effects and are mostly deduced from verbal or historic reference behaviour of systems. Understandings can also be deduced and developed from observed trends in system reaction over time. It also forms a connection between structure and decisions that generate system behaviour. Technically there may be several causes to an effect and also several effects to a cause. Thus the ability to distinguish which cause and effects to model becomes a key issue with the modeller. To put a structure around causal loop models, cause and effects are created around the product based BOCs. This restriction helps place cause and effects in context. In order to generate a robust causal loop model, which is the starting point for the transformation process outlined, a set of rules is required. This is because since it is fairly easy to create CLMs, there is a high tendency of creating models which are difficult to be translated into simulation models. This is possible since there are always many connection ‘possibilities’ between variables involved in the model. Following up on earlier works by Sterman (Sterman 2000), to maximize the clarity and impact of causal loop models:

1. causality must be distinguished from correlation
2. polarities of links must be clearly assigned without any level of ambiguity
3. important delays must be indicated in the causal links
4. curved lines should be used for information feedbacks whilst important loops follow circular or oval paths.

5. models should be organized to minimize crossed lines and models could be drawn iteratively until the best layout is achieved.
6. The goals of negative loops should be explicit.

The methodology proposed in this study for translating causal loop models to quantitative simulation models, starts with redefining already created CLMs to obey a set of rules identified to be useful in creating good CLMs. The constraints imposed at this stage are assumed to be sufficient to ensure an easier transformation of the resultant CLMs to stock and flow diagrams. This leads to the revision of the causal loop models to include influences which are causal, deterministic and time variant. In compliance with the recommendation of Burns (Burns 2001), the following formulations are disallowed:

1. self-loops involving a single quantity
2. loops involving exclusively information paths or auxiliary variables
3. more than one connector joining any two quantities and
4. connectors which have more than one originating quantity or more than one destination quantity.

In view of these formulation mechanisms, the main elements of the causal loop models are scrutinized and classified possibly as stocks, flows and auxiliaries. It is possible to identify stocks in the model by observing the links which flowed into it. Also stocks can be identified by observing which of the factors accumulate or by noting the units of measure. Depending on the nature of outgoing dependencies, all non-stocks are classified as flows or auxiliaries. The only means by which a stock could change is through the influence of a flow. Hence a measure of the flow is the unit of the stock per unit time. This definition allows the model to be modified to include other flow dependencies. Other factors to be recognized include inputs and outputs. Inputs are defined as all factors which affect nothing (no other factors). Outputs also do not affect anything. A table is drawn to list the various different factors in the model. Based on this classification, the existing structured CLM is transformed into equivalent iThink models. Obviously results generated through the application of a continuous simulation tool like iThink will only satisfy the earlier requirement of quantitative alternative business analysis of the processes in the ME.

Another well established method for analysing cause and effects in manufacturing industries is the Ishikawa or fish bone method (Ishikawa 1990). Although it appears dominant in many manufacturing industries, a critical review of this method shows that its application is limited to product design projects and defect prevention, thus attention in this Thesis was maintained on the application of system dynamics techniques in the analysis of process dynamics.

On the other hand, another objective to be realized through the application of virtual simulation models is to observe potential improvements which can be derived through the segmented analysis of product types and their associated individual dynamics. Also cost and values generated through the production of different products should be able to be analysed so that management decisions related to specific products can be realized Alternative manufacturing scenarios can also be experimented before their implementation. Discrete event simulation tools offer themselves useful for such analysis. Thus Simul8, a commercially available process simulator is proposed to be useful. The developed Simul8 model becomes the dynamic cost and value stream model for process improvements. The static cost and value stream model becomes the backbone for the enhanced dynamic cost and value stream model. Thus various factors impacting on decisions related to future state value stream models can thus be experimented.

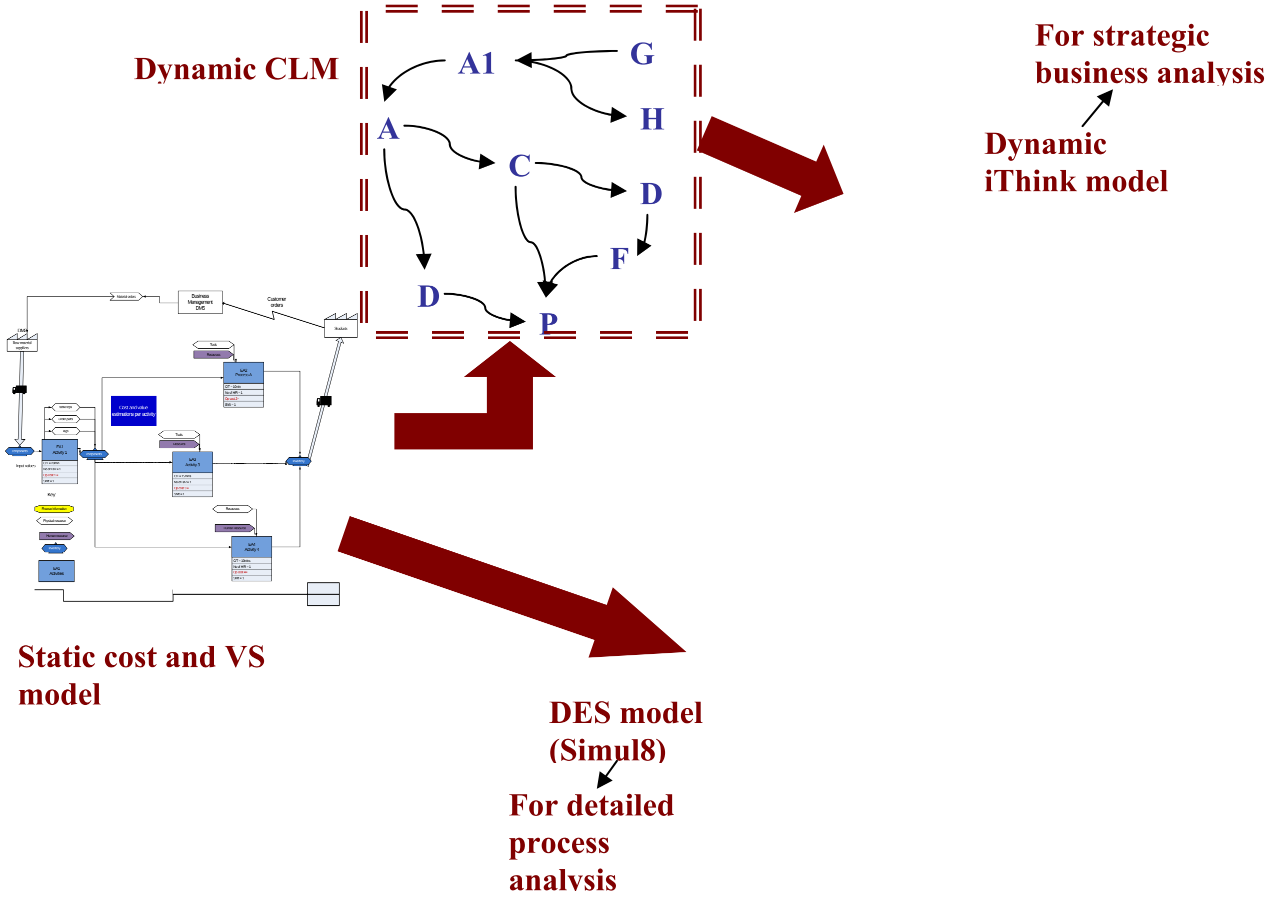


Figure 16: Overview of dynamic cost and value stream modelling

4.6 Summary of proposed methodology for the derivation of multiproduct dynamic cost and value streams

From the foregoing discussions, it can be deduced that the derived methodology is composed of integrated and enhanced aspects of various techniques. It comprises the uniform application of knowledge and techniques from Enterprise modelling, process mapping, system dynamics and simulation modelling. Through this integration, the weaknesses in any of the individual techniques will be overcome and the cumulative strength of the new technique used to solve potential problems in Industries. A diagram describing the proposed technique is shown in figure 17 .

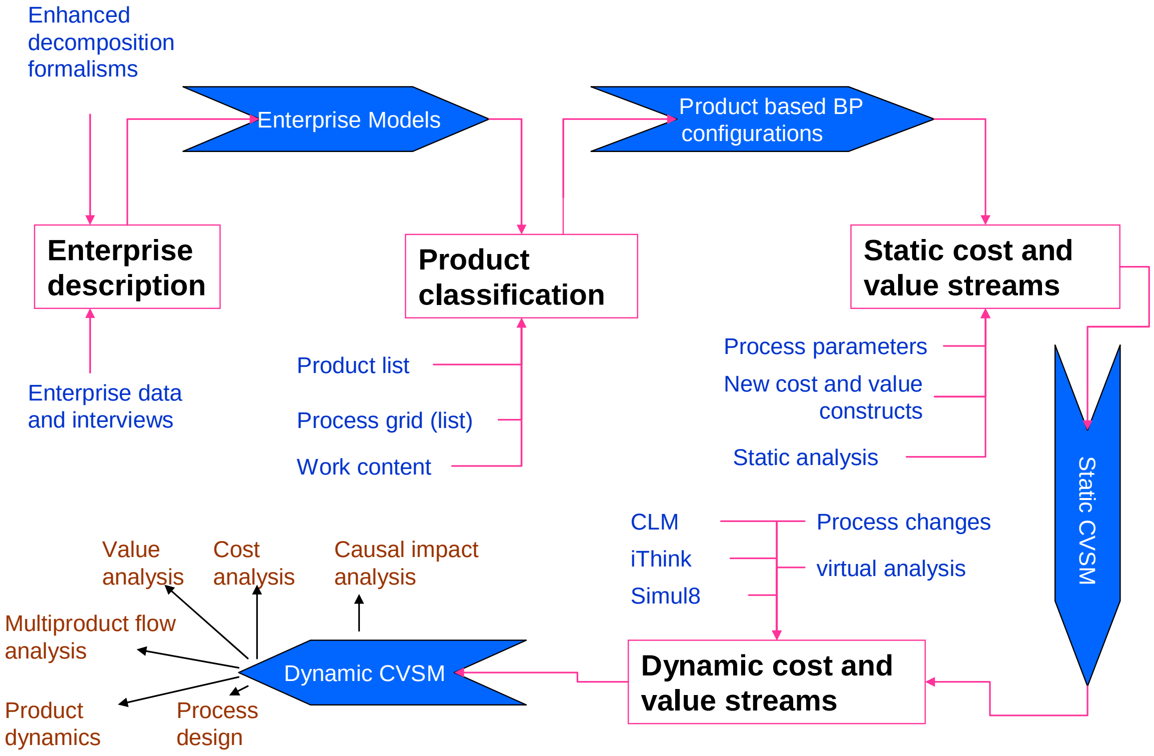


Figure 17: Proposed modelling methodology

Figure 17 shows the various process stages involved in the derivation of the proposed modelling technique. At each process stage, the needed inputs are described. For example, to generate enterprise models of MEs, key ME information will be required. This can be derived from ME data sheets or through interviewing key knowledge holders in the ME. The modelling decomposition formalism offered by the CIMOSA technique provides a basis for capturing knowledge and structured and unstructured information. The net outcome of that process is a set of enterprise models describing in perspective the various process and flows that exist in the ME. When this outcome is transferred to the next stage of the modelling exercise, together with other data on product types and operation times, the modeller is in a position to generate a product based business process oriented configuration (BOC). The derived BOC is supported with value and cost constructs together with various process parameters to form an enhanced static cost and value stream models capable of being used for various forms of static cost and value stream analysis. The end result of that process is translated into suitable simulation models for dynamic cost and value stream analysis. The finally derived model is useful for multiproduct flow product dynamic analysis, causal impact demonstrations, dynamic cost and value analysis as well as providing a tool and specific case models for process improvement and process redesign.

Figure 18 further describes how various modelling capabilities of existing modelling techniques are integrated to form a comprehensive multiproduct dynamic cost and value stream model. As shown in figure 18, enterprise models are generated through the application of the CIMOSA modelling technique. Section 4.2 has explained the contributions made in respect of decomposition of processes through the CIMOSA technique. Process classification and other lean based value metrics are derived through existing VSM technique. The integration of enterprise models and process classification at stage 1 of the modelling process, generates a product based BP configuration which is then combined with the derived cost and value estimation metrics at stage 2. The outcome of this combination is a static cost and value stream model. At the next stage of modelling, the static model is transformed into DES and SD models depending on the modelling intent. The integration of the modelling techniques is based on files, transfer of data from one stage to the other and the merging of constructs.

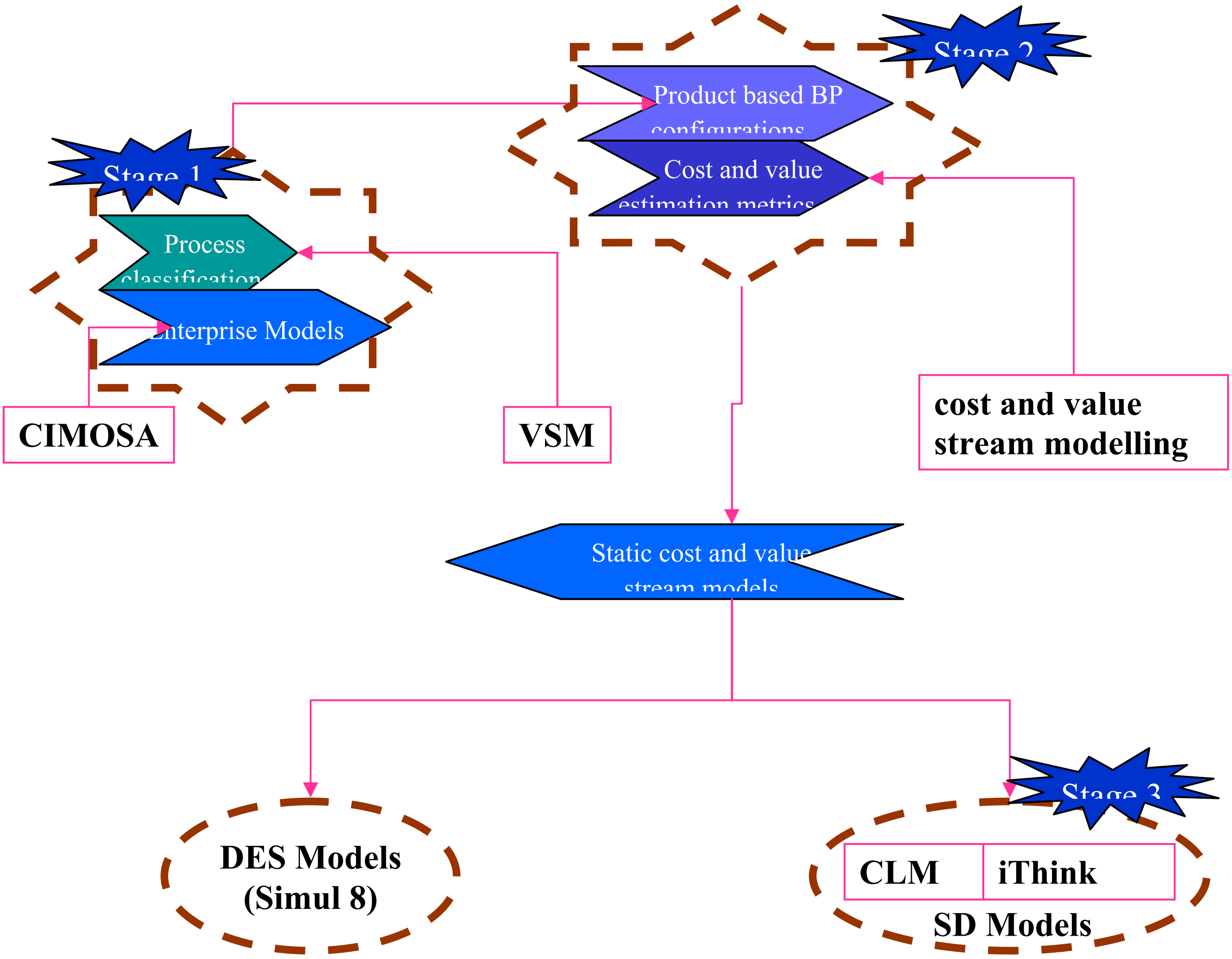


Figure 18: Integration of modelling techniques

5. Case 1 application of the proposed modelling methodology

5.1 Introduction

The previous section followed up on the need to derive an alternative modelling technique capable of addressing a series of limitations observed in respect of current value stream mapping techniques. This led to the proposition of a modelling methodology which enhances value stream mapping through an integrated use of the strengths of state of the art methods and tools for Enterprise Modelling (EM), System Dynamics (SD) modelling and Simulation Modelling (SM). It was also assumed in the derivation of the new method that an appropriate integrated deployment of VSM, EM, SD and SM techniques can help capture salient process information related to value generation and cost consumption such that useful process analysis and management decisions impacting on business profitability and sustainability can be accessed scientifically. This assertion was purely based on understandings and observations derived from existing literature in the scope of study.

To help verify the applicability of the method, the method was applied in four different manufacturing environments. These case applications spanned cases drawn from ‘Make to Order’ and complex ‘Engineer to Order’ scenarios. Initial demonstration of the method was based on applying aspects of the methodology in two different case companies. This view point was taken with the underlining notion that process modelling and aspects of process improvement analysis can be performed through the synergistic use of VSM, CIMOSA and discrete event simulations, whilst system complexities and related cost and value dynamics can best be examined through the enhanced use of VSM, CIMOSA, CLM and a continuous event simulation tool like iThink. The first two cases are reported in Chapters 5 and 6. After testing these techniques in the two case companies, the methodology was further refined and consistently applied in two more complex engineer to order MEs, as reported in Chapters 7, 8 and 9. The results show how the methodology proved to be a useful tool in analysing the cost and value implications of the deployment of alternative manufacturing paradigms and when making other key management decisions.

The first case study reported in this Chapter is related to a Make to Order furniture manufacturing company, herein referred to as Brad Ltd. The research was conducted in Brad Ltd with the aim to help: 1) establish the need for an enhanced value stream modelling technique; 2) derive a method for estimating process cost and values; 3) and to also show how the current value stream mapping technique can be enabled to capture diverging and converging processes (multi-processes) in a ME. The third objective was introduced because in most cases (if not all) for MEs which need to assemble one or more components, sets of processes either converge or diverge into other processes and it is necessary to be able to capture such processes. It was also the case that the general research aims were consistent with specific problems Brad Ltd needed to solve to remain competitive over a long time period. These problems are described in Section 5.5.

Attempts to arrive at the three objectives naturally lead to the application of knowledge in value stream mapping and CIMOSA modelling. The outcome of the application of these techniques led to the generation of static models which represented graphically a process description of the company. Essential aspects of these static models were transformed and utilized in a simulation modelling environment using 'Simul8' software. Therefore Chapter 5 describes how these sub objectives were realized through case application of aspects of the proposed modelling technique.

5.2 Background to Brad Ltd

The example 'make-to-order' manufacturing company was established as a privately owned furniture manufacturing company in 1979. Brad Ltd is a small scale ME located in the East Midlands of the United Kingdom and operates with about fifty regular employees. The company is managed by two Directors who respectively direct internal and external operations of the company. Brad Ltd trades only through stockists and not directly to the general public. These stockist are dispersed throughout UK and Ireland. Three years prior to the commencement of the research, the company had experienced significant growth as shown in the sales pattern depicted by figure 19. A report from the sales division revealed that the growth of the company could be attributed to their brand awareness which was maintained through an aggressive marketing strategy. Other reasons included their ability to supply quality products meeting customer specifications, within relatively shorter lead times as compared to their competitors. Also the business viability of one of their competitors had diminished, giving them a competitive edge in the furniture market.

Brad Ltd receives various orders from their stockists (distributors) and manufactures about three hundred and thirty nine (339) different furniture products, ranging from different varieties of tables, cabinets and beds. The finished products have the options of being made from 8 different colour finishes. The different products are primarily manufactured from pine wood supplied from the Scandinavian countries.

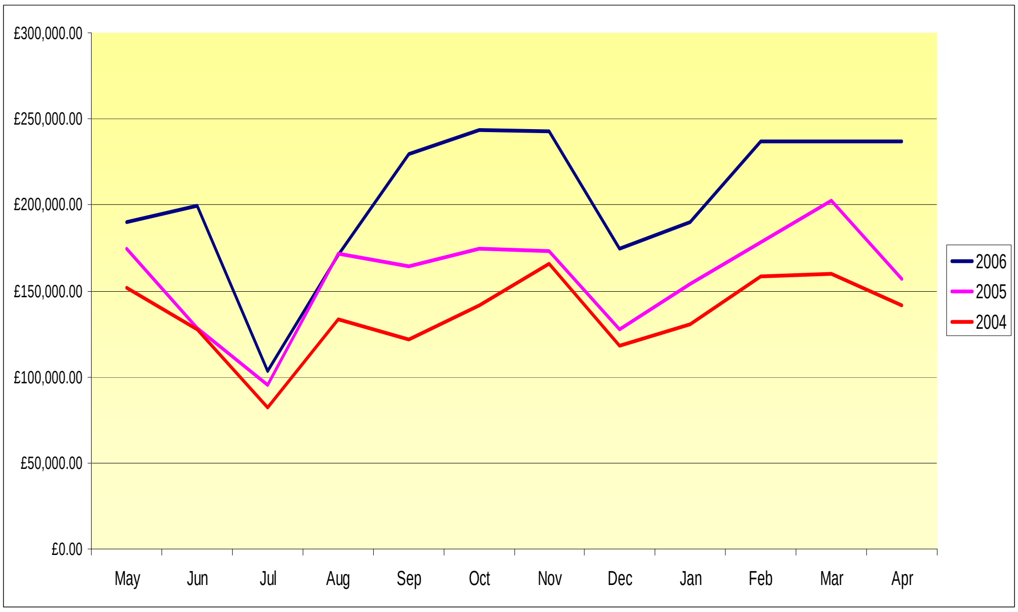


Figure 19: Description of sales growth

5.3 Description of production system of Brad Ltd

Upon interaction with the Managers of Brad Ltd, an initial understanding of the multi-product production system of the company was deemed to consist of order processing; assembly; machining; painting; packaging and delivery units (see figure 20). Order processing is based on aggregating orders received from many stockists over specific timeframes. Orders received are grouped and transformed into ‘runs’. These runs are based on the capacity of the fleet of transport vehicles owned by Brad Ltd and logistical criteria related to the geographical location of stockists. These runs are converted unto a ‘so called’ picking list which specifies the furniture items that need to be manufactured and dispatched to the assembly section. On receipt of a picking list the assembly shop supervisor issues a mini-order to the machine shop for parts which need to be machined. The machine shop however usually makes predictions about assembly shop demands (based on experience) and therefore produces stockpiles of parts in racks located within the assembly shop. These stockpiles can supply much of any current assembly shop demand but, in general, additional machining will be required when predictions are not accurate.

Parts assembled are transferred to the painting shop. Finishing operations are performed on these sub-assembled parts as they are released from the painting shop, before final delivery. It takes approximately four weeks for picking lists to be transformed into physical deliveries of products. This lead time had changed significantly to eight weeks when there was an unexpected increase in customer demand.

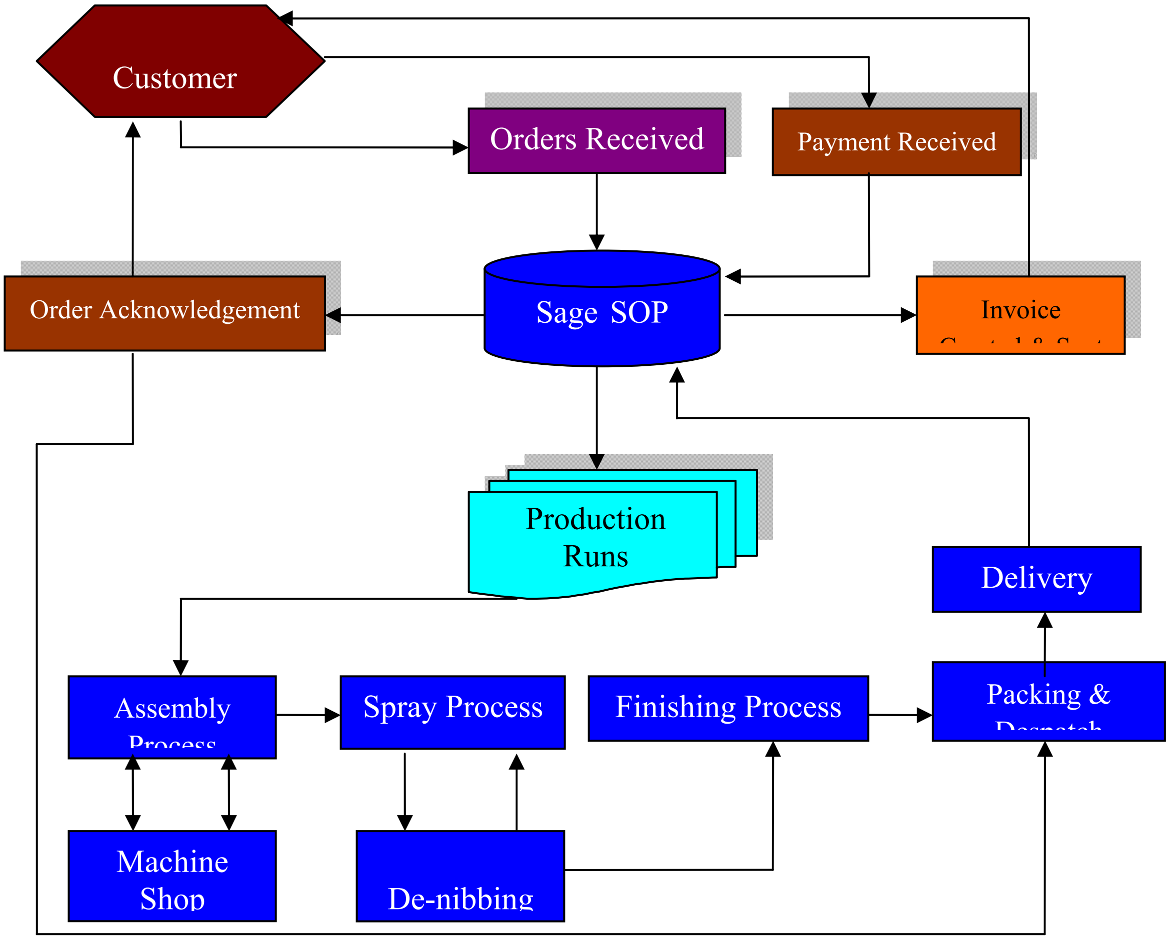


Figure 20: Overview of production system

The Managers explained that the increase in lead time was partly due to the company's inability to increase their 'effective' manufacturing capacity to match the customer demands. Basically the company have had to cope with the finite capacities of basic furniture manufacturing equipment like sanders, grinders, polishes, benches, saws and planers.

5.4 Problem domain under investigation

Based on the increase in demand from their stockists, the company had need of increasing their resources to be able to match up to the demand. Their inability to adjust to these changes led to an overwhelming increase in their total production lead time from 4 weeks to 8 weeks. Taking decisions to improve aspects of their production system was critical but detailed analysis was required to identify which specific aspects of the production system needed to be improved. The other challenge with respect to improving their resource capabilities was the fact that any investment needed to be justified before financial commitments could be made. In addition, Management was not certain about the sustainability of the increase in demand. Thus further spending was to be done cautiously since any fall in demand might make the investment less worthy.

There were issues of possibly producing furniture at reduced cost so that whilst maintaining or increasing their product value they might generate more profit to help maintain the company. All these issues were major management concerns because practically over the period 2004-2006, there had been an annual sales increase of 25%, which had forced the company into an unexpected rapid growth causing the existing mostly manual processes to be insufficient for their operations.

Attempts to investigate supporting work in the area of process engineering in Brad Ltd, revealed that previous research work in the company had centred on testing and validating existing and new process and resource modelling concepts. Building on the earlier works and with the aims of the research in mind, it was decided that a multi product dynamic cost and value stream modelling approach will be utilized to help generate results capable of providing support to Brad Ltd in meeting their current challenges. It was also expected that the accurate deployment of the methodology should help:
1) reduce their current inventory sizes and hence inventory cost; 2) support analysis of investment options and help predict suitable combinations of resources for optimal performances; 3) improve their existing manufacturing process lead times. These outcomes were to be part of the outputs of the proposed methodology. An added objective was to also observe the suitability of the modelling technique being proposed and where necessary improve upon its modelling schemes. The next sections therefore show how the modelling technique was enacted and used to capture the current state of Brad Ltd and based on the improvement specifications, how the manufacturing processes were improved.

5.5 Generation of multiproduct dynamic cost and value stream models of Brad Ltd

To help understand and therefore generate useful ‘as-is’ value stream models of Brad Ltd, primary data in the form of company ordering cycle, sales and production information were obtained from the Managers of the company (shown in Appendix A1-A4). During the initial investigations, it became evident that some EMs of the company had been created with the view of externalizing understandings about the company’s processes. Thus the initial efforts were concentrated on generating questions to help verify whether the EMs generated years ago still mimicked the current business operations. The verification of the existing EMs assisted the author to further understand the processes and flows that existed in the company and how they had changed over the years.

Ideally, the proposed methodology recommends capturing processes and their associated objectives and grouping the processes with similar objectives and deliverables into a supposed chain of processes belonging to the same domain. However the exercise of verifying the existing models showed that although significant changes in company processes had occurred, their process classifications and hence domain and business processes were not extremely different from what had been captured by previous researchers. However there were significant changes in their activities which had related effects on how the EM needed to be organized. It was therefore decided to abandon the use of the conceived spreadsheet means of grouping processes and rather modify the existing EM based on the new understandings derived from the interviews and shop floor visits. Notwithstanding, the inherent understanding of systematic process decomposition guided the generation of the new EM of Brad Ltd. In addition, when carrying out this exploratory exercise, the author was of the view that it would be advantageous to take advantage of a newly 'non-commercial MS Visio tool' developed by the MSI team for creating CIMOSA based EMs. In principle this new tool possessed greater modelling flexibility and was more user-friendly than the previous 'MS PowerPoint' based approaches used for creating EMs. Subsequent sections describing the creation of the EM of Brad Ltd, show example models created by this tool.

5.6 Enterprise Modelling of Case 1

5.6.1 Creation of the CIMOSA Enterprise Model (EM) of Brad Ltd

Unlike previously published approaches to mapping value streams, for which mapping begins by linking customer order information with physical business operations that mostly are influenced by material or component supply frequencies, the CIMOSA approach to enterprise modelling represents MEs as a network of dependent processes. A basic assumption made when applying the CIMOSA modelling technique is that it is appropriate to segment organisations being modelled into enterprise domains. Each enterprise domain has responsibility for one or more domain processes which need to communicate with other domain processes (belonging to the same and/or other domains) through events and results. Domain processes related to Brad Ltd and its supply chain partners was therefore decomposed into business processes, which themselves comprised more elemental business processes and enterprise activities. Enterprise activities were considered to be atomic building blocks of domain and business processes, because they corresponded to the lowest level of modelling abstraction considered by the author.

Attempts to modify the existing EM of Brad Ltd to reflect the current business operations led to the use of the four types of CIMOSA diagramming templates, namely, 'context', 'interaction', 'structure' and 'activity' diagrams to coherently represent the 'as-is' flows in the company. Typically many instances of these template types are used in conjunction with a consistent numbering convention to provide a multi-perspective, graphical description of networks of processes used by any given target company. This was also the case for the company studied.

Figure 21 shows the ‘Top Level Context Diagram’ which was created to imitate the ‘operational’ processes of Brad Ltd. Six prime stakeholders were identified with respect to Brad Ltd and its supply chain, which were assigned domain numbers 1 to 6. To help understand the operations and processes which add value to inputs (for them to be transformed into outputs meeting customer’s requirement), it was decided that two of the identified domains were most critical. This was because in the two domains, management is required to utilize company internal resources so that related process improvements can be developed. The selected domains observed to be central to value generation processes of Brad Ltd were the ‘Produce and Deliver’ (DM4) and ‘Business Management’ (DM5) domains. The remaining four contributing domains (and their associated organisational units) actually function externally with respect to the case study company, so that their operations are not under the control of Brad Ltd. Because these other four domains were not modelled they are considered to be non-CIMOSA domains. However the flows from these external domains (DMs1,2,3 and 6) were modelled and their respective lead times were also identified. This was important because when modelling value streams it was important to identify influences of these domains on the main operations of the company. It was also understood, when modelling, that it might later prove beneficial to understand and capture models of external domains to satisfy their business purposes yet to be specified.

DM1 is a collection of processes under the control of the stockists. The stockists are the main distributors of the end products. They are the retailers who stock the finished products and distribute to the smaller shops for onward customer purchase and delivery. At the top level of the modelling exercise, the stockist are described as the customers. DM2 is a range of processes performed by the companies raw material suppliers. At the time of model capture, these were primarily Scandinavia pine suppliers. They supply base on orders received from many companies. Internally, a raw material store was maintained to keep stock of critical parts with relatively short usage intervals. Besides these raw materials, there were other components and fixtures which were essential parts of furniture production. For example ‘parts’ like chairs which were not manufactured by Brad Ltd, but needed to be ‘finished’ (e.g painted or polished) accompany the orders. Hinges, screws, and other fittings were essential parts which were supplied to the company in short intervals. The group of activities related to these miscellaneous supplies was classified as DM3. As shown in figure 21, the main body of the order fulfilment process is the ‘Produce and Deliver domain’, DM4. In theory, DM4 refers to all the ‘direct value and non-value adding processes and activities’ which are required to transform customer orders to finished goods, thereby meeting customer requirements. Based on the objective of this research, this domain became a focal point upon which further analysis was based during case study 1. All other domains primarily provided support for this main stream domain. With this objective in mind, it was observed upon further analysis that a set of processes existed that are related to the supervisory and managerial activities required to fulfil customer orders. This domain was described as DM5, the Business Management domain.

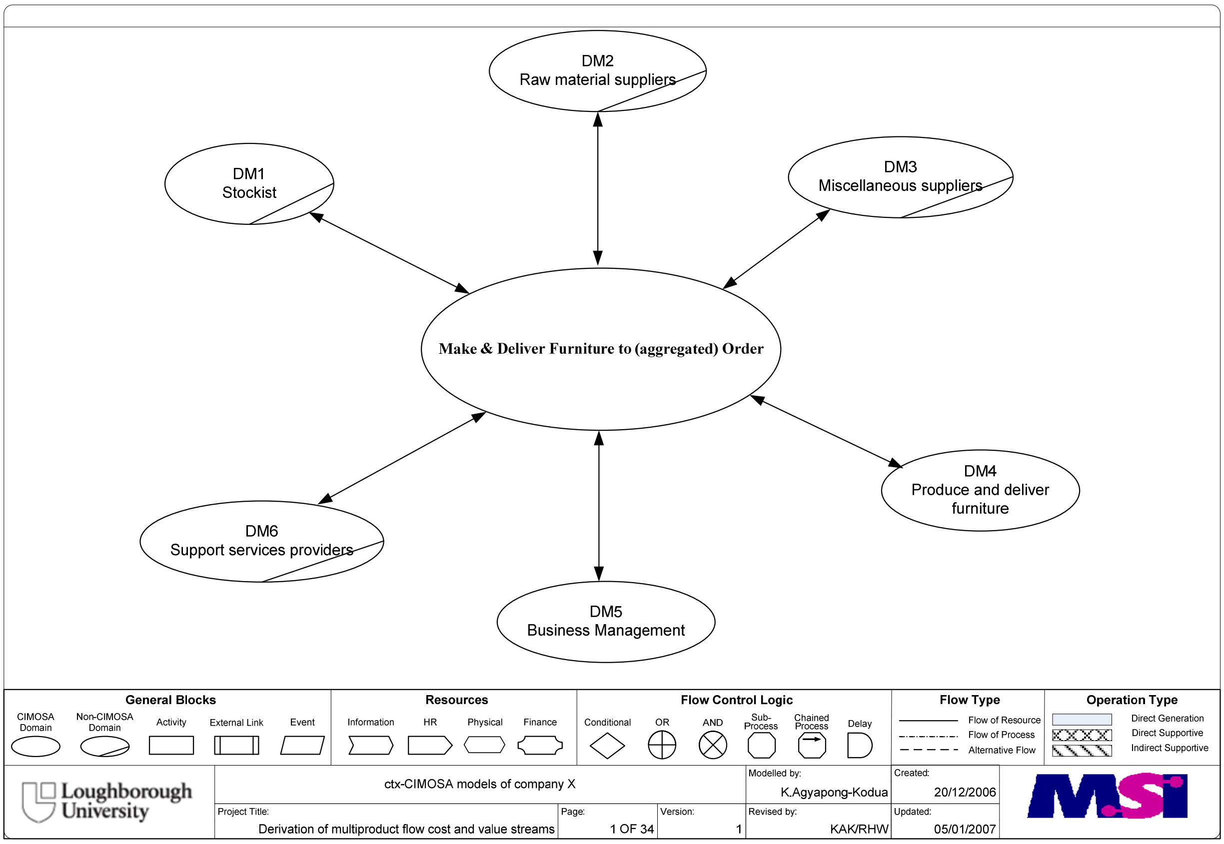


Figure 21: Top level context diagram

The last collection of processes was called the ‘Support Services Providers’ and denoted as DM6. This was used to represent all auxiliary services required to support domains 4 and 5. This included processes for maintaining machines and IT systems and the activities of technology vendors.

The second level of modelling showed how processes belonging to these domains interacted. This is demonstrated in the form of a high level interaction diagram (see figure 22). To demonstrate the elements of the interaction, DM4 and DM5 were subsequently decomposed into their respective domain processes, DP4 and DP5. The top level Interaction Diagram (ID) was created to explicitly describe interactions that occur primarily between the ‘Produce and Deliver (DP4) domain process’ and ‘Business Management (DP5) domain process’. The resultant CIMOSA model captured information about the interchange of production schedules, delivery and handling requirements, picking lists and necessary flows of these entities between domain processes. Instances of DP4 and

DP5 also needed to interoperate with other domain processes such as DP1, 2,3 and 6, which constituted the order provision, supply of raw material, supply of sub-products and miscellaneous fixtures, and provision of support services respectively.

From the stockist domain, the process relevant to internal operations of Brad Ltd was their ‘provide order’, DP1. As shown in figure 22, through the realization of DP1, orders are generated by the stockists and faxed to Brad Ltd. These faxed orders are introduced to the ‘manage business’ domain process (DP5) and then transformed into production schedules which are transferred to the ‘Produce and deliver’ process (DP4). The ‘produce and deliver’ process receive other physical items like raw materials, fixtures, fittings. These items are received via the ‘produce and deliver’ domain process and through the ‘supply raw materials (DP2) and supply miscellaneous items (DP3) domain processes respectively. Prior to the supply of these materials, purchase orders are raised and issued to the ‘suppliers’ domain through the ‘Manage business’ (DP5) domain process. A number of interactions occur between the ‘supply raw materials (DP2) domain process, supply miscellaneous items (DP3) domain process and the ‘manage business’ (DP5) domain process, before final supply of materials is achieved. After the supply of materials, invoices are sent to the ‘manage business’ (DP5) domain process for payment to be effected. A set of background activities are undertaken through the ‘provide support services’ (DP6) domain process which enables the smooth running of the ‘produce and deliver’ domain process.

Based on the production schedules received from the manage business domain process (DP5) and the arrival of physical materials from the supply raw material domain process (DP2) and supply miscellaneous parts domain process (DP3), the produce and deliver domain process (DP4) is able to make furniture that meets customer requirements. The successful delivery of furniture to stockists initiates payments from DP1 to DP5. Where there are errors in supply, communication is established between DP1 and DP5 for the necessary errors to be corrected.

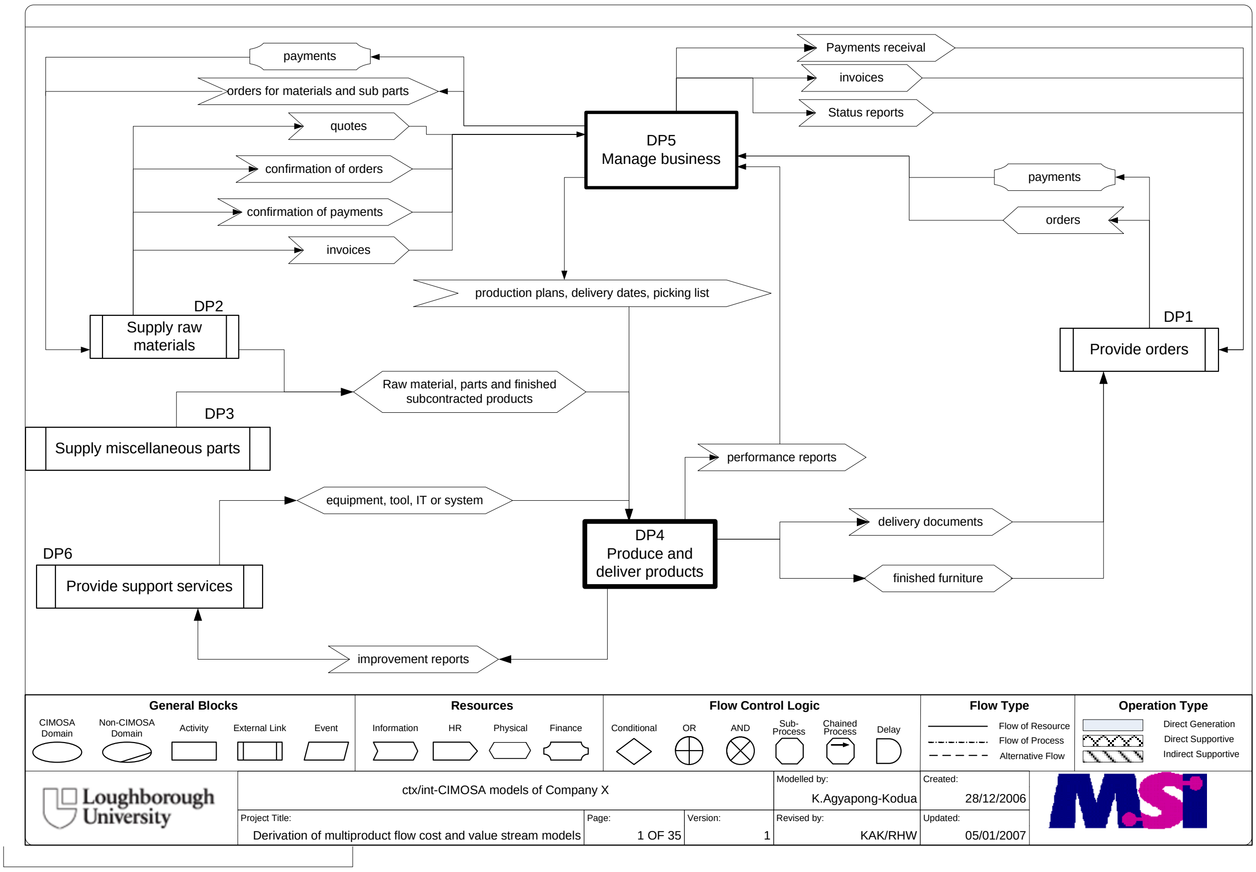


Figure 22: Top level interaction diagram of Brad Ltd

As can be realized, a number of minor or sub processes exist in the various domain processes described in the top level interaction diagram. Previous CIMOSA modelling templates generated by the MSI Research Institute (Monfared 2000) showed the creation of sub interaction diagrams as the next level diagram to be created after the development of top level interaction diagrams. However, when creating models for Brad Ltd in this study, it was observed that better understanding was required about how DPs are decomposed into Business Processes (BPs) before interactions are explicitly detailed. Hence structure diagrams which showed the decomposition of DPs to their respective BPs were created next. Based on the focus of the research, structure diagrams were created for only DP4 and DP5. Figure 26 shows the structural decomposition of the 'produce and deliver' domain process, DP4. From the figure, it can be observed that DP4 consists of three main BPs: Make furniture (BP4.1), Spray and Finish furniture (BP4.2) and Package and Deliver furniture (BP4.3). These top level BPs themselves are decomposed into sub BPs. For example, the Make furniture business process (BP4.1) is decomposed further into four sub BPs such as: 'Machine furniture components' (BP4.1.1), 'Transport components' (BP4.1.2), 'Assemble carcass and components' (BP4.1.3) and 'Prepare carcass and components for spraying' (BP4.1.4). Similarly, the Spray and Finish furniture business process (BP 4.2) is decomposed into sub BPs of 'Spray and rag carcass and components' (BP4.2.1), 'Denibble and reassemble furniture' (BP4.2.2), ‘Fix fittings’ (BP4.2.3) and ‘Fine finish furniture’ (BP4.2.4). The decomposed sub-business processes belonging to the ‘Package and deliver’ business process (BP4.3) are also shown in figure 23.

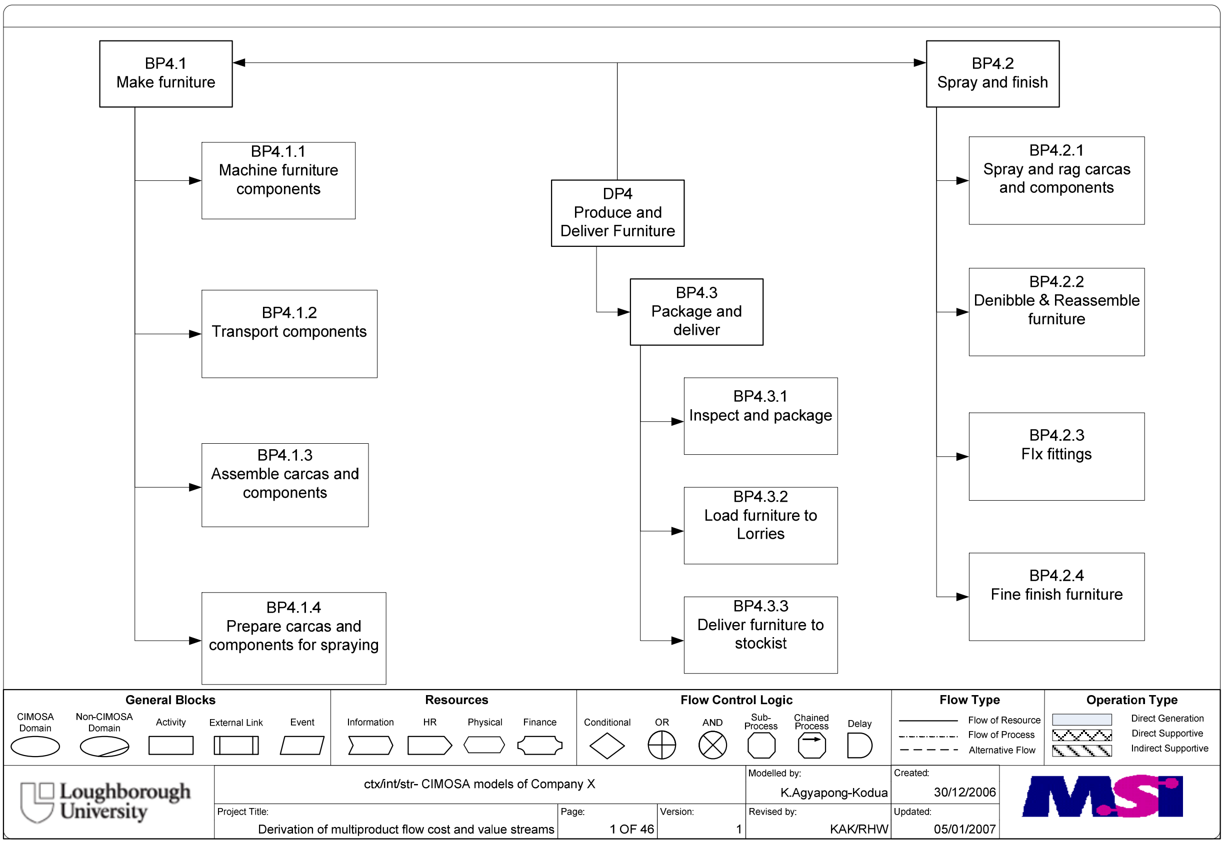


Figure 23: Structural decomposition of DP4

On a similar note, the ‘Manage business’ domain process, DP5, is decomposed into its elemental BPs. As shown in figure 24, four top level BPs were identified which are further decomposed into sub BPs (BP5.1-BP5.4). BP5.1 is identified as the ‘Interact with Stockists’ business process. This represents the set of processes involved in preparation of internal sales orders based on customer requests from stockists. These requests are received in the form of faxes and emails and transformed into equivalent ‘internal-based’ sales orders. Another aspect of BP5.1 is related to preparation of invoices after production of furniture is complete. When production is complete, the finance department is notified for them to raise invoices for the stockists. Another process exist for receiving payments from stockists.

An aspect of DP5 is involved in planning and controlling product realization and this aspect is depicted as BP5.2. BP5.2 was observed to have two other sub processes focussing on scheduling of production and delivery as well as monitoring and controlling production. This included supervisory and managerial activities required for furniture production in Brad Ltd. Distinctively, whilst BP4.1 focussed on the ‘direct machine-human value addition’ to material inputs, BP5.2 was used to describe the ‘indirect documentary and supervisory activities’ necessary for the realization of BP4.1.

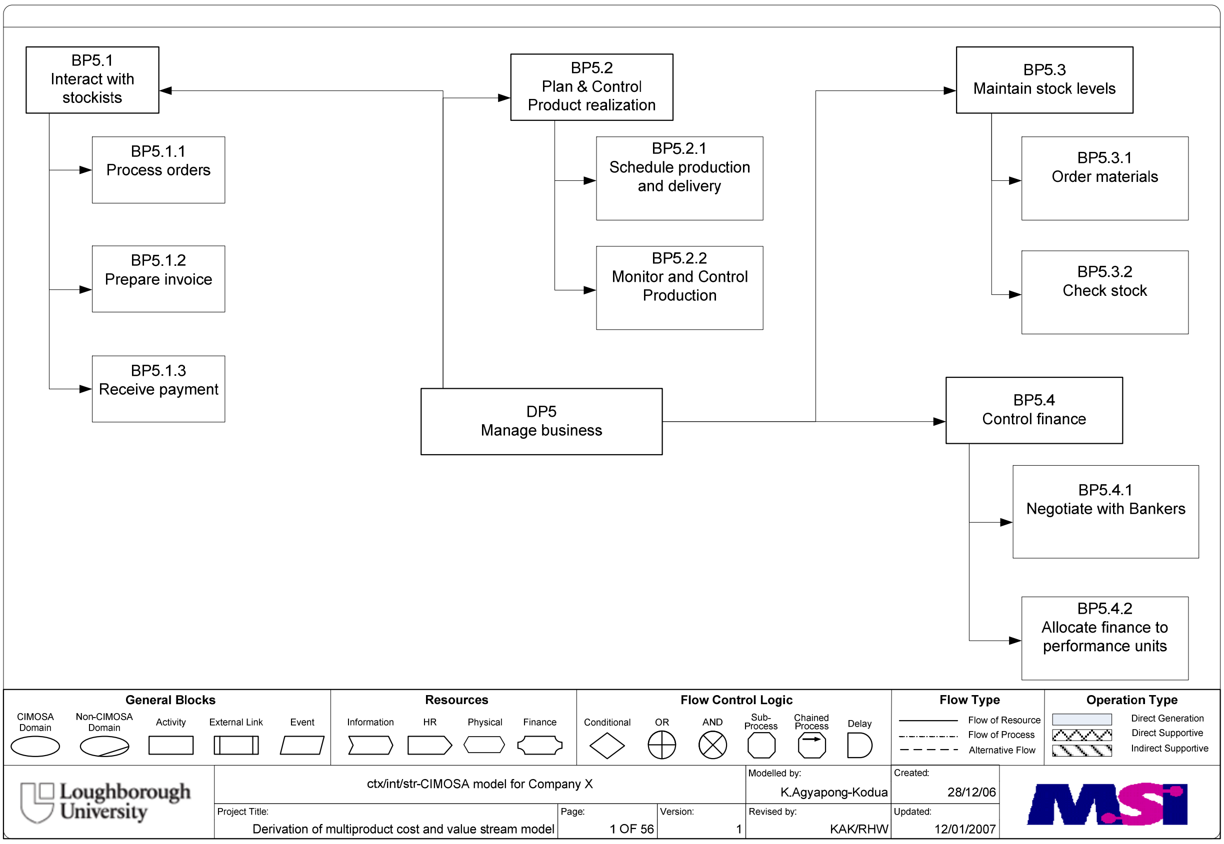


Figure 24: Structure diagram of Manage Business, DP5

However, to maintain smooth production flow, material availability had to be synchronized with production, thus in Brad Ltd, there existed a business process dedicated to the maintenance of stock levels (BP5.3). This top level BP was required to generate purchase orders for materials, fixtures and components, in time. To ensure that right materials, fixtures and components were raised, there existed a process for checking stock of materials, fixtures and other required components. This part of the ‘maintain stock level business process’ (BP5.3) was denoted a sub business process notation of BP5.3.2.

Another key top level business process identified under DP5 was the ‘Control finance’ business process denoted as BP5.4. BP5.4 related to the set of processes required to maintain healthy cash balances in Brad Ltd. This required regular and professional interactions with bankers, follow up of payments from stockists and controlling cost through the efficient distribution of financial resources to the operational units in Brad Ltd.

After generating the structure diagrams, it was deemed necessary to show how the units of BPs interact with each other. This led to the creation of sub interaction diagrams which showed how material and information flowed between the BPs identified. Two of the sub interaction diagrams created to depict understanding about the flows in the BPs of DP4 and DP5 are shown in figures 25 and 26 respectively.

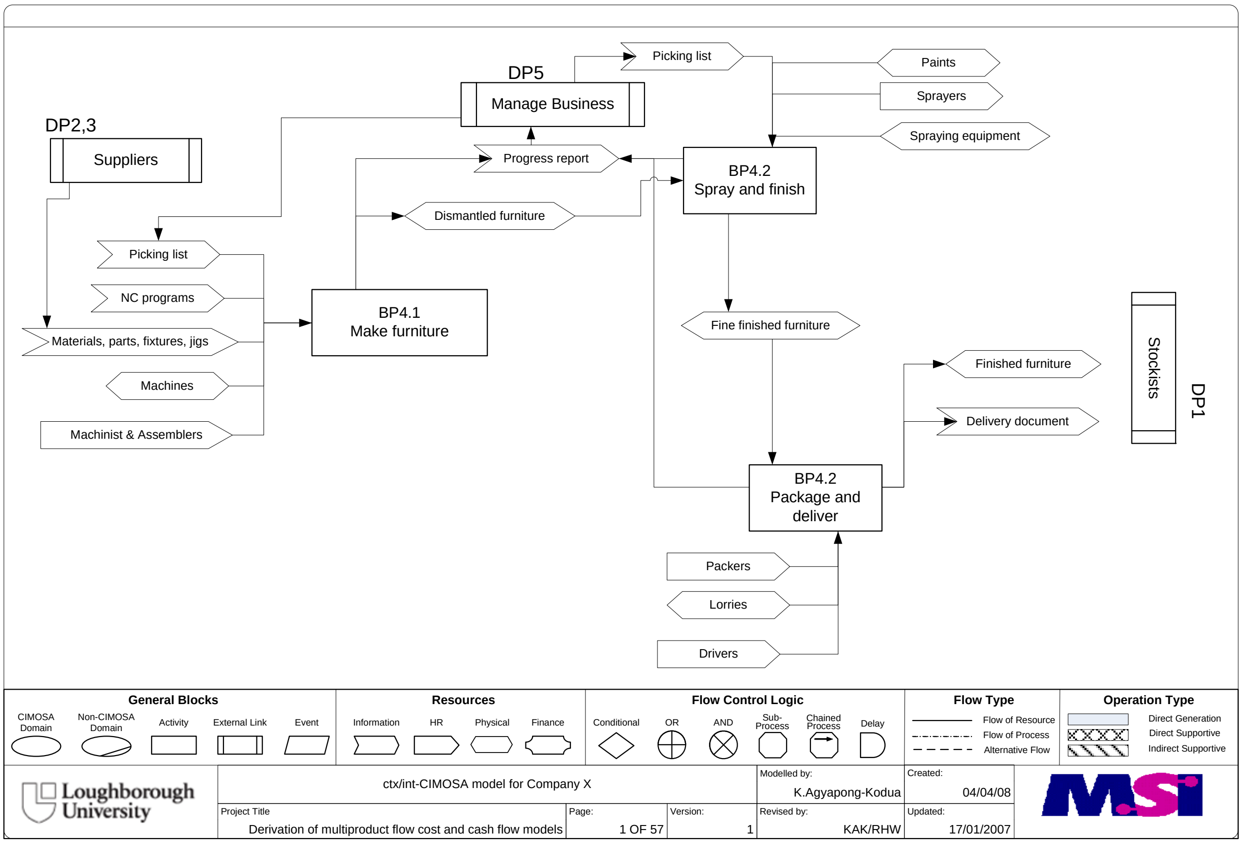


Figure 25: Sub interaction diagram of 'Make and deliver' (DP4) process

As depicted in figure 22, materials and components of furniture are transferred from suppliers to the 'Make furniture business process' (BP4.1). Between 'make furniture' (BP4.1) and 'spray and finish' (BP4.2), dismantled furniture parts, which mostly are carcasses and components ware transferred. Progress reports are also sent across BPs 4.1, 4.2 and 4.3 to DP5, Manage Business; which is an external domain to DP4. Fine finished furniture are transferred to the 'Package and deliver' business process, BP4.3. Based on availability of resources and the required delivery conditions finished furniture are transported to stockists.

Another sub-interaction diagram showing further (and hence more detailed) decomposition of DP5 into its elemental Business Processes is shown in figure 23. The sub interaction diagram for DP5 show that orders are received from stockists, DP1 through the 'interact with stockists' process, BP5.1. Also orders are then sent from one of the internal processes of 'Maintain stock level'

(BP5.3) to suppliers who also supply various materials, components and fixtures for production purposes. Outputs from BP5.1 and BP5.3 influence the ‘plan and control product realization’ process (BP5.2). A key output from BP5.2 is production schedules which dictate the pace and organization of work and resources on the production shop floor.

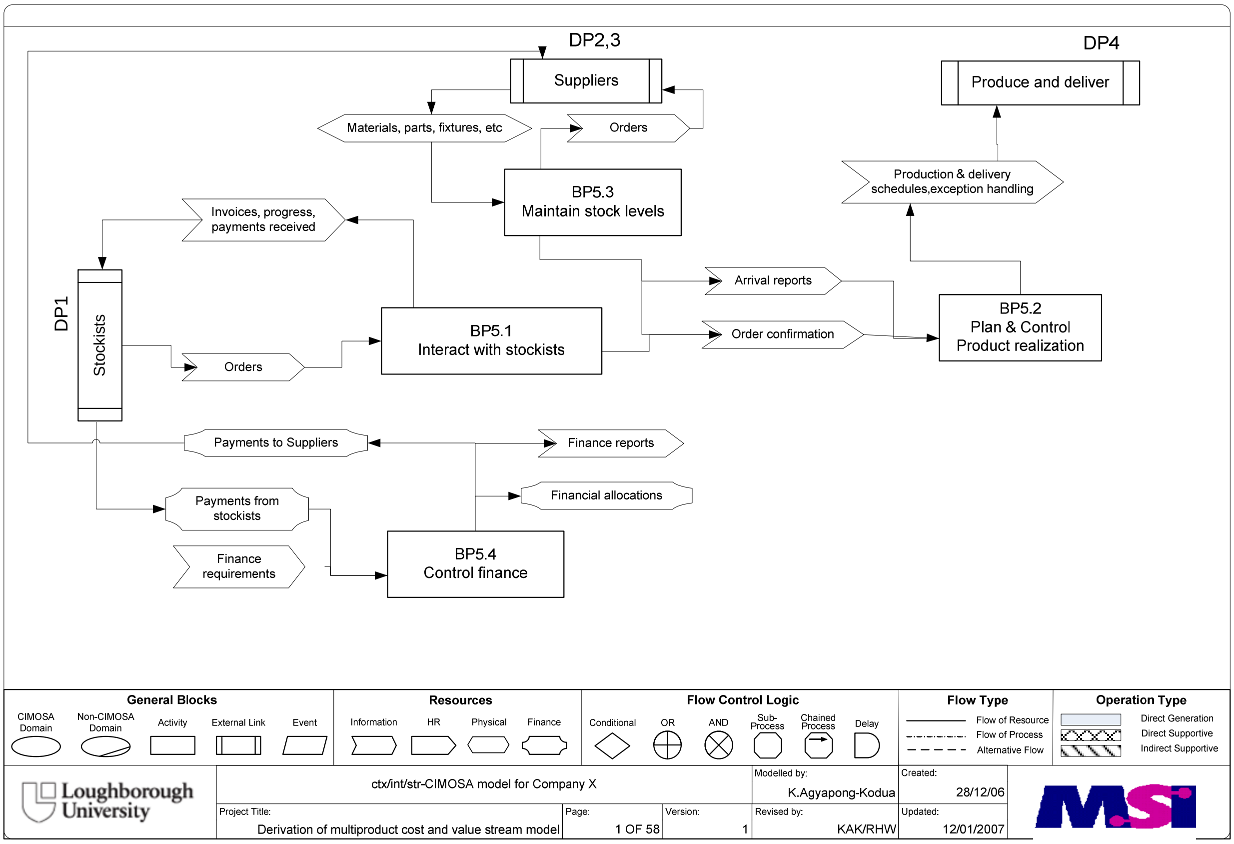


Figure 26: Sub interaction diagram of DP5

An associated parallel process exist for ‘control finance’ (BP5.4) where payments are received from stockists. Also payments to suppliers and distribution of finance resources are made through BP5.4.

Further sub-sub interaction diagrams can be created by considering the interactions that exist between the sub BPs of a given top level BP, however it was not considered relevant at this stage of the modelling exercise because of the intended use of the enterprise models as a base for determining an enhanced approach of modelling cost and value streams. Therefore at the next stage of the modelling exercise, a significant number of activity diagrams were created to detail relatively enduring temporal relationships between process and activity elements of the structure diagram. Essentially, for each of the BPs specified in the structure diagrams, activity diagrams were created to shown how these BPs were decomposed to Enterprise Activities (EAs). Appendix A5 shows a number of activity diagrams which were created to depict the different activities that needed to be performed during fulfilment of orders. They related mostly to the operational activities required to execute BPs related to DP4 and DP5 (BP4.1.1 - BP4.1.4; BP4.2.1 - BP4.2.4; BP4.3.1 - BP4.3.3;

BP5.1.1 - BP5.1.3; BP5.2.1 - BP5.2.2; BP5.3.1 - BP5.3.2; BP5.4.1 - BP5.4.2). Although these activity diagrams were created, for purposes of multiproduct flow value stream models, the activity diagrams were created and linked automatically to their business processes and only revealed where detailed analysis of specific BPs were required.

Constructing the activity diagrams for ‘machine furniture components’, BP 4.1.1, it was observed that based on the picking list received at the machine shop through the assembly shop supervisor, materials and needed parts were picked from the materials shop. The collection of materials was performed by machinists and the items were collected on pallet trucks. A CNC Router which is programmed to cut various shapes was used to cut the materials collected to dimensions specified on drawings which often accompanied the picking lists. Before machining, NC programs were verified to see their suitability for the jobs specified by the drawings. Machining is performed after the verification process.

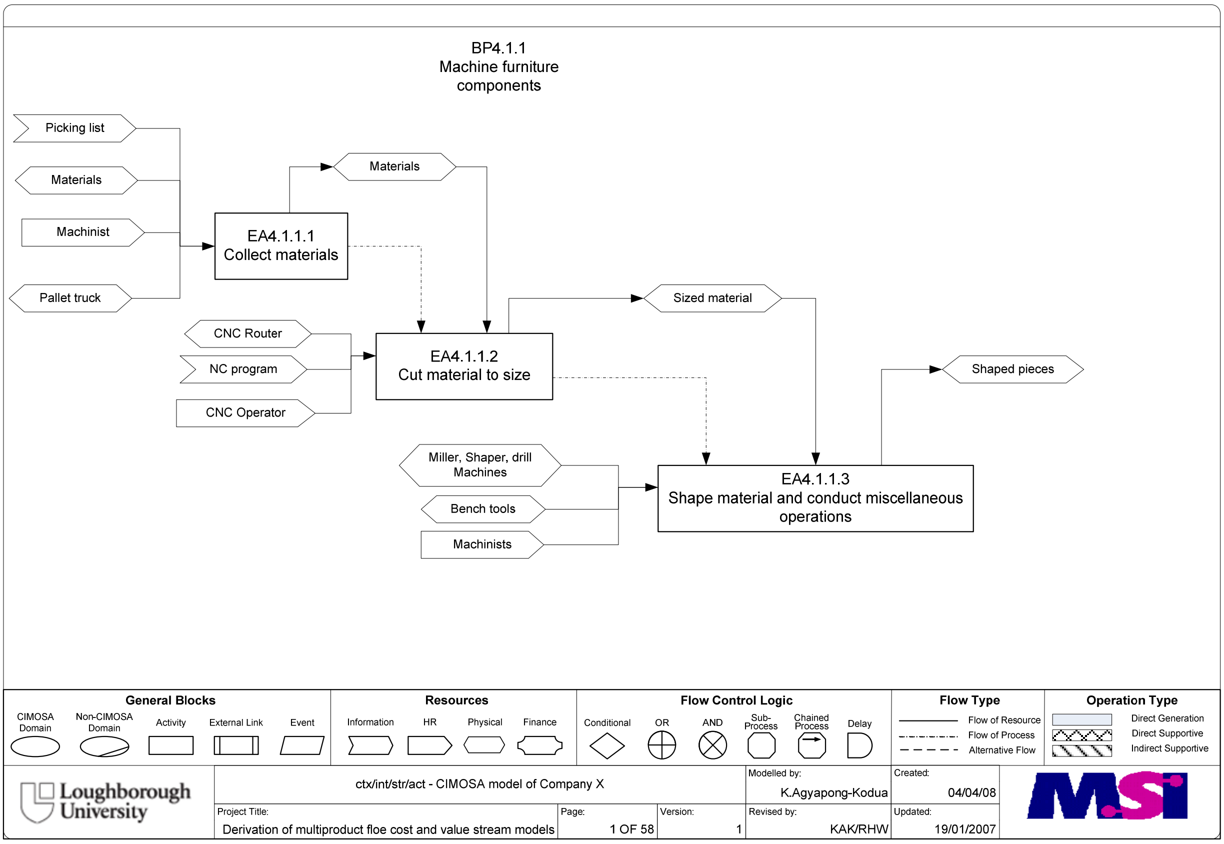


Figure 27: Activity diagram of ‘machine furniture components’, BP4.1.1

The time for completion of machining varies from one job to the other. After the initial machining activities, further shaping and miscellaneous bench work activities such as drilling, tapping, polishing, grinding, etc are performed on the work pieces depending on their applications at the assembly shop.. The final components are visually inspected before being transferred and arranged on the racks in the assembly shop.

When the jobs are completed and certified by the Machine shop supervisor as meeting the specifications of the drawing the parts from each of the workstations are gathered by Packers unto pallet trucks. Usually when demand was not high, the packers would wait for a collection of work pieces that they could conveniently carry on the pallet truck without them having to travel several times to and fro the assembly shop. This was because of the distance that existed between the machine and assembly shops. Under high demand conditions, parts were readily transferred to the assembly shop without having to wait for other components which were still being machined. After transfer of parts to the assembly shop, parts were arranged on racks close to their assembly points as described by figure 28.

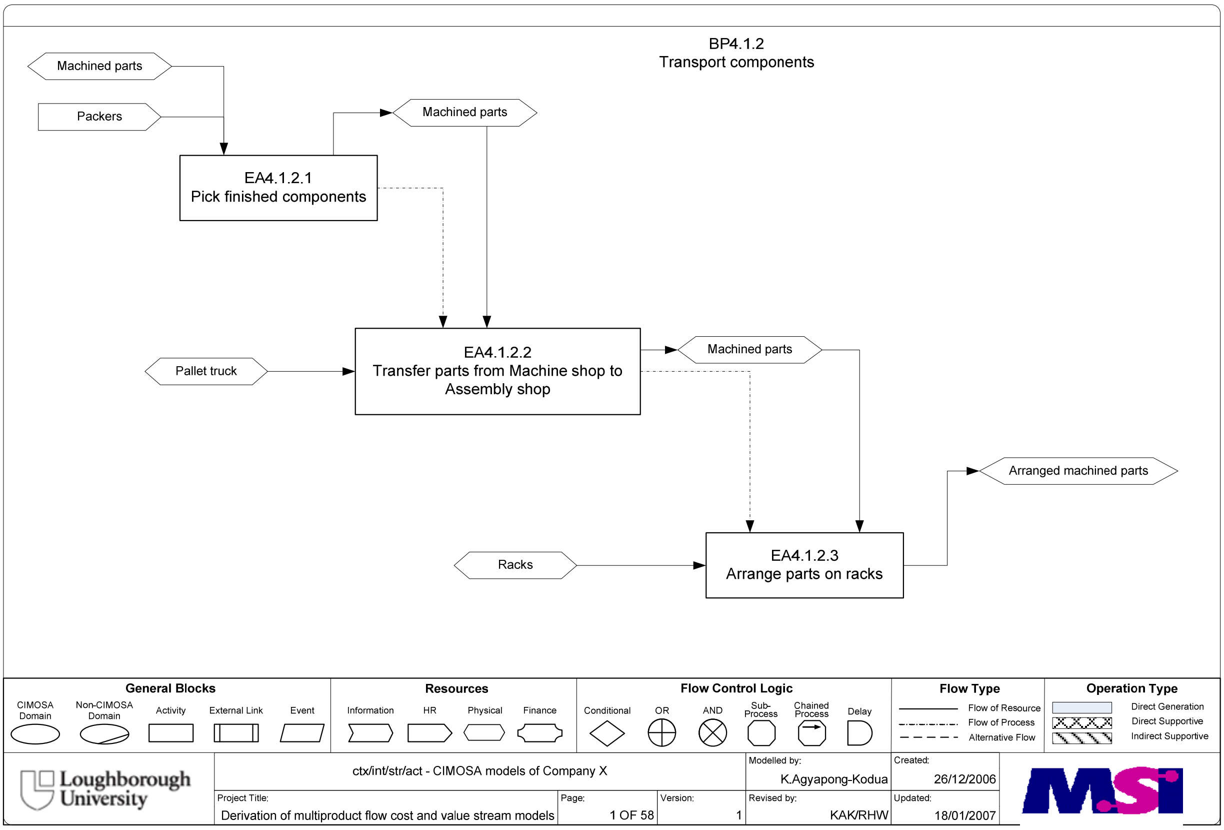


Figure 28: Activity diagram for BP4.1.2

The assembly process, described as ‘Assemble carcass and components’, BP4.1.3, had significantly different activities diagrams based on product types assembled by Brad Ltd. Activity diagrams depicting how drawers and tables are made are shown in figures 29 and 30 respectively.

Components for drawer assembly are classified in the assembly shop as side components, back components and front parts. There are two main human resources assigned to drawer making. Normally the human resources are assigned to the job and they moved with the work. The process of drawer making begins with one drawer maker picking side and back components of the drawer and fitting them together by means of a drawer press. The sub assembled drawer parts get transferred unto a work bench where another person performed some drilling activities on them. After the drilling exercise, front components of the drawers are fitted and then sent to the spray shop.

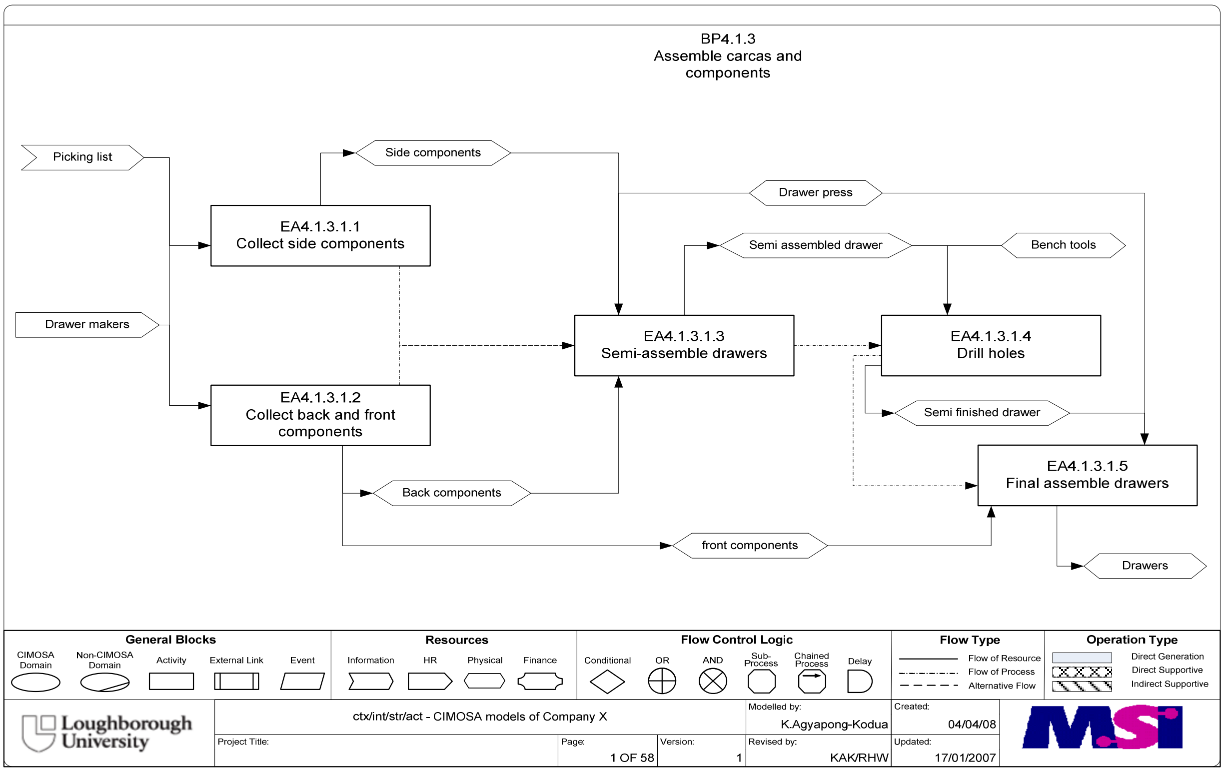


Figure 29: Activity diagram for making drawers

At the time when the EM of Brad Ltd was created, table making also began with the reception of a picking list which specified needed quantities of components for the assemblage. The human resources needed to realize the assembly process were basically Table Makers. Table assembly generally deployed three main human resources with separate machines for processing and assemblage. The tables consisted of three subassemblies. These were table top, under frame and legs sub-assemblies. As shown in the activity diagram in figure 30, piano hinges were fitted to the top assembly and sent to the machine shop for shaping on the CNC Router. After completion of this exercise, the top was sanded by the Table Sander before spraying took place at the spray shop. Miscellaneous bench work activities such as drilling, turning and components assembly took place during the assemblage of the under frame. When this was completed, the top sub assembly was assembled to the under frame sub-assembly and transferred to the spraying shop. In a similar manner, bench work activities such as drilling, turning and sanding were performed on the leg sub-assembly before transferred to the spraying shop. After the spraying of these sub assemblies, the legs were finally assembled to the top sub-assembly to achieve a complete table.

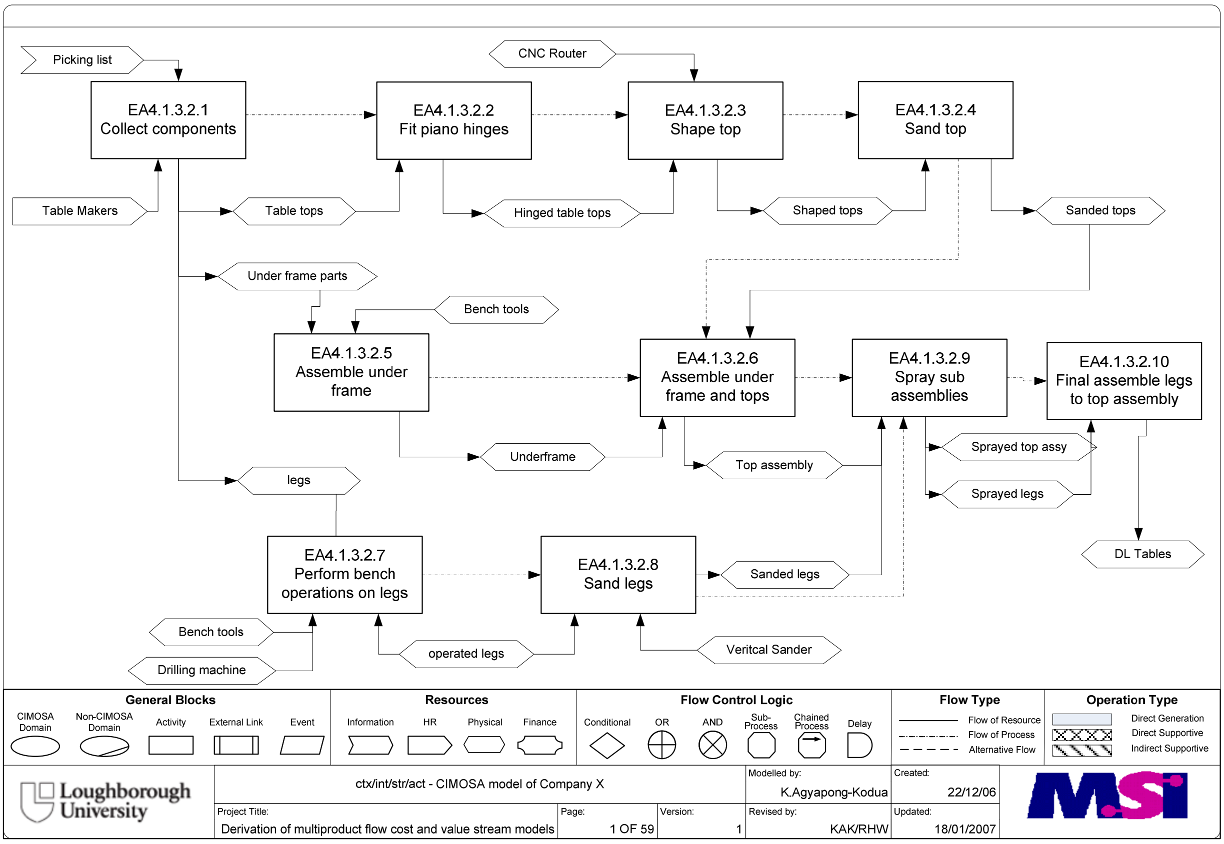


Figure 30: Activity diagram for assembling Tables

5.6.2 Derivation of cost and value stream models of assembly shop of Brad Ltd

As explained in the previous section, a number of activity diagrams were created to depict the different activities involved in the making and assembling of furniture. Two example activity diagrams are shown in figures 29 and 30. At the next stage of the modelling exercise, it was decided that further analysis of cost and values should be focussed on the assembly shop. This was because the assembly shop served as the 'pacemaker' for the production processes of Brad Ltd and was labour intensive. Another reason from a research point of view was that it was necessary to test the applicability of the proposed modelling technique in stages by reducing modelling complexity until adequate knowledge had been gained in the relevant areas of modelling. Thus focussing on the assembly shop was considered adequate to initially test the value stream modelling ideas.

Following a discussion with the Managers of the company it was understood that based on product functions, furniture produced by Brad Ltd had been classified into tables, cabinets and drawers. Since these product classes are all routed through the assembly shop it was decided also that values and cost generated through the realization of these product classes will be analysed. At this stage detailed product family examination was not conducted to verify the similarity in process routes for each of the product families mentioned. Essentially activity diagrams and process timings for each of the assembly processes for the three product families had been created so little was required to generate value stream maps for the assembly shop.

5.6.2.1 Creation of lean based value stream models

To also help provide a background for the deployment of alternative value stream modelling techniques, the initial approach was to map the assembly processes through the ‘conventional lean value stream mapping approach’ (Hines and Taylor 2000; Womack and Jones 2003). Based on this requirement, the ‘lean meaning of value stream’ referring to the sequence of processes, including *value adding* and *non value adding* activities, identified from the raw material to the final customer (Womack and Jones 1996; Bicheno 2000) was the basis for the mapping. It involved identifying waste through sequential mapping of the processes needed to assemble a table. Value adding activities were identified as activities which customers were willing to pay for, whilst the converse was classed non-value adding (McManus and Millard 2002; Lee 2005). Practically, the main parameter used was ‘time’, which formed the basis for determining waste.

Table 6 shows the data used for modelling the value streams and process cost of the assembly of tables in Brad Ltd. This was based on observation and confirmed data from the shop floor supervisors.

To facilitate construction of the current state value stream map of the assembly section of Brad Ltd some assumptions were made. These included:

1) Fixed customer ordering pattern: This assumption was to help give steady flow of orders into the production system. In reality customer orders are not predictable but because Brad Ltd operated the ‘stockist based order system’ it was less complex than other companies.

2) Fixed delivery rate from suppliers: This was based on observed trends of supply fulfilment schemes in Brad Ltd. Delays in supplies was observed to be less than 5% and therefore it was deemed reasonably appropriate to assume that orders to suppliers and delivery of raw material and

sub-products from suppliers were fixed and deterministic. This assumption was to help describe the material flow pattern.

3) Although many operations influenced the flow of material and other resources in the assembly shop, it was also decided to assume that all supporting operations were performed such that material and other resources were available based on the current operations.

Process description	Duration of process
1.0 *Delivery rate of sub-supplier 1	2X monthly
2.0 *Delivery rate of sub-supplier 2	2X monthly
3.0 *Delivery rate of raw material supplier	2X weekly
4.0 Machine shop lead time	5 days
5.0 Processing time for benches	5 – 15minutes
6.0 Queue time for CNC Router	5 days
7.0 Processing time for CNC Router	20 minutes
8.0 Queue time for Table sander	1 day
9.0 Queue time for vertical sander	1 day
10.0 Processing time for table sander	10 minutes
11.0 Processing time for vertical sander	10 minutes
12.0 Processing time at Spray shop	60 minutes
13.0 Overall customer order lead time	4 weeks

Table 11 Data for constructing value stream maps

Literature has explained the steps required in generating lean based value stream maps. Key examples are outlines provided by (Bicheno 2000; Hines and Taylor 2000; Lee 2005). Based on approaches recommended by literature, data related to customer requirements, information flows and physical flows were collated and mapped. The map shown in figure 31, describes the processes involved in the production of tables. In the case of Brad Ltd, orders from the customers, who are usually stockists, are received by the Business Management section. Three important information are deduced from these orders. The first information is in the form of purchase requests which are sent to the raw material and sub-product suppliers. The delivery of the raw materials to the company is based on the lead time of the supplier. The second information is sent to the shop floor supervisor in the form of pickling list. The pickling list plays a vital role in determining the quantities of the parts to be produced. The next (and third piece of) information is the delivery schedule which is sent to the package and delivery section.

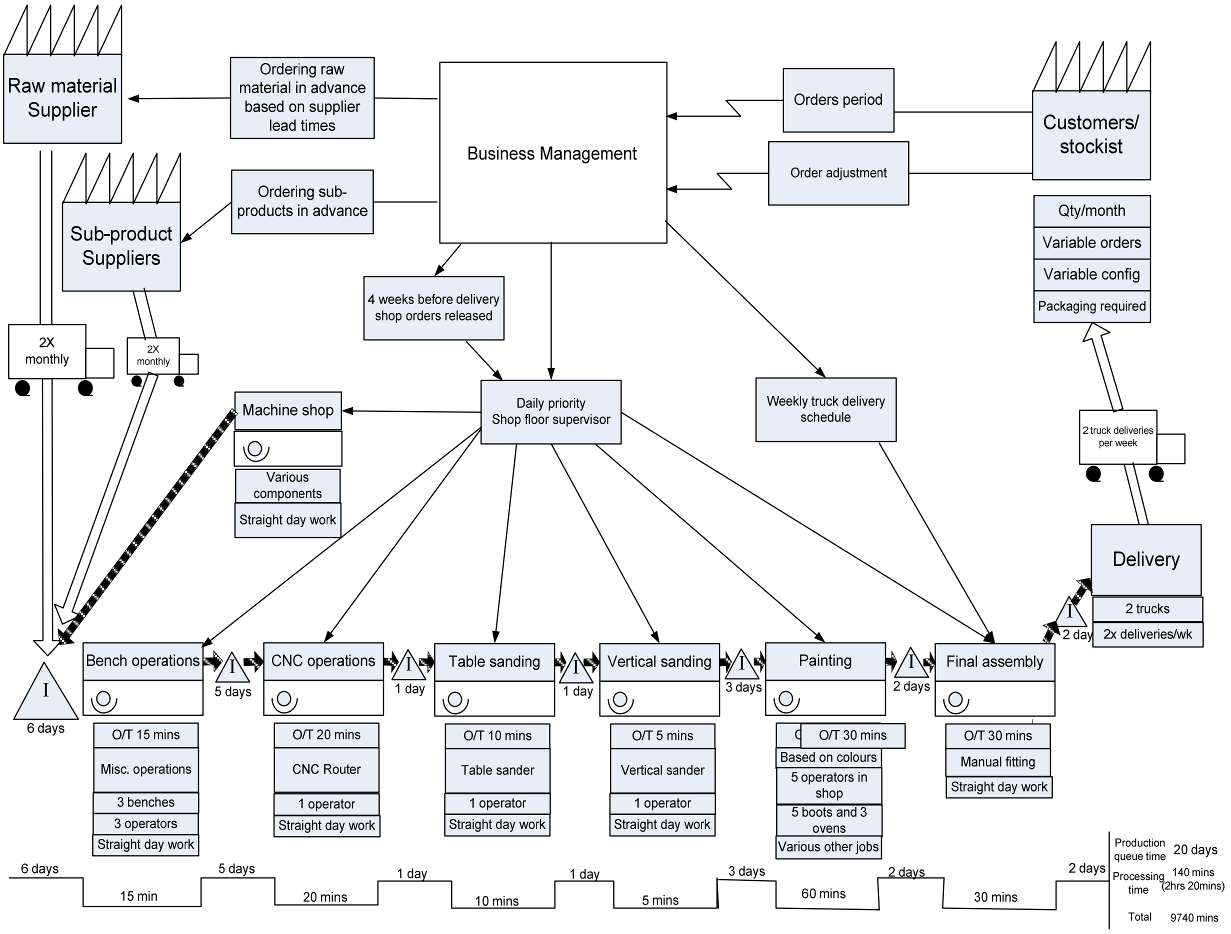


Figure 31 Lean based value stream map for table assembly

The various delivery details, operation times, operator information and scheduling details for each operation is stated underneath. The bottom line shows the queue and processing times at every stage of the process. The cumulative sum of the queue times and processing times give the total process lead time.

5.6.2.2 Discussion and analysis of lean based current state value stream map

From the map shown in figure 31, the total queue time is 20 days whilst the total operation time is 2hours and 20 minutes. The total table assembly process lead time therefore is 9740 minutes (representing 20 days, 2 hours and 20 minutes). The assembly shop supervisor confirmed that this assembly process lead time was slightly less than the reality and it was difficult to initially identify which information was inaccurate. Comparing the delay time and the actual 'value adding time, it was clear that only 1.43% of the process lead time was used effectively for value addition (processing).

Although the map was an important tool initially to explain part of the problems to the Workshop Supervisors, after comparing the lean value stream map with the CIMOSA activity diagram for table assembly it became clear that some salient operations were omitted in the maps created earlier on. The fundamental observation was that the assembly of tables was not a linear process. This is because the actual process involved different components being processed through separate routes and finally these components assembled together. It was therefore convincing that these routes needed to be included for an accurate reflection of the process reality. These process routes were overlooked by the lean map initially generated.

As explained in previous sections, cost and values are two important key performance indicators in manufacturing process improvement exercises, thus there is the need to demonstrate how process parameters derived from value stream maps can be used to estimate cost and values generated through the process.

In view of these, an enterprise based approach incorporating the strengths of CIMOSA in the lean based value stream mapping technique was developed. This exercise involved embedding queue and process information, obtained through the mapping exercise, on activity diagrams created through CIMOSA modelling techniques.

5.6.2.3 Enterprise based value stream models of the assembly section of Brad Ltd

As a result of the observed limitations in the lean based value stream map of the assembly section, an enterprise based approach to modelling cost and value streams was conceived and used. One of the initial assumptions was that the value of a product was its price. The time-based process metrics derived from the lean value stream map was essential for the derivation of process cost.

The enterprise based value stream modelling approach builds on already created EMs, thus enabling enterprises to be decomposed to their minute levels of abstraction such that all functional operations are captured. Figure 31 shows the value stream map for assembling tables.

The basis of the model is to decompose enterprise processes into their elemental activities and to observe the material and resource flows across activities. Queues are built in between activities and a symbol was introduced to describe the type of material and the size as well as time spent in inventory. Here it was envisaged that the later attachment of relevant information related to the construct could be used in most (if not all) enhanced VSM applications to estimate storage cost.

Movement cost is also estimated for activities which require significant movements or travels. Other process information gathered was used as basis for estimating movement cost, storage cost, operational cost and other cost that becomes eminent in the process. Based on sales values, the value generated by the process under consideration is estimated and the figure obtained is compared with the cost required to accomplish the process. The premise of this idea is to consider cost and value as flows which are transferred from one activity to the other. Technically it is assumed that cost is pushed through processes whilst value is pulled from the selling point (price) unto the processes. The process data assists in estimating process cost whilst sales data supports an analysis of the monetary values generated.

For the sake of clarity, the cost and value figures are not displayed on the static value stream map shown in figure 32. But related calculations and analysis involved have been explained in the section below. Another important information the model offers is the material and resource types required to realize an activity. This is not offered in the lean based value stream mapping approach. The addition of material and resource flows give indications on how resource utilization and hence resource cost can be improved or how resources can be configured for optimal performance and low cost realization. Also the information on material flows shown on the model gives light to the estimation of material cost as well as indicating how materials are transformed from one state to the other.

From the value stream model shown in figure 32, the total queue time is 22 days whilst the total operation (value adding) time is 3hours. The total assembly process lead time therefore is 22 days plus 3 hours. Higher queuing times were identified and the total process lead time was higher when compared to figures derived from the lean value stream map. The assembly shop supervisor confirmed 22days as the usual assembly process lead time and hence was confident that some processes which were overlooked in the lean value stream maps had now been captured. The difference was actually based on the decomposition formalisms the later offered. The lean based approach offered a method for mapping linear processes but the enterprise based approach allowed modelling multiple processes (both converging and diverging).

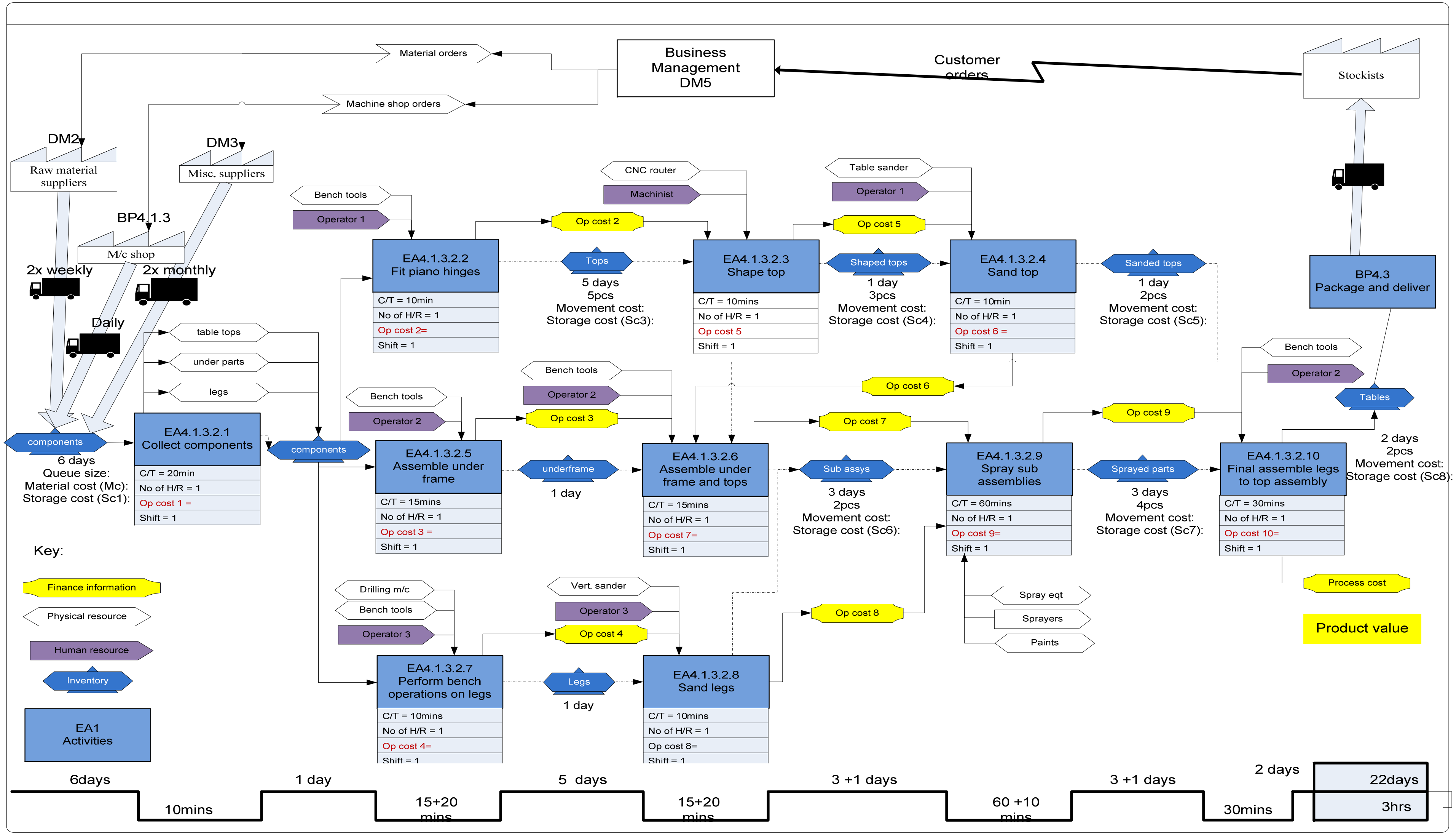


Figure 32 Enterprise based current state value stream model for table assembly

5.6.2.3.1 Cost and value stream analysis of the assembly shop

Because of the rich data the enterprise based value stream model gives, a number of useful cost and value stream analysis can be conducted for operations at the assembly shop. It was assumed that all products assembled in Brad Ltd can be conveniently classified as belonging to the table, drawer or cabinet families. To further simplify the analysis, it was assumed that within a product family, there was no significant price difference among products. Based on these assumptions, products were consolidated and assigned to their respective price bands. For example cabinets were sold at £450, tables-£200 and drawers, £90.

To estimate the total value generated by Brad Ltd over a time period, the production volume and selling prizes of the different products sold was considered. For 'y' different product types with 'N' sales volumes at 'p' selling prices, the monetary or sales value generated is expressed as:

$$\sum_{y=1}^{y} \mathbf{P_y N_y} \qquad \mathbf{(13)}$$

It was noted that equation (13) can be used to calculate generated revenues at different abstraction levels, e.g. for product families or for product types within a family. Based on equation (13), the value generated per month was estimated and used as a basis for estimating the total value generated over a twelve months production period (see Table 12).

Months	Tables			Cabinets			Drawers			Total (£)
	Production volume	Unit price (£)	Sales value (£)	Production volume	Unit price (£)	Sales value (£)	Production volume	Unit price (£)	Sales value(£)	
Jan	150	200	30,000	60	450.00	27,000	190	90	17,100	74,100.00
Feb	80	200	16,000	63	450.00	28,350	183	90	16,470	60,820.00
Mar	200	200	40,000	70	450.00	31,500	192	90	17,280	88,780.00
April	220	200	44,000	50	450.00	22,500	190	90	17,100	83,600.00
May	210	200	42,000	58	450.00	26,100	168	90	15,120	83,220.00
June	90	200	18,000	22	450.00	9,900	78	90	7,020	34,920.00
July	80	200	16,000	20	450.00	9,000	80	90	7,200	32,200.00
Aug	75	200	15,000	18	450.00	8,100	72	90	6,480	29,580.00
Sept	180	200	36,000	60	450.00	27,000	189	90	17,010	80,010.00
Oct	192	200	38,400	62	450.00	27,900	187	90	16,830	83,130.00
Nov	175	200	35,000	67	450.00	30,150	170	90	15,300	80,450.00
Dec	200	200	40,000	59	450.00	26,550	171	90	15,390	81,940.00
Total	1852		370,400	550		274,050	1870		168,300	**812,750.00**

Table 12: Estimation of sales value generated

From a valuation exercise previously conducted, it was revealed that in terms of resource attribution, on average over the time period covered by Table 12, the assembly shop contributed 40% of the total company value. Hence it is assumed that all things being equal, the assembly shop generated in approximation 40% of the total sales value.

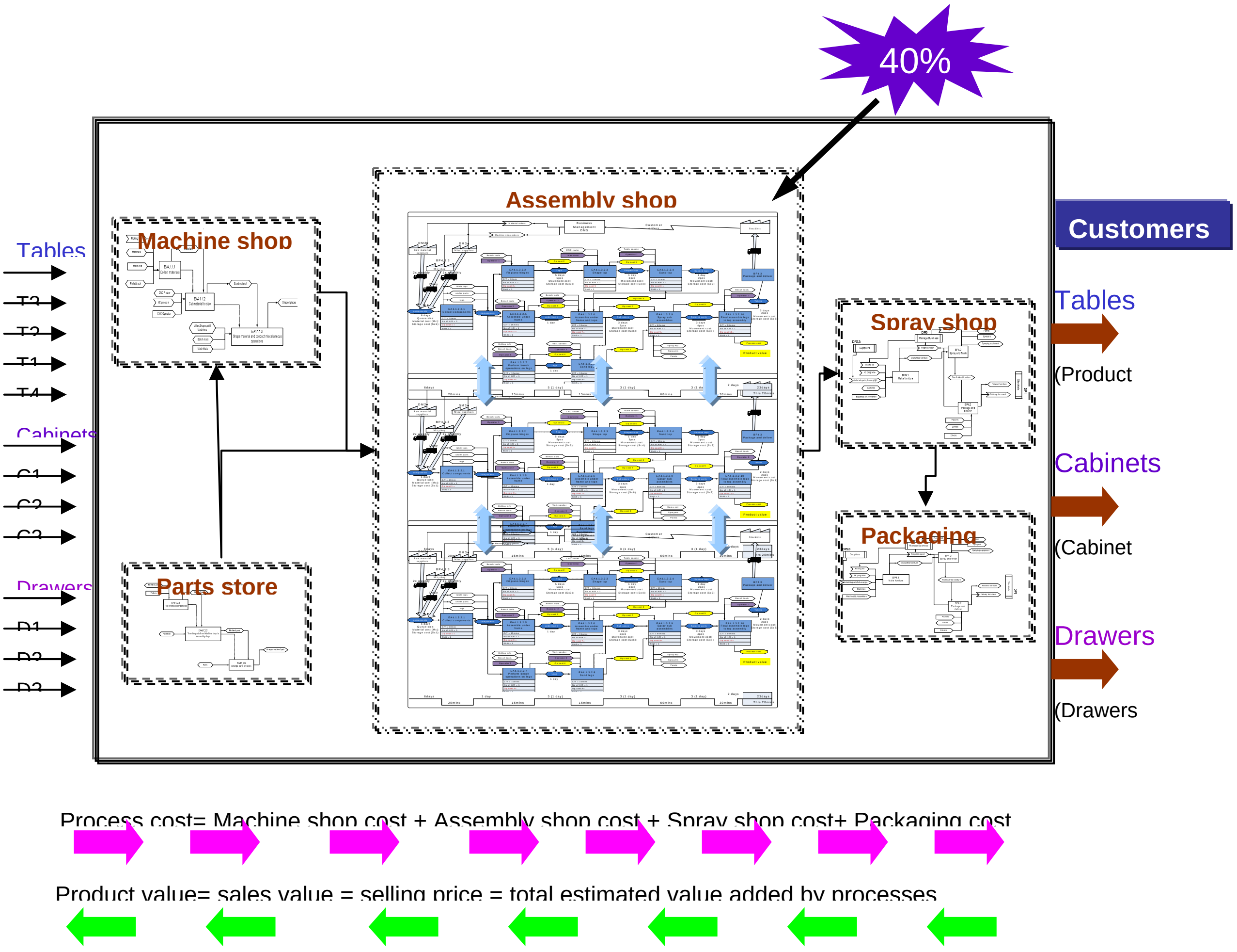


Figure 33: Cost and value description of production processes at Brad Ltd

As shown in figure 33, customer orders for various product types are processed and input as production orders to the production system of Brad Ltd. This can be viewed as initiating the introduction of materials which undergo many production processes for value to be added to them. However as material is transformed and flows through these processes because of the utilization of resources, costs are incurred. Therefore what Brad Ltd delivers to their customers consist of a valued product at a certain cost.

As a development of Table 12, Table 13 further shows the actual values generated by the assembly shop for the different products sold. The last column of Table 13 shows the actual value for each product family. This is defined as the ratio of value per product type generated by the assembly shop to the total production volume per product type.

Actual product values generated by assembly shop				
Average sales value for the year		**Value generated by assembly shop (£) =40% of total product value**	**Annual production volume**	**Value per product generated through assembly shop (£)**
Tables	370,400	148,160	1852	80.00
Cabinets	274,050	109,620	550	199.31
Drawers	168,300	67,320	1870	36.00
Total	**812,750**	**325,100**	**4272**	

Table 13 Estimation of values generated

After estimating the values generated by the assembly shop, the assembly process cost was estimated by defining the cost elements observed to be associated with the assembly process. This was done to be able to estimate per activity the perceived 'cost concentration' and based on the value stream model, derive the total process cost. Several cost accounting and cost engineering theories and practices have specified various means of estimating operation cost in manufacturing systems. Key reference was made to public domain literature provided by Son (Son 1991), Drury (Drury 1991), Barfield (Barfield, Raiborn et al. 1994) Johnson (Johnson and Kaplan 1987) and Samid (Samid 1990).

Son (Son 1991) has attempted to provide mathematical expressions for estimating cost elements in advanced manufacturing systems. These expression provided by Son (Son 1991) were found suitable for process oriented modelling of cost and values. In theory, for a piece of material, **m**, to be routed through a process class, **Pid**, comprising, **αp** activities (or process steps) which are realized through the application of **dp** set of resources, if the overall cost involved in achieving, **Pid** is **Pc**, then process cost can be expressed as a mathematical function of cost parameter, **c**, involving the factors observed to be contributing to the realization of **Pid**. Thus:

Pc= c{ αp,dp,} ….. (2) (Vernadat 1996; Agyapong-Kodua, Wahid et al. 2007)

Son (Son 1991) has shown that:

for a labour intensive activity described by the value stream model, the actual manual labour which transforms the material piece, **m**, is defined by, $L_{d},:= n_{o}tr\alpha$

where $\mathbf{n_o}$ is the number of operators; **t** is the time spent; **r** is the existing rate of pay or wages per time and α is a percentage availability factor. In actual fact, this is the labour cost which should be paid. The difference between this cost and the actual labour cost paid is the lost that the company incurs in paying incompetent and unavailable workers. It was also decided that indirect labour and benefits where necessary would be added to labour cost since in most advanced manufacturing environments, direct labour is giving way to indirect labour because of automation. Thus if '**y**' different numbers of jobs use indirect labour of salary **s**, then for **z** numbers of indirect labour units, the total indirect labour cost, $\mathbf{L_i}$ is given by: $\sum_{y=1}^{y} \mathbf{s_y z_y}$

The total labour cost for a process class, Pid, then becomes $\mathbf{L_d} + \mathbf{L_i}$. Similarly, for a machine intensive work centre with, $\mathbf{m_r}$, usage cost of **N** numbers of machines, if **t** is the total machine usage time then the total usage cost is $\mathbf{M_u}$: $\sum_{N=1}^{N} \mathbf{m_{rN} t_N}$

Conventionally, machine cost is considered as overhead with its allocation based on direct labour hours (Barfield, Raiborn et al. 1994), since collecting data on machine hours for individual jobs can be exhausting and time wasting. However in computer controlled machines like CNC routers, machine hours can reliably be identified (Son 1991). Adding up the necessary cost elements associated with machine utilization provides a total machine cost, $\mathbf{M_t}$**,** estimated in the form (Son 1991):

$$\mathbf{M_t = usage\ cost + maintenance\ cost + repair\ cost + insurance\ cost + property\ tax}$$

Mathematically, for process, **Pid**, involving **N** numbers of machines operating over a period **T**, the total machine cost, $\mathbf{M_t}$ is: $\sum_{N=1}^{N} \mathbf{\{(m_{rN}t_N + m_N v_N + b_N u_N) + af + W\}}$

Where **m** is the maintenance cost per unit whilst **v** is the total maintenance time; **b** is the repair cost per unit time whilst **u** is the total repair time; **a** is the insurance premium rate whilst **f** is the cost of machine and **W** is the property tax of machine **N**.

Considering the floor space cost, if the floor square metre cost is $\mathbf{f_s}$ and the manufacturing floor space is $\mathbf{M_s}$, then the floor space cost, $\mathbf{C_{fs} = f_s \times M_s}$

The storage cost, $\mathbf{S_c}$ is expressed in terms of the floor space cost and the cost of keeping materials in storage over a given time. Thus for $\mathbf{n_m}$ number of materials or components in storage with $\mathbf{C_s}$ unit cost, stored over **t** length of time, the inventory cost, $\mathbf{C_i}$, is expressed as: $\mathbf{C_i = n_m C_s t}$. Therefore for

N different types of machines with **p** number of storage points, the total storage cost is expressed as:

$$\mathbf{S_c} = \sum_{N=1}^{N} \mathbf{C_{fsN}} + \sum_{p=1}^{p} \mathbf{C_{ip}}$$

In estimating tool cost, $\mathbf{T_c}$**,** assuming a tool has a useful life **n**, then the total tool cost can be expressed as: $\mathbf{T_c = C_t N_t}$

Where $\mathbf{C_t}$ is the unit cost per tool and $\mathbf{N_t}$, the total number of different tools changed..

Based on the mathematical equations specified, a spreadsheet was used to estimate the essential costs as specified in the value stream model. Table 13 shows the list of activities specified already by the value stream model and their associated cost elements.

To estimate the direct labour cost per minute, it is considered that the assembly shop works on 8 hour shift for five (5) days in a week and fifty two (52) weeks in a year, thus the shop is in operation in a year for:

$$\mathbf{= 5 \times 8 \times 60 \times 52 = 124800\ minutes}$$

For an average annual salary of an operator, £25,000, the direct operator cost per minute is:

$$\frac{£25000}{124800\,\mathrm{min}}$$

$$\mathbf{= £\ 0.20/min}$$

Ignoring the competence rating of operators, the direct labour cost for activity EA4.1.3.2.1 is:

$$\mathbf{20min \times £0.20 = £4}$$

In estimating the indirect labour cost, it was observed that the assembly shop was managed by 2 Line Managers of average annual salary of £35,000.00. Simplifying the cost per task for the managers, data based on previous job studies was used. It was estimated in approximation that 55 individual tasks were performed by the managers each day. Therefore based on equation (4), the portion of indirect labour cost related to activity EA4.1.3.2.1 is expressed as:

$$\mathbf{(£35000 \times 2)/(52 \times 5 \times 55) = £4.90}$$

This is purely for estimation purposes. For accurate figures, an activity diagram describing the process sequences of the managers will be required and used as basis for estimating the indirect cost. Alternatively, based on conventional accounting practices (Barfield, Raiborn et al. 1994), the indirect cost can be cumulated and calculated against the assembly shop. The total labour cost then becomes the sum of the direct and indirect labour costs.

Similarly by referring to equations (5) and (6), Table 14 was generated to help estimate the total machine cost. The last set of estimation performed on the actual operation activities related to the manufacturing floor space cost, tools and depreciation per task. These estimates were made through the application of equations (7) and (9). Summing the total labour cost, machine cost, storage cost and other associated cost elements, the total operation cost was calculated and tabulated (see Table 15).

EA Nos:	Activities	Operation/movement/storage times (t) minutes	Number of operators, (no)	Rate of pay, wages, salaries, r/min	Estimated percentage of salary for assigned task	Direct labour cost, Ld	Indirect labour cost, Li	Total labour cost, Lc
	Operational activities							
EA4.1.3.2.1	Collect components	20	1	0.2	4.90	4	4.90	8.90
EA4.1.3.2.2	Fit piano hinges	10	1	0.2	4.90	2	4.90	6.90
EA4.1.3.2.3	Shape top	10	1	0.2	4.90	2	4.90	6.90
EA4.1.3.2.4	Sand top	10	1	0.2	4.90	2	4.90	6.90
EA4.1.3.2.5	Assemble under frames	15	1	0.2	4.90	3	4.90	7.90
EA4.1.3.2.6	Assemble under frames and tops	15	1	0.2	4.90	3	4.90	7.90
EA4.1.3.2.7	Perform bench operations on legs	10	1	0.2	4.90	2	4.90	6.90
EA4.1.3.2.8	Sand legs	10	1	0.2	4.90	2	4.90	6.90
EA4.1.3.2.9	Spray sub assemblies	60	1	0.2	4.90	12	4.90	16.90
EA4.1.3.2.10	Final assemble tops sub assy and legs	30	1	0.2	4.90	6	4.90	10.90
	Total	**190**						86.95

Table 13: Estimation of labour cost

EA Nos:	Activities	Number of machines, N	Machine unit usage cost, mr	Machine usage cost, Mu	Maintenance cost,m	Unit repair cost, b	Repair time,u	Repair cost	Insurance premium rate, a	Initial invest cost, f	Insurance cost	Property tax, W	Total machine cost
EA4.1.3.2.1	Collect components	0	0.00	0.00	0.000	0	0	0	0	-	0.00	0	0.00
EA4.1.3.2.2	Fit piano hinges	0	0.00	0.00	0.014	0	0	0	0	-	0.00	0	0.01
EA4.1.3.2.3	Shape top	1	0.02	0.17	0.014	0	0	0	0.15	13,000.00	0.01	0	0.19
EA4.1.3.2.4	Sand top	1	0.03	0.25	0.014	0	0	0	0.15	10,000.00	0.01	0	0.27
EA4.1.3.2.5	Assemble under frames	0	0.00	0.00	0.022	0	0	0	0	-	0.00	0	0.02
EA4.1.3.2.6	Assemble under frames and tops	0	0.00	0.00	0.022	0	0	0	0	-	0.00	0	0.02
EA4.1.3.2.7	Perform bench operations on legs	0	0.00	0.00	0.014	0	0	0	0	-	0.00	0	0.01
EA4.1.3.2.8	Sand legs	1	0.03	0.25	0.014	0	0	0	0.15	10,000.00	0.01	0	0.27
EA4.1.3.2.9	Spray sub assemblies	1	0.08	5.00	0.087	0	0	0	0.2	15,000.00	0.12	0	5.21
EA4.1.3.2.10	Final assemble tops sub assy and legs	0	0.00	0.00	0.043	0	0	0	0	-	0.00	0	0.04

	Total												**6.07**

Table 14: Estimation of machine cost

EA Nos:	**Activities**	**Manuf' floor space (Ms)**	**Floor space cost per sq metre (fs)**	**floor space cost (Cfs)= Ms x fs x t**	**Number of materials, nm**	**Unit cost of material, Cs**	**Inventory cost $C_i = n_m C_s t$**	**Storage cost, $S_{c=}$Cfs + Ci**	**Other cost (tools + depreciation)**	**Total operation cost**
EA4.1.3.2.1	Collect components	0	0	0	0	0	0	0	0.000	8.895
EA4.1.3.2.2	Fit piano hinges	2	2.00	4	0	0	0	4	0.000	10.924
EA4.1.3.2.3	Shape top	9	2.00	18	0	0	0	18	0.208	25.479
EA4.1.3.2.4	Sand top	4	2.00	8	0	0	0	8	0.160	15.594
EA4.1.3.2.5	Assemble under frames	4	2.00	8	0	0	0	8	0.000	15.938
EA4.1.3.2.6	Assemble under frames and tops	4	2.00	8	0	0	0	8	0.000	15.938
EA4.1.3.2.7	Perform bench operations on legs	2	2.00	4	0	0	0	4	0.000	10.924
EA4.1.3.2.8	Sand legs	4	2.00	8	0	0	0	8	0.160	15.594
EA4.1.3.2.9	Spray sub assemblies	9	2.00	18	0	0	0	18	1.442	46.631
EA4.1.3.2.10	Final assemble tops sub assy and legs	4	2.00	8	0	0	0	8	0.000	18.982
	Total									184.899

Table 15: Estimation of manufacturing space cost and total operation cost

Studying the value stream model, it was important to identify the movements that existed between the work centres. The average movement times were estimated and used as a basis together with the resource requirement, for determining the movement cost. As shown in Table 6, the total movement cost consists of the total human labour cost together with the total machine cost. Twelve (12) separate movements were observed to exist during the assembly processing of tables. The total movement cost for table assembly was estimated to be £80.33 per batch of 10. In a similar manner, storage and inventory cost was estimated for the queues as shown in Table 16. Equations describing how storage and inventory cost are estimated are shown in equations (7), (8) and (9).

Movement activities	**Movement times (t) min**	**Rate of pay, wages, salaries, r/min**	**Estimated percentage of salary for assigned task**	**Direct labour cost, Ld**	**Indirect labour cost, Li**	**Total labour cost, Lc**	**No of mac's, N**	**Unit usage cost, mr**	**Machine usage cost, Mu**	**Maintenance cost, m**	**Insurance cost**	**Total machine cost**	**Other cost (tools + depreciation)**	**Total movement cost**
From machine shop to assembly shop	10	0.2	4.90	2	4.90	6.90	1	0.033	0.33	0.014	0.01	0.36	0.024	7.28
Between EA4.1.3.2.1 and EA4.1.3.2.2	5	0.2	4.90	1	4.90	5.90	0	0	0.00	0.000	0.00	0.00	0.000	5.90
Between EA4.1.3.2.1 and EA4.1.3.2.5	7	0.2	4.90	1.4	4.90	6.30	0	0	0.00	0.000	0.00	0.00	0.000	6.30
Between EA4.1.3.2.1 and EA4.1.3.2.7	7	0.2	4.90	1.4	4.90	6.30	0	0	0.00	0.000	0.00	0.00	0.000	6.30
Between EA4.1.3.2.2 and EA4.1.3.2.3	15	0.2	4.90	3	4.90	7.90	0	0	0.00	0.000	0.00	0.00	0.000	7.90
Between EA4.1.3.2.3 and EA4.1.3.2.4	15	0.2	4.90	3	4.90	7.90	0	0	0.00	0.000	0.00	0.00	0.000	7.90
Between EA4.1.3.2.4 and EA4.1.3.2.6	5	0.2	4.90	1	4.90	5.90	0	0	0.00	0.000	0.00	0.00	0.000	5.90
Between EA4.1.3.2.5 and EA4.1.3.2.6	5	0.2	4.90	1	4.90	5.90	0	0	0.00	0.000	0.00	0.00	0.000	5.90
Between EA4.1.3.2.7 and EA4.1.3.2.8	5	0.2	4.90	1	4.90	5.90	0	0	0.00	0.000	0.00	0.00	0.000	5.90
Between EA4.1.3.2.8 and EA4.1.3.2.9	12	0.2	4.90	2.4	4.90	7.30	0	0	0.00	0.000	0.00	0.00	0.000	7.30
Between EA4.1.3.2.6 and EA4.1.3.2.9	12	0.2	4.90	2.4	4.90	7.30	0	0	0.00	0.000	0.00	0.00	0.000	7.30
Between EA4.1.3.2.9 and EA4.1.3.2.10	8	0.2	4.90	1.6	4.90	6.50	0	0	0.00	0.000	0.00	0.00	0.000	6.50
Total														**80.33**

Table 16: Estimation of movement costs

	Storage points	Storage times (t) min	Estimated percentage of salary for assigned task	Indirect labour cost, Li	Total labour cost, Lc	Manuf floor space (Ms)	Floor space cost per sq metre (fs)	Floor space cost (Cfs)= Ms x fs x t	Number of materials, nm	Unit cost of material, Cs	Inventory cost $C_i = n_m C_s t$	Storage cost, $S_{c=}$Cfs + Ci	Total storage cost
Q1	Queue before EA4.1.3.2.1	2880	4.90	4.90	4.90	1	0.05	0.05	5	0.01	144	144.05	148.95
Q2	Queue before EA4.1.3.2.2, 5 and 7	480	4.90	4.90	4.90	1	0.05	0.05	5	0.01	24	24.05	28.95
Q3	Queue before EA4.1.3.2.3	2400	4.90	4.90	4.90	1	0.05	0.05	1	0.01	24	24.05	28.95
Q4	Queue before EA4.1.3.2.4	480	4.90	4.90	4.90	1	0.05	0.05	1	0.01	4.8	4.85	9.75
Q5	Queue before EA4.1.3.2.6	480	4.90	4.90	4.90	1	0.05	0.05	2	0.01	9.6	9.65	14.55
Q6	Queue before EA4.1.3.2.8	480	4.90	4.90	4.90	1	0.05	0.05	1	0.01	4.8	4.85	9.75
Q7	Queue before EA4.1.3.2.9	1440	4.90	4.90	4.90	1	0.05	0.05	2	0.01	28.8	28.85	33.75

Q8	Queue before EA4.1.3.2.10	1440	4.90	4.90	4.90	1	0.05	0.05	1	0.01	14.4	14.45	19.35
	Total												**293.96**

Table 17: Estimation of storage cost

Following up on cost figures derived through use of the equations and the data representation into tables, it was deduced that because of the excessive delays and inventory times, the storage cost was £293.98 per batch of 10 whilst the operational cost per product was 184.899. The movement cost was also observed to be £80.33 for the batch processed. These figures show the need for reducing queue sizes and delays in Brad Ltd. Following up on figures derived from Tables 4-7, these cost figures were not obvious to the managers as they were not captured in their account sheets.. Estimating process cost in this manner further exposed hidden costs in process realizations and hence the need to improve processes for best reduced cost. Another observation was that in the conventional approach, storage cost generated as a result of delays, queue sizes and queue times are grossly underestimated. This is because without adopting the process based approach to cost engineering, it is fairly difficult to identify how queues are accumulated and stored between activity work centres. Further analysis show that movement costs were also critical. A study of the value stream model shows that the major wastes in the assembly process were due to storage and movements. It is therefore essential to specify the financial implications of these waste. It was understood from studying the value stream models of the different product types that significant differences existed in the activities making up their value streams, hence a top level estimation of percentages may not be very accurate and it was necessary to observe the processes as separate with different resource requirements. The managers of Brad Ltd agreed to these explanations and were particularly happy about the new understandings given to them related to the cost incurred as a result of the wasteful activities performed at the shop floor. Based on these, cost results derived from the process based approach were used as a benchmark for understanding process efficiencies in financial terms. This was achieved by comparing process costs with assembly process values. Table 18 shows that in the current assembly process configuration, Brad Ltd spends directly £184.99 to produce a type of table of value £80.00 and in the process generates a total waste of 374.31 per batch of 10. Similar results were obtained for the assembly of cabinets and drawers. Clearly it showed that the business was running at a lost and processes were inefficient. This was not obvious and could not be predicted by the company until probably the end of the accounting year. However, the value stream model assisted in bringing out the individual activities which contributed to these results, hence specific activities influencing the consumption of high cost can be improved where possible, to make Brad Ltd competitive.

Product type	Operation cost per unit	Value generated per unit by assembly shop	Cost of waste	
			Storage per batch	Movement per batch
Tables	184.90	80.00	293.98	80.33
Cabinets	204.55	199.00	310.00	100.00
Drawers	50.00	36.00	60.00	45.00

Table 18: Cost and value compared

5.6.3 Creation of dynamic value stream models

The foregoing sections have provided a contextual overview of process-related issues in the assembly section of Brad Ltd. The value stream models provided a graphical representation and also a simplified ‘point in time’ analysis of the different products which were assembled. Hence this model is termed ‘static value stream model’. With the help of the CIMOSA diagramming template, the complex network of processes, process segments, activities and their relatively enduring structural interdependencies were established. Further decomposition through the CIMOSA technique enabled detailed elemental analysis to be conducted in respect of multi activities which were performed. Also the new constructs introduced allowed materials and resource elements to be indicated on the model. Queue sizes and other process parameters were also indicated. More critically, process cost for the individual processes or activities is estimated and compared with values generated by the assembly shop. These process estimates supported the need to improve processes related to the assembling of specific products.

To help verify some of the assumptions underlining the static value stream models and also to experiment with alternative means of optimizing the assembly processes and performance of Brad Ltd, it was necessary to enhance the static models into states where virtual simulations can be performed. This was also necessary to help satisfy the requirements for multiproduct flow analysis. Also noted was the fact that to effectively investigate possible resource combinations in view of obtaining efficient resource outputs, it was necessary to experiment various combinations and process reorganizations and deduce which options would generate best results and hence help Brad Ltd remain competitive. The static value stream models provided insight on the current state of assembly processes in Brad Ltd but became limited when decisions about future organization of processes and resources for optimal performance was needed. Hence to reduce process lead times, inventory cost, process cost and improve values generated by the shop the decision to deploy process simulation tools was confirmed. A critical fact which was also observed was that although separate value stream maps were prepared to analysis process cost and values generated for different products, the real situation is that the realization of all these processes are through the application of common resources. Hence in the shop there were many instances of delays because resources were being shared. In addition to the resource sharing, in practice there were instances of material supply delays which affected production flows. But these scenarios were not possible to be displayed by the static value stream models generated. In addition multiple products (materials) are flowing through the assembly process and it is necessary to depict this scenario more accurately.

From literature analysis on process simulation modelling tools (see Section 3.4), it was evident that ‘Simul8’ offers enhanced capabilities for multiproduct flow modelling and complex manufacturing systems design, over its counterpart simulation software (iThink and Lean Modeller), which were reviewed. Hence because of its availability and technical support in MSI Research Institute, a decision was taken to use ‘Simul8’ to replicate and further understand process behaviours related to the ‘as-is’ static value stream model of the assembly shop. Following up on the interest of Brad Ltd, it was decided to also use this tool to help specify in detail what needed to be done to improve specific product realization processes in order to shorten their lead time. Other investment implications were also analysed through the application of the simulator to help Managers decide on possible improvements in resource usage. It was envisaged therefore that the tool would help analyse possible improvement opportunities for reducing process cost whilst improving product values.

Generally, Simul8 models are created using four main model building blocks: ‘work entry points’; ‘queues’; ‘work centres’ and ‘work exit’ points. Two other important elements are the ‘work items’ and ‘resources’. Many other process logic and flow indicators are used to mimic real process controls, operations and behaviours in a virtual environment. In addition to these modelling attributes, Simul8 is supported by Visual logic programming sequences so that complex process flows or logics especially related to multiproduct flows can be described fairly accurately. Functional matrices denoting how different cycle times are applied for different product types flowing through resource centres, called work centres, in Simul8, exist to support multiproduct flow analysis.

An initial Simul8 model created to represent the table assembly process is shown in the Simul8 screen shot of figure 34. This model was based on understandings gained about the job or product flow sequences in the assembly shop; with the underlining assumptions that materials and parts needed for assembly were already available at each work centre. Thus material flows were not major issues considered in this initial simulation model, which will be referred to as SM1.

To introduce dynamics due to multiproduct flows in the assembly section of Brad Ltd, two main table variants, Drop Leaf Table (DLT) and Farmhouse Table (FHT) were introduced into the assembly value stream model. This was an initial attempt to understand modelling implications and complexities associated with multiproduct flows. As shown in the screen shot of SM1, the work entry point consist of table components stored on racks and located within the assembly shop. The work items followed a queue to three identified workbenches which are for manual processing of the components. After being processed by any of the benches, DL tables follow the upper route through to the CNC Router, then to the Table Sander. DL tables then join the queue to the benches for further processing. After the processing work, they are routed to the vertical sander and finally come out through the work exit point.

FH tables however get routed through the benches and then to the vertical sander and then exit out of the system, as shown in 34.

Figure 34 Initial 'as-is' Simlu8 model SM1 used to represent and execute table assembly

The initial exercise was to verify if SM1 created adequately mimicked the process steps required to assemble tables. Although all the process stages were captured in the model, it was clear that because material inflows were overlooked during the model creation, essential process limitations and bottlenecks could be underestimated. Although the approach deployed was seen as common in many simulation modelling procedures, it was observed to depict an assumed underlining sequential product flow, which was not the case in the table assembly process. It thus ignored the process routes for the different components. Operating with this underlining assumption obviously is unsuitable for multiple process which either converge or diverge towards multiple assembly lines. Thus an alternative approach, relying on material flows through the different component process routes was used to represent the assembly processes of DLTs and FHTs. Therefore the model, SM2 shown in figure 35, was created which models flows of three different material types. These material flows enter the model with different arrival times. As shown in figure 35, and depicted in the static value stream model for the assembly of tables, components were grouped into three separate 'part families', namely: table tops, under frames and legs. As already depicted by the static value stream model, the table tops are routed to the CNC router whilst the under frames undergo bench operations through a different route. The legs are also sanded and some bench works, such as drilling and turning are done on them via a separate route.

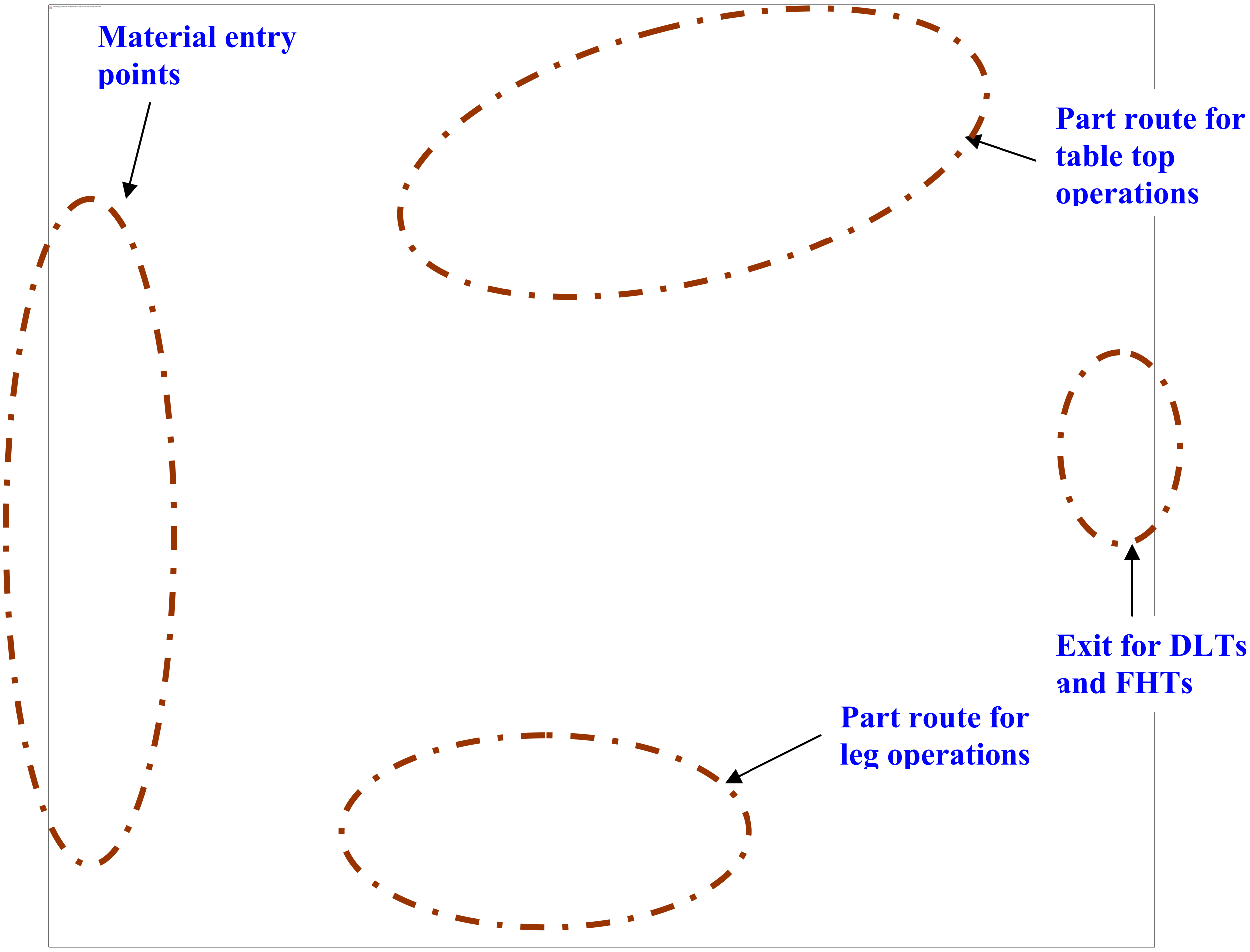


Figure 35: 'As-is' Simul8 table assembly model SM2, based on a material flow approach

To ensure accurate flow of work in the simulation model, numeric labels were assigned to the different work items (table tops, under frames and legs). The work items were designed to change their appearance in the model, as they move from one work centre to the other so that they can be traced through the simulation. For example, based on the labels assigned, on bench 2 (see figure 35) table tops and under frames are assembled together to form one sub assembly with a unique appearance. This made it possible for only two different work items, legs and top-under frame sub assemblies, to enter the spray shop. To show how different material types are required for assembly purposes, two queues were shown to exist before the assembly station (denoted as bench finish in figure 35). This enabled the two material types to enter the bench finish work centre at different times and thus delays in any of the materials could be visualized. At the work exit point, two different table flows were designed to come out of the simulation model based on the overall process lead times.

The material flow value stream modelling approach initially studied by creating SM2 was used to develop other separate models for drawer and cabinet assembly as depicted by their activity diagrams. Snap shots of these models, SM3 and SM4 are shown in figures 36 and 37.

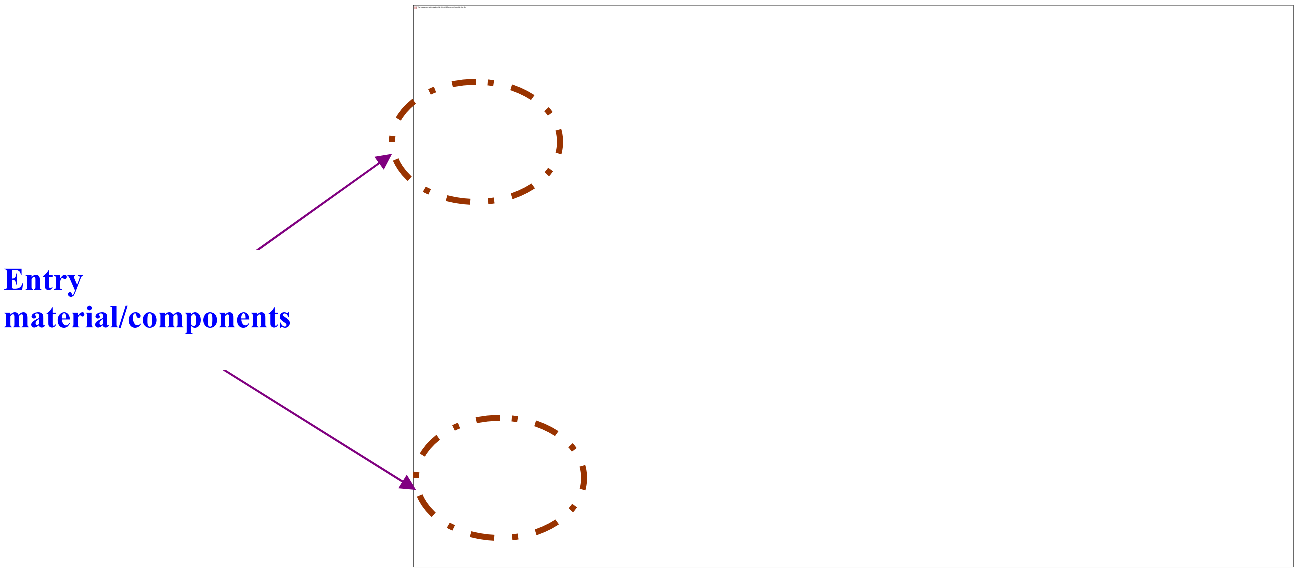


Figure 36: As-is Simul8 model SM3 for drawer assembly

In SM4 (see figure 37), process routes and logics for the assembly of four different cabinets types have been shown. The entry point also shows different material or component inputs required for the assembly of the different cabinet types.

Figure 37: As-is Simul8 model SM4 for cabinet assembly (4 different types)

Considering the time frame allocated to the case study and available company resources, a decision was taken to conduct further analysis and improvements on areas related to table assembly. This decision was also supported by the fact that managers of the company felt that a higher percentage of their business operations were concentrated on the provisions of tables to their stockists. Thus the creation of the various models for the other products assembled was considered a necessary learning process in the use of various modelling methodologies. The next stage therefore was narrowed down to verify and apply dynamic models of table assembly to support decisions of process redesign and optimization, in view of the original objectives.

5.6.3.1 Testing, validation and sample results from simulation models

To help verify the models SM1 to SM4 created, efforts were made to observe how the structures of the model reflected the reality. This was done through studying the already created static value stream models and asking the managers of the shop to help verify if the model structure fairly represented the processes under consideration. It was agreed by the Managers of Brad Ltd that models developed based on the material flow approach best described the case study assembly operations. To validate the process logics and controls of the simulation models, actual historic data in the form of production orders, inter-arrival times, order batch sizes, operation times and resources deployed, were inputted into the models. When the data set was inputted into the model, the average throughput which is represented by the number of products that came out of work exit points of SM2 was observed to be 25 which represented approximately the real life situation. Other metrics such as make span, queue times and sizes were found to conform to real life situations and hence the model was found to be sufficiently valid to use for further experimentation.

Following the validation, tests were conducted to understand in detail the ‘as-is’ behaviour of the assembly section and to recommend ‘to-be’ models based on improved process costs, values and efficiencies. Five trial runs were conducted to see the effect of SM2 model behaviour on processing times, queue times and overall assembly time. The results generated were exported to MS Excel. Sample results of throughput for the five test runs are depicted by Table 19 and figure 38.

Performance Measure	Run 1	2	3	4	5	-95%	Average	95%
Number Completed	24.0	26.0	28.0	24.0	24.0	23.0	25.2	27.4

Table 19 Quantity completed for 5 test runs

Figure 38 Results from the work exit point of SM2

During the five test runs, results from the storage area of the CNC router are as shown in Table 20 and figure 39.

Performance Measure	Run 1	2	3	4	5	-95%	Average	95%
Average Queuing Time	3275.9	3428.9	1821.1	3159.5	3180.7	2162.8	2973.2	3783.6

Table 20: SM2 results from the storage area of CNC router

Figure 39: Average queue time for CNC router in SM2

The queue before the work bench for assembling under frame to table tops is as shown in Table 21 and figure 40.

Performance Measure	Run 1	2	3	4	5	-95%	Average	95%
Average Queuing Time	3057.9	2961.7	2822.1	2974.2	3638.1	2696.7	3090.8	3484.9

Table 21 SM2 queuing time for assembling under frames and table top

Figure 40 SM2 queue times for assembling under frames to table tops

The queue to the spray shop also showed some significant results as shown below in Table 22 and figure 41

Performance Measure	Run 1	2	3	4	5	-95%	Average	95%
Average Queuing Time	23.3	27.2	42.6	23.3	53.2	17.3	33.9	50.6

Table 22 SM2 Average queue time to spray shop

Figure 41 SM2 queue to spray shop

The Simul8 software further gave indications of the total process costs and values generated by the realization of tables. This is shown in the assembly process financial statement shown by Table 23.

Simulation Object	Performance Measure	Run 1	2	3	4	5	Average
Simulation Total	Total Costs on Income Statement	277,030.00	278,496.10	274,709.40	276,195.10	280,353.20	277,356.80
Simulation Total	Total Revenue on Income Statement	281,787.50	281,936.50	282,085.40	281,787.50	281,787.50	281,876.90
Simulation Total	Total Profit on Income Statement	4,757.50	3,440.40	7,376.10	5,592.40	1,434.30	4,520.10

Table 23 Cost and value estimates for ‘as-is’ model

5.6.3.2 Analysis of results from SM2

From the sample results displayed in section 5.6.3.1, it can be seen that the average queue time for the CNC operations over the 5 runs was 2973.2, which is equivalent to a lead time of 6 days as depicted by the static value stream analysis. The delay caused by the CNC operation tended to delay all the other downstream processes. For example, the further delays at the under frame and table top sub-assembling point was as a result of the delay in processing of the table tops by the CNC router which was physically separately located in the machine shop. These delays were caused by the increase in production orders which necessitated the use of the CNC router for other machining applications. Thus it was concluded that the major constraint in the assembly process of the case study company is that of CNC operations on table tops.

Also from figure 40, the highest output was realized during the third run. Another observation was that the shortest queuing time was recorded during the third run. Therefore linking the output of the third run to the queue time at the CNC router, it can be deduced that the highest output was generated when the system observed the shortest queue time at the CNC router station. It was therefore concluded that to reduce the inventory sizes and delays which was leading to longer delivery times and hence high inventory cost, there was the need to investigate possible improvement solutions that can be offered to the CNC operations. With this objective in mind, a number of change variables was conceived and use to conduct experiments which would enable creation of future or 'to-be' models of the assembly shop. In conceiving the possible changes to be effected to achieve optimal operational results in the assembly process of Brad Ltd, selected process variables or elements belonging to broad change classes (Weston 1999) of:

- Process change – (such as process instances, process logic, flow controls and the required roles and relationships);
- Product change – (such as product properties, product mix, product volumes, material availability);
- People (and related mechanical resource) change – (such as resource availabilities, resource competencies and capacities, resource controls and resource organisation) were used.

The selection of these classes of process change variables was based on the assumption that in general selected process variables (or elements) belonging to any of the above classes can be used as control levers that effect other process variables (or elements) so as to make required improvements to the process results. In a more practical way, the extent to which changes can be made are constrained by the circumstances and environments surrounding the processes under consideration.

5.6.3.2.1 Experimenting changes in variables in view of the derivation of enhanced 'to-be' models

With the view of meeting the need for alternative ‘to-be’ models that can support the attainment of better process cost, lead time and value streams, a set of change variables were selected to help specify the needed changes and organizations from a virtual modelling environment. This was necessary to depict quantitatively the benefits that could be derived from alternative investment and possible process redesign scenarios.

From studying the results generated by the ‘as-is’ dynamic value stream model, it was deduced that changing the ‘rate at which materials’ (product change) were introduced to some of the work stations was necessary. For example, long queues were experienced at the ‘bench finish work centre’ because table legs had to be in a queue until the table top sub assemblies were ready. The limitation placed on the table top sub assembly was the delay caused by the CNC operations in the machine shop. Changing the material flow rate required that the rate of flow of leg components at the legs work entry point would be altered and introduced at intervals matching the pace of the CNC machining operations. This was to help reduce the high inventory and delays in the system. Table 24 shows the significant process improvement that can be obtained by reducing the rate at which leg components were introduced in the assembly shop. These improvements were obtained without however affecting the total production lead times. These improvements are shown as reduced inventory or queue sizes and hence reduced inventory cost. An approximate inventory reduction of 87.94% was observed.

Simulation Object	**Performance Measure**	**Run 1**	**2**	**3**	**4**	**5**	**Average**	**Process improvement (Inventory reduction)**
Q bench finish 2 'as-is'	**Average queue size**	18.0	22.6	16.4	16.4	26.2	19.9	**87.94%**
Inventory cost: ‘as is’		**0.3**	**0.4**	**0.3**	**0.3**	**0.4**	**0.3**	
Q bench finish 2 'to-be'	**Average queue size**	2.5	3.0	0.1	0.0	6.5	2.4	
Inventory cost: ‘to-be’		**0.0**	**0.1**	**0.0**	**0.0**	**0.1**	**0.0**	

Table 24 SM2 results-Inventory reduction at queue for bench finish work centre

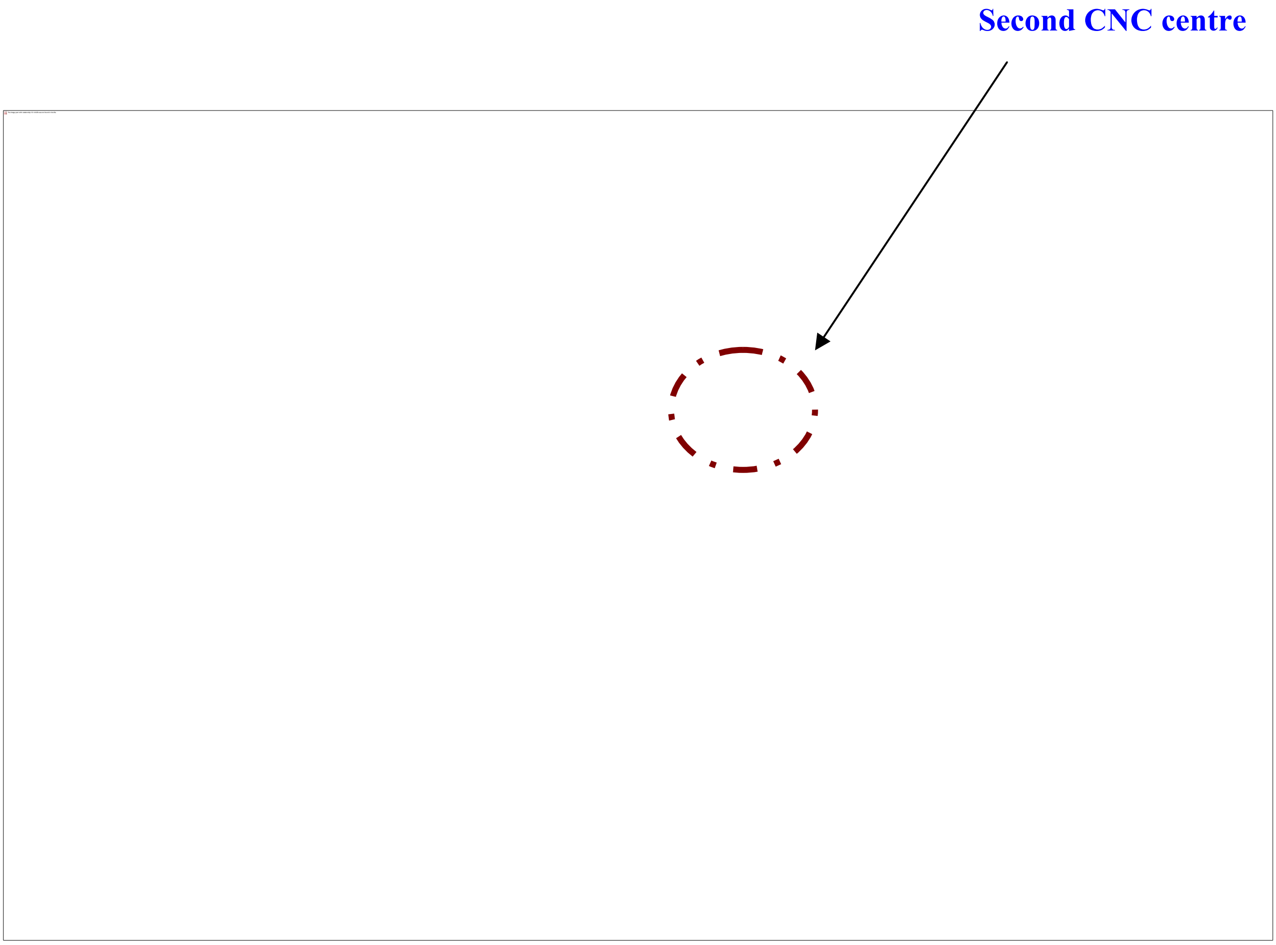
Another key parameter which was identified as being critical to improving the process was that of reducing the rate of entry of table tops at the CNC router. When the rate of flow of table tops to the CNC router was reduced, the queue to the CNC work centre was significantly reduced without affecting the total quantities assembled. This directly had positive influence on the inventory cost of the company. Hence process cost was significantly reduced as compared to the 'as-is' situation. Results shown in Table 25, show how absolutely queues can be reduced by regulating the inflow of jobs (table tops) to the CNC work centre.

Simulation Object	Performance Measure	Run 1	2	3	4	5	Average	Process improvement (Inventory time reduction)
Queue for CNC router: 'as-is'	**Average queue size: 'as-is'**	3275.9	3428.9	1821.1	3159.5	3180.7	2973.2	**99.8%**
Queue for CNC router: 'to-be'	**Average queue size: 'to-be'**	6.2	10.1	0.6	6.5	8.4	6.3	

Table 25: SM2 results-Inventory time reduction at queue for CNC router

Despite these significant improvements, it was observed that there was still long lead times and queues prior to the assembly of under frame parts to top sub assemblies. Therefore a third experimental variable considered was a 'mechanical resource change' which involved the introduction of a second CNC machine located physically in the assembly shop with the view to further reducing the overall process lead time and queues accrued prior to the assembly of under frames to top sub assemblies and further to avoid the time consuming trips to and from the machine shop during the assembly of tables. Figure 42 shows a screen dump of the dynamic value stream model SM5, which is a modified version of SM2, with a second CNC router included.

Introducing a second CNC router into SM2 provided a number of useful results which was discussed with the Managers of Brad Ltd.



Second CNC centre

Figure 42: SM5 model showing two CNC machines in operation

As shown in the results table (Table 26), the minimum queue size in SM5 is 1 whilst the maximum queue size is 13. The maximum queue size is obtained at the queue centre for the finish work centre. This work centre is the final work centre before the finished products are packaged and delivered. Thus it was deemed good to at least have 13 pieces of nearly finished products. Also noted in the results was that the longest average queue time in SM5 was 1368.114 minutes which is equivalent to 2.85 (3)working days. This time was recorded again in the queue next to the finishing table. Again the managers were convinced this delay was acceptable considering the business domain of Brad Ltd.

Table 26: SM5 results: improved inventories

A forth parametric change related to human resource assignments to units of work. This parameter was analysed to determine potential benefits that alternative work assignments might bring to Brad Ltd. The first situation trialled was to change the work load and the nature of work done. Extra work loads were added, because a study of the resource utilization results shown in Table 27 depicted that human resources, especially Table makers 1 and 2 at the bench sections were grossly underutilised. Percentage utilizations were 6.988% and 6.887% respectively.

Table 27: SM5 results for human resource utilization

Based on this observation it was also decided to maximize work in the model. The results proved worthwhile. The average resource utilization for SM5 rose from 62.08% to 72%, whilst the output showed a gradual increase as depicted in figure 43. It follows that by systematically increasing the work load, a corresponding output can be expected.

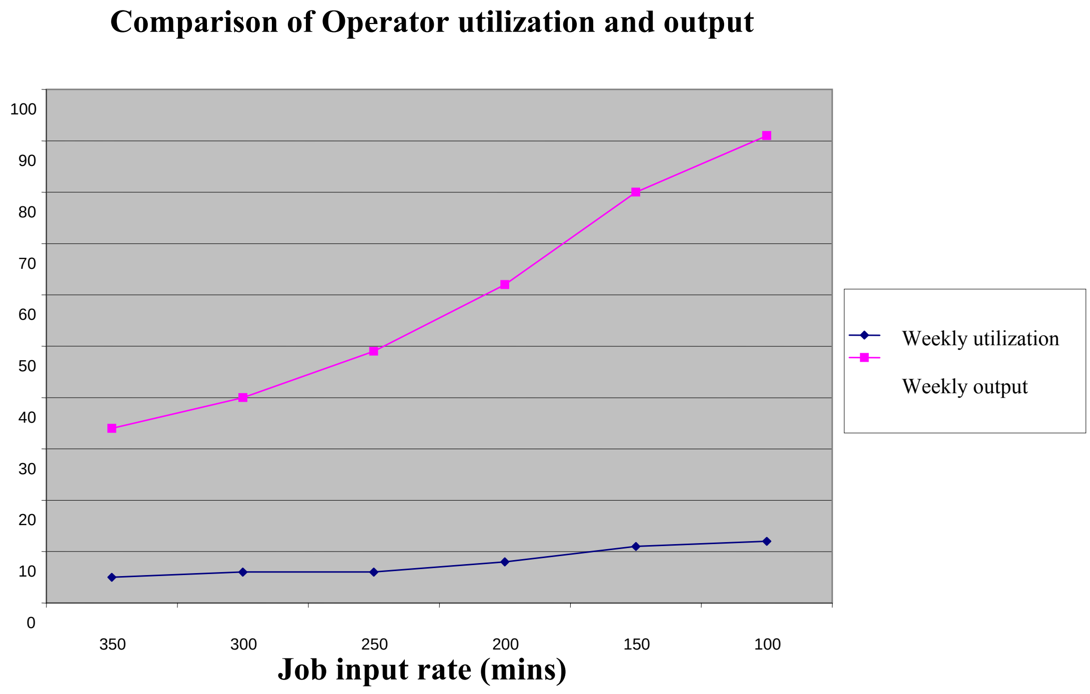


Figure 43 – Graphical comparison of operator utilisation and outputs

Based on the above four experiments, it was appropriate to specify a 'to-be' model which can deliver enhanced process benefits, reduced inventory sizes and times, increased value and reduced process cost. A snap shot of the derived 'to-be' model, SM6 based on the factors specified, is shown in figure 44. In deriving the to-be model, four main changes were enacted. These changes related to reducing the rate at which legs were introduced to the benches, reducing the material inflow rate of table tops at the CNC work centre, increasing their mechanical resources by introducing an extra CNC machine and finally reorganizing the operators. The results derived from implementing these changes in the model proved worthwhile. As shown in the to-be model SM6 (see screen shot in figure 44), the implementation of the changes mentioned, resulted in significant reduction of queue times. Typical examples are the 87.94% and 99.8% reductions in queue time at the 'bench finish' and CNC router storage bins respectively. Also the largest queue size reduced to 13 and the longest delay was reduced to 3 days (see Table 26). On average no queues were observed at the CNC router work station (see Table 25). The delay recognized in the to-be model was observed to be at the 'bench finish' work centre, which practically was acceptable by the Managers of Brad Ltd due to the nature of their business.

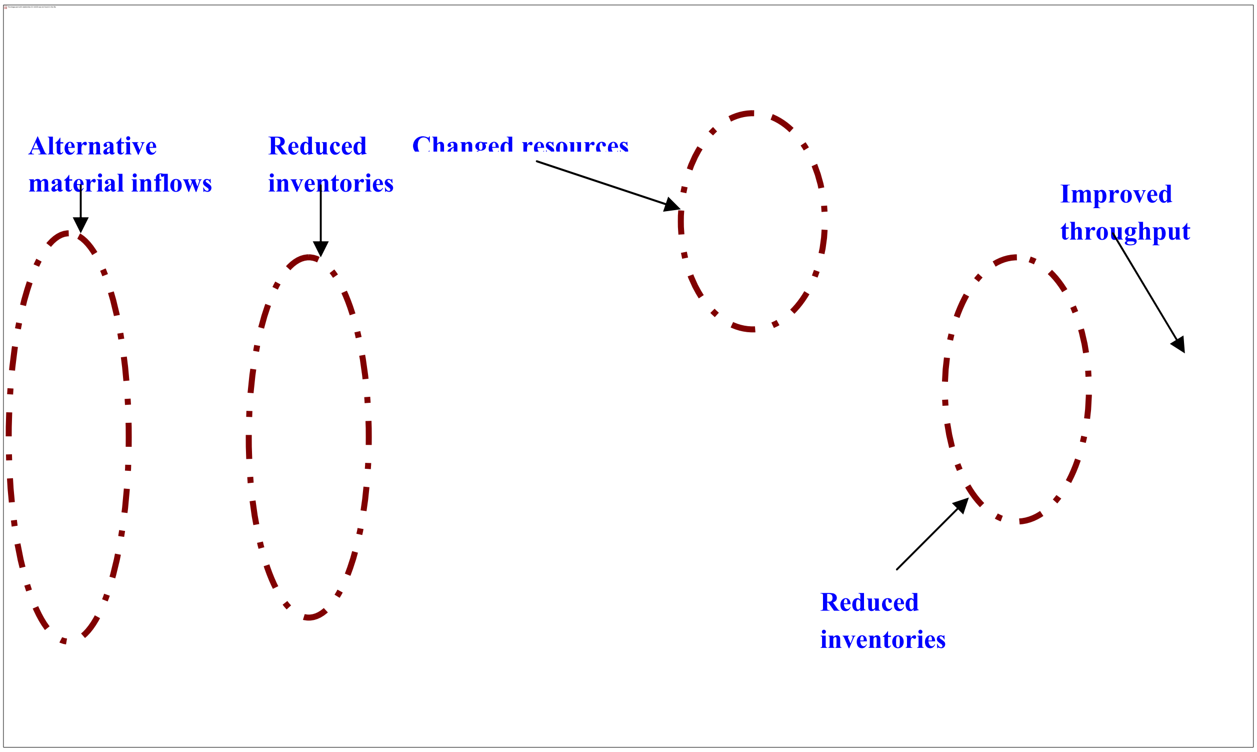


Figure 44: To be model SM6

Also observed in the results provided by the to-be model SM6 was a significant improvement in resource utilization. Typical resource improvements were observed to rise from 62.08% to 72%. Further to the above results, financial benefits taking into account usage cost of the newly introduced CNC router were derived from the to-be model SM6 and shown in Table 28.

Simulation Object	Performance Measure	Run 1	2	3	4	5	Average	Estimated increase in value (compared with results shown in Table 11)
Simulation Total	Total Costs on Income Statement	266	267	267	266	267	266	69.87%
Simulation Total	Total Revenue on Income Statement	282	282	281	282	282	282	
Simulation Total	Total Profit on Income Statement	16	15	14	15	15	16	

Table 28: Financial report of SM6 'to-be' model (figures in '000)

Comparing the financial figures quoted in Table 28 with the financial figures obtained by running the as-is model (Table 23), it can be noted that an average estimated value increase of 69.87% can be obtained through the realization of the assembly shop configuration described by SM6, the to-be model.

5.7 Observations about modelling technique and Brad Ltd improvements

Previous sections of this chapter have illustrated how the current value stream methodology can be enhanced through a coherent and systematic application of enterprise and simulation modelling techniques. This led to the derivation of an alternative method for capturing 'as-is' value stream models of Brad Ltd and based on controlled and selected experiments, the identification and creation of 'to-be' value stream models of better process costs, values, lead times and inventories were realized. This led to the observation of possible process improvement benefits for Brad Ltd. The following sections show the observations and understanding derived through the modelling exercise. The second part of this section shows how Brad Ltd could benefit from the implementation of the to-be models.

5.7.1 Observations about modelling technique

Throughout the study, it was observed that the lean based value stream mapping technique was most suitable for single flow manufacturing systems. It became limited in its application in multiple processes especially those observed to possess multiple numbers of diverging or converging processes. Also because of its oversimplification nature, process decompositions were not thoroughly achieved and this led to the underestimation of process delays and total lead times. A need to enhance the lean based value stream mapping technique as specified in the initial research aims related to this case study, was confirmed.

The introduction of the enterprise based value stream models as well as process based cost and value estimations provided a number of benefits. They ensured that systems were decomposed in a way that semantic rich and coherent understandings about relatively enduring aspects of the enterprise was achieved. Typically the CIMOSA templates and modelling constructs aided the value stream mapping technique by providing an effective and reusable way of decomposing complete networks of enterprise functionalities into process segments of some level of abstraction. The enterprise based value stream models technique provided an integrated view forming the basis of knowledge sharing about the ME and its environment which informed decision making about process improvement, process cost, values, resource allocation, evaluation of manufacturing lead time, total system output and inventories, change and so forth.

The newly introduced constructs for process cost, queue sizes and times, resource types and the combination of lean based value stream and CIMOSA constructs offered a comprehensive process description of the case company. Further to this a method was developed to help estimate process cost and values generated by the assembly shop. The representation of process cost on the value stream model ensured that process elements impacting on cost were quantified financially. Cost information were embedded on the value stream models to visually demonstrate how cost was generated along process segments. In effect cost is represented as a ‘flow’ from one activity to the other.

Based on the above observations, it is deduced that for most MEs deploying multi-product flows in a dynamic market, it is more appropriate for their systems to be modelled comprehensively by the enterprise modelling approach and analysed through the application of the process based cost and value stream technique specified in this chapter. Otherwise the tendency of overlooking important process segments during mapping could be high. Also other wastes in the process can be ignored and not quantified. Thus the application of the enterprise based value stream modelling technique can ensure better process design and planning.

Despite the benefits in the proposed method, it was observed that there was the need for adequate data collection and thorough understanding of the processes being modelled. The close collaboration of the author and the staff of Brad Ltd was necessary for the successful data collection, validation and results analysis. However it was also realised during the modelling exercise that, it takes a relatively long time to 1) capture information from case study companies, 2) populate the modelling templates, 3) validate and finalise the modelling templates, before a comprehensive enterprise model can be accepted and used for deriving static value stream models. In the case where enterprise models have been developed already, the compounded problem of working with a wrong or doubtful model is also real. The challenge of creating a valid enterprise model of a given process segment under consideration is real and measures must be taken to ensure that models which serve as backbones for dynamic models are accurate, else the disaster of working and proposing conclusions based on inaccurate models cannot be avoided. Furthermore, although the benefits of the static value stream model cannot be doubted, it was also observed that it could not be used to mimic or predict relative ME behaviours, especially related to change. Notwithstanding, the static value stream models gave a solid foundation upon which the simulation models were generated.

The dynamic value stream model enabled management decisions related to possible process improvements to be tested in a virtual world before their implementation. These decisions invariably affected process designs which in turn impacted significantly on the output, timeliness, process cost, inventories and values generated.

Critically observing the modelling methodology described in this chapter, it can be observed that not all the stages of the modelling method specified in chapter 4 was applied. In addition to that, product variances were simplified and in the dynamic value stream model only analysis related to one product class, tables, was performed. This was not the initial understanding about the application of the modelling methodology, but as explained previously, the simplification of product variance was to help develop and limit the complexities that can be observed in real life multiproduct systems. Although this assumption helped to simplify the models created, it will be required that more realistic approach which illustrates the dynamics associated with multiproduct flows be incorporated. Also elements of system dynamics were not utilized in the aspect of the modelling techniques described by this Chapter. This is based on the fact that case study 1 did not require indepth analysis of process dynamics. Chapter 6 attempts to describe how system dynamics was used to capture process elements impacting on cost and values observed in the second case study.

5.7.2 Observations about improvements in Brad Ltd processes

To encourage the support of Brad Ltd, it was necessary to structure the outcomes of the case study such that results generated could be usefully applied in Brad Ltd to enable them improve upon their processes and become more competitive. This meant using the developed method to: 1) help reduce the current inventory sizes and inventory cost 2) support analysis of investment options and helping predict suitable combinations of resources for optimal performances and 3) improving manufacturing process lead times.

A critical assessment of results derived from the dynamic value stream model enabled prediction and verification of current bottleneck activities. This concerned operations at which delays caused longest queue times. Delays at bottleneck operations subsequently affected the total processing time of the complete process. These bottleneck activities included the CNC machining operation and the assembly of legs to table tops. Coherently, when the rate of flow of product components was altered, it was observed that significant improvements were realised, predicting the fact that alternative arrangements of the flow of product can affect the ultimate fulfilment of the product or customer order, avoiding excessive delays and inventory accumulation. Example inventory reductions amounted to 87.94% and 99.8% process improvements. This led to the queue at the CNC operation being drastically reduced without affecting the output quantities. The experiments described in Section 5.6.3.2.1 showed how inventory sizes and cost were reduced through experimental and controlled changes due to varying material inflows, people resource changes and related mechanical resource change. Investigating alternative investment options and possible resource combinations, showed that the introduction of a second CNC router could possibly improve overall process lead times and cause an overall value addition of 69.87%. Results from the influence of the planned ME changes in view of ensuring better process efficiencies ensured that in the to-be value stream model, human resource utilization rose from 62.08% to 72%, whilst total inventory cost was reduced by 30%.

Discussing the outcome of the experiments and hence possible to-be scenarios with the Managers, it became evident that the models enabled them to better understand their processes and the possible effects of activities on cost and value generation. Although they were prepared to implement the to-be model, it was explained to them that in the real situation a number of factors will have to be considered. Also detailed cost-benefit analysis was required before the introduction of a second CNC router at the assembly shop. It was however easier to implement the alternative flow of materials to their work centres since essentially the alternative flow of material affected how jobs were scheduled.

In summary, the lean based value stream mapping technique can be enhanced based on the methods described in this chapter, to support alternative business analysis related to process improvements, higher value generation and low process costs, especially for multiproduct flow manufacturing systems.

6. Case 2 application of the proposed modelling methodology

6.1 Introduction

To help verify the applicability of the proposed multiproduct dynamic cost and value stream modelling technique, the technique was initially applied in Brad Ltd, a make-to-order furniture manufacturing company located in the East Midlands of the United Kingdom. A description of this first case study was provided in chapter 5. The objective behind the first case study was to exemplify and exercise the need for an enhanced modelling technique with potential to support management decision making through the capture and use of information related to cost and values generated along manufacturing process segments. This was to begin to show how perceived wider industrial requirements for multiproduct flow value stream modelling (as specified in section 3.3) can be satisfied via a methodological use of state of the art modelling technologies. In addition, there was an observed need to address specific problems which were eminent in the case company production system. Chapter 5 therefore provided an insight into the synergistic application of VSM, CIMOSA and Simul8 modelling techniques, which showed promise to support the development of key process improvement solutions.

In this chapter, the proposed methodology is extended and reapplied in a new case company. It was envisaged that after the creation of an enterprise model of the new case company, process variables inducing dynamics which impact on cost and values can be modelled and their effect captured and controlled to ensure improved process behaviours and performance. Therefore to more extensively test the modelling approach and particularly its dynamic systems modelling capabilities, a second case study was conceived and centred on a make-to-order bearing manufacturing company located in Yorkshire, UK.

Referring to the literature analysis presented in Chapter 2, it can be deduced that systems dynamics modelling techniques in the form of causal loops and iThink continuous event simulation tools render useful means of capturing and modelling aspects of process dynamics. What was not clear from literature was how these methods could be applied in detailed manufacturing process modelling exercises as well as when utilizing and deriving cost and value information through use of these techniques. Also realized was that there were no clear transformation mechanisms between the two techniques and most literature presented them as separate tools with distinct applications. Where a link between CLM and iThink was provided, the transformation mechanism consisted of complex mathematics. Thus any combined application was limited to the expert systems modeller who often lived outside the domain of manufacturing operations. In effect although these techniques have had extensive applications in policy and economic analysis, their applications are limited in

manufacturing industries. To fulfil the requirements of the proposed modelling methodology specified in chapter 4, a second case study was conducted to assess the possibility of:
1) modelling system dynamics and complexities; 2) transforming CLMs to iThink; 3) modelling cost and value dynamics.

6.2 Background to second case study company

The second case study company, referred to as ACAM Ltd, is a small to medium sized bearing manufacturing company located in the United Kingdom. In Shin Won, South Korea, company and has developed a similar bearing production facility that has been sited to meet the market demands of Asia. ACAM Ltd makes to order a range of advanced composites bearings. These products are normally fibre reinforced plastic laminates, ideally suited to highly loaded bearing applications in agricultural, marine, mechanical, pharmaceutical and food processing environments. In addition to producing customised bearings and specialized structural bearings, washers, wear rings, wear pads, wear strips, rollers, and bushes, ACAM Ltd also produces semi-finished bearing materials which are made available in tube and sheet forms.

ACAM Ltd has progressively increased its production volumes and product types in the past two years and its success is attributed to the company's culture of continuous improvement and innovative management strategies. Another acclaimed reason is their ability to compete based on shorter customer lead times. Currently whilst the company's competitors are operating at a customer lead time of eight to nine weeks, the company has progressively reduced its lead time from eight weeks to four weeks by increasing their mechanical resources whilst reorganizing their work patterns. Also as a strategy to boost employee morale, the management of the company makes discretionary payments to top performing workers, pays end of year bonuses and contributes 3% towards a staff' pension scheme.

6.3 Description of the production system of ACAM Ltd

Initiation of the manufacturing processes of the company follows the reception of customer order by the Technical division. These orders are received mainly through e-faxes (45%) and emails (45%). Only a few orders are received through the post (9%) and telephone (1%). The Technical division of ACAM Ltd processes the customer orders and releases them as works orders to the raw material processing shop floor in the form of job-cards as shown in figure 45. Approximately orders spend 24 to 48 hours in the Technical Office, whilst the team creates working drawings, process plans and job-cards. At the raw material processing shop, based on the job order, different combinations of resins and colours are mixed and applied on different materials to determine the shape and thickness of the product. Basically all products come out of the raw material processing section in the form of flat or round products depending on their customer specified geometry. Flat products are then sanded and machined to achieve flat sheets or strips (depending on the width of the product). On the other hand round products are routed to the machine shop for further machining activities. Typically in the raw material shop, for a flat sheet product, after a job card is received, the operator picks the specified cloth on the job card and sets up the bath for the flat sheets. The operator then sets up the laminate table as well as the mandrel. The chemicals required for the job as specified on the job card is collected, measured and mixed together where necessary. At the next stage of the process, the cloth is wrapped on the mandrel and sent to the Laminate Table. The laminated sheets are then cut to size and the required number of laminates press heated. Product output from the press becomes the required flat sheet.

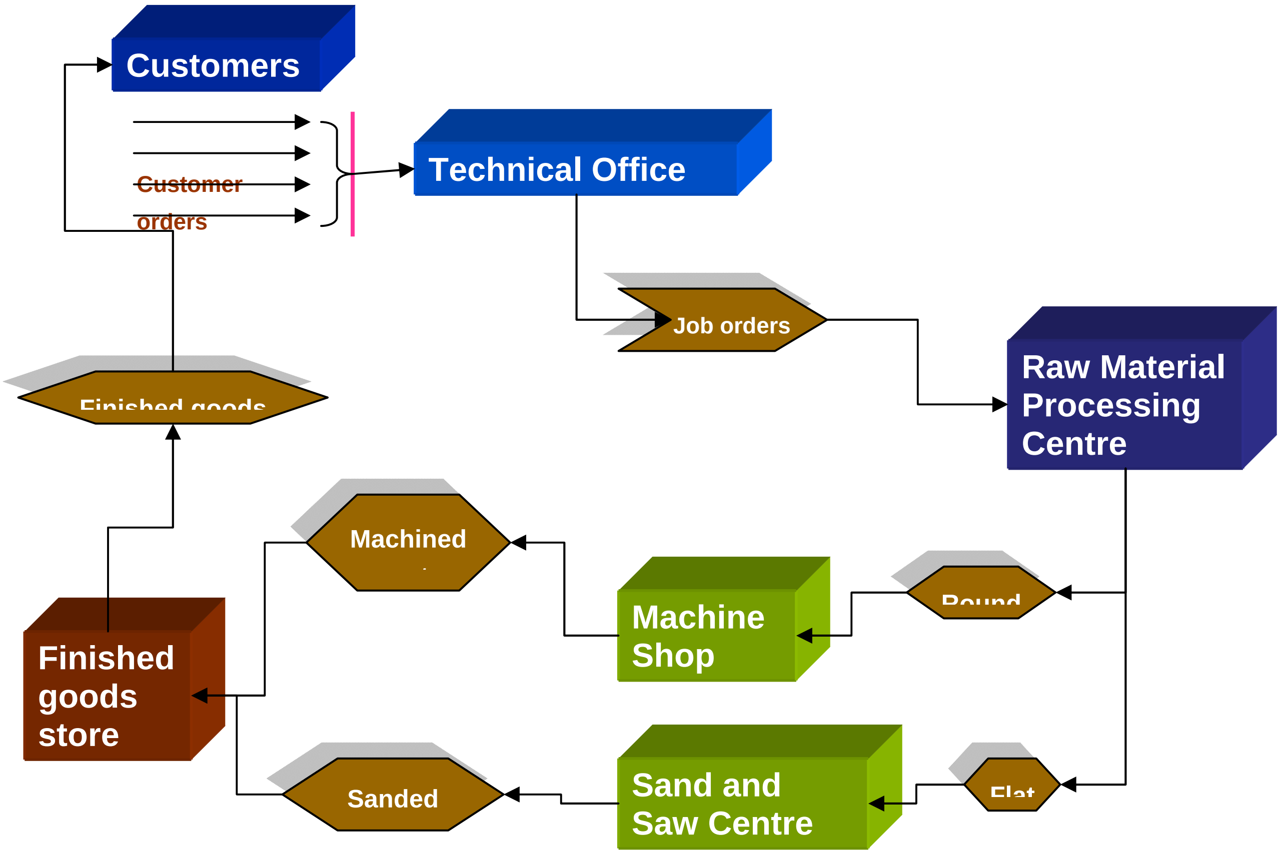


Figure 45: Schematic diagram of production process

6.4 Modelling of dynamics impacting on cost and value streams

To help exemplify the application of aspects of the proposed multiproduct flow dynamic cost and value stream modelling technique, efforts were initially concentrated on understanding the processes that existed in ACAM Ltd. This desire led to the application of the CIMOSA enterprise modelling templates which ensured that thorough decomposition of the processes was achieved, whilst externalizing deeper understanding of the process domains, attributes, roles and resource requirements. Another benefit derived was an understanding and structured description of the interactions that existed between business processes and their resultant activities. It was assumed at this point that as a result of the interaction between processes, changes related to any process will trigger effects on other processes which are causally related hence producing ‘chains of reactions’ in the ME. It was therefore considered important to reuse the CIMOSA interaction diagrams, to build system dynamics models which usefully capture dynamic behaviours resulting from these cause and effect relationships. In addition to the internal factors such as machine breakdowns, human resource unavailability and incompetence, material shortage, improper product and resource routings, there are other external factors which impact on ME operations. This is deemed to consist of factors such as changes in machine and computer technologies, environmental and social constraints, legal and changing customer requirements. As would be expected, these external and internal factors impact on the operations and thus processes of the ME therefore having implication on the cost and value generation in the respective ME. Also assumed is that because both the internal and external changes can be random and uncontrolled, complex dynamic behaviours can occur along process threads based on the relatively minor change in the transient operational state of factors mat causally influencing other ‘process states’.

As a way of illustrating how the proposed methodology can be enacted, in order to help manage complexity and dynamic behaviours as well as their impacts on cost and value generation, a five staged modelling approach was enacted. This involved creating enterprise models and embellishing them with causal loop models. Therefore causal loop models are enhanced to form what is termed ‘structured causal loop models’ which are then transformed into ‘stock and flow’ models. Finally they are transferred into iThink models. Subsequent section of this chapter show how these modelling stages were achieved.

6.4.1 Creation of the CIMOSA Enterprise model of ACAM Ltd

Initial steps taken to realise the stated objectives involved the creation of a ‘static’ enterprise model that capture relatively enduring aspects of the processes and systems used by the Bearing Manufacturing Company. Experience in enterprise modelling derived from the first case study showed that the CIMOSA modelling constructs and representational formalisms were capable of decomposing complex systems into sub systems that can be analysed independently.

On the resumption of the modelling exercise, a series of structured and unstructured interviews and shop floor visits were conducted to enable better understanding of ACAM Ltd processes. In addition to these data and information gathering exercises, company production data, human resource organization charts, sales and finance data were also examined. Initial understandings of the company processes were documented and described in the form of a spreadsheet, as shown in Table 29. The table shows the initially identified Enterprise Domains.

Bearing Manufacturing Company
Derivation of Enterprise Domains (DMs) based on domain objectives and associated distinct processes

Main domain of interest: Make bearings to order

No.	Enterprise domains (DM)	Domain objectives	Main domain process (DP)	Business Processes (BPs)	Sub Business Processes (BPs)	Comments
1	**Customers**	To provide orders to company, receive products in time and make payments of goods received	Provide orders	**No further decomposition**	**No further decompositions**	Non-CIMOSA domain
2	**Raw material suppliers**	To receive orders from Company and supply materials in time	Supply raw materials	**No further decomposition**	**No further decompositions**	Non-CIMOSA domain
3	**Front end business domain**	To obtain customer orders, design, plan and schedule production	Realize front end operations	1. Obtain and process customer order	1. Obtain customer orders	CIMOSA domain
					2. Create job card	
					3. Interact with internal business	
				2. Produce designs	1. Develop initial draft designs	
					2. Amend designs	
					3. Develop BOMs	
				3. Plan and schedule production	1. Generate production schedules	
					2. Amend and distribute PS	
4	**Produce and deliver products domain**	To produce various components, pack and coordinate the delivery of finished products to customers	Produce and deliver bearings	1. Produce bearings	1. Produce raw materials	CIMOSA domain
					2. Process Flat products	
					3. Produce strips	
					4. Machine Round products	
				2. Pack finished products	1. Create pack list & delivery note	
					2. Actual packing process	
				3. Despatch	1. Arrange for transport	
					2. Loading process	

5	**Business Management domain**	Manage obtain order, order fulfilment and support processes	Manage business	1. Manage demand uncertainties	1. Long/medium term forecasting	CIMOSA domain
					2. Long term/medium term capacity planning	
				2. Manage human resources	1. Recruitment process	
					2. Train staff	
					3. Reduncdancy process	
					4. Appraise staff	
				3. Control quality	1. Inspect incoming items	
					2. Inspect in-process items	
					3. Inspect finished products	
					4. Generate non-conformance report	
				4. Manage finance	1. Prepare invoice	
					2. Estimate product cost	
					3. Valuate stock/inventory	
					4. Process payments of goods	
					5. Process salaries	
				5. Manage purchases	1. Plan purchases	
					2. Develop suppliers list	
					3. Maintain current stock list	
					4. Deliver purchase items	
				6. Manage inventory	1. Control inventory	
					2. Take stock	
6	**Support services domain**	To provide various forms of support services including IT, Maintenance, Lean Technology, etc.	Provide support services	**No further decomposition**	**No further decompositions**	Non-CIMOSA domain

Table 29: Derivation of DMs, DPs and BPs

(DMs) and their associated Domain Processes (DPs) and Business Processes (BPs). From Table 29, it can be observed that based on the domain objectives, six main Enterprise Domains were identified. Deriving DMs required processes to be classified according to clearly identified process objectives and roles. These observed domains and their associated processes were discussed with key knowledge holders of the company. The initial concerns expressed by the company knowledge holders, showed that they lacked thorough understanding of the CIMOSA modelling formalisms. They interpreted the enterprise domains to mean the author’s understanding of their different departments and therefore when the specified DMs did not match exactly with their organizational chart, they expressed some concerns. The author therefore explained the terminologies, background and theoretical perspective of the CIMOSA modelling language. When the managers were satisfied with their understanding of the CIMOSA modelling terminologies they assisted in modifying the spreadsheet to indicate the ‘as-is’ description of their processes. The modified spreadsheet assisted in the creation of ‘as-is’ enterprise model for ACAM Ltd.

Building up from Table 29, a context diagram, as shown in figure 46, was created to represent all the DMs observed in the company.

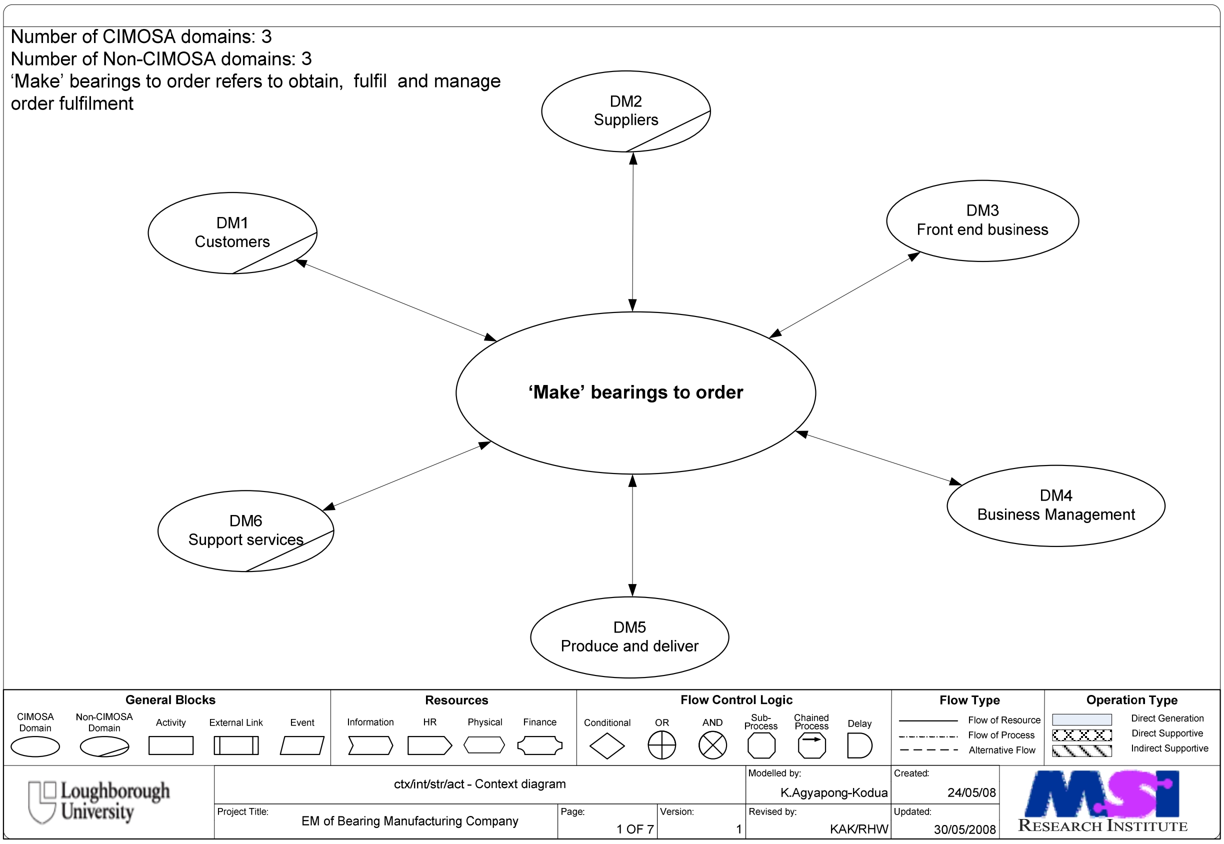


Figure 46: Context diagram of ACAM Ltd

In correspondence with the main theme of the DMs, a high level interaction diagram (see figure 47) shows how respective domain processes interact. From this high level interaction diagram it can be seen that customer requests are released from the 'provide orders' domain process (DP1) and input to the 'realize front end operations' domain process (DP3). These orders are converted to sales orders and production schedules which are sent physically to the 'manage business' (DP4) and 'produce and deliver' (DP5) processes. Based on the content of sales orders and their material requests, proforma invoices are obtained from suppliers and when the decision is made on where to purchase the materials, purchase orders are raised through the 'manage business' (DP4) process and delivered to the supplier domain. The relevant process within the suppliers domain which has to interact with the processes of ACAM Ltd is that of 'supply raw materials' (DP2). Through the execution of DP2 raw materials are supplied to the 'produce and deliver' domain process (DP4). Whilst delivering the raw materials to DP4, invoices and receipts are delivered to DP5. After completed manufacture of the bearings by DP4, finished bearings are delivered together with drawings and delivery documents to DP1, the customer domain process.

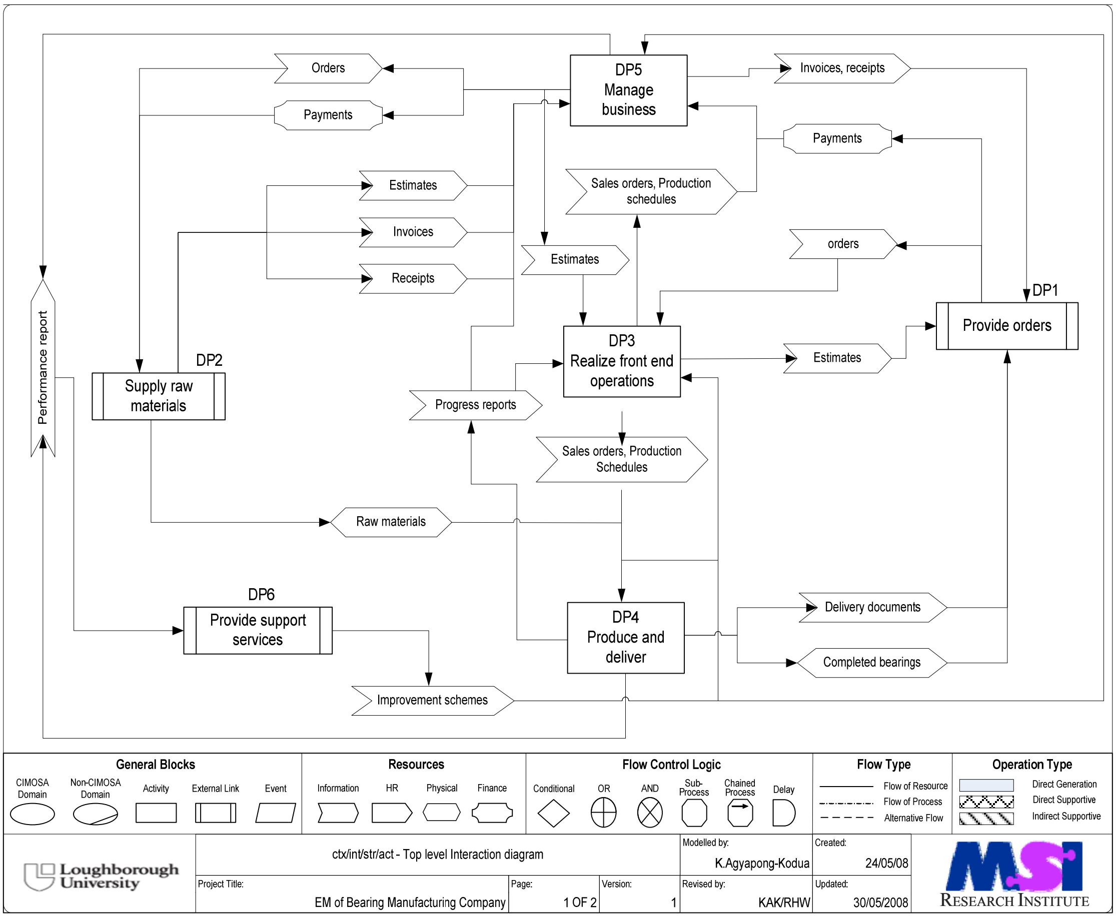


Figure 47: Top level interaction diagram

Whilst DP4 supplies the finished bearings to DP1, DP5 posts invoices to DP1. As a result, payments are made from DP1 to DP5. The 'support services' process (DP6) provides assistance to DP3, 4 and 5 after receiving requests for improvements from these domain processes.

As was observed from Table 29, each domain process consists of a chain of business processes which spanned across respective areas of the Enterprise. The next stage of the modelling exercise was to create a structure diagram showing how the observed DPs were decomposed into their respective BPs. A structure diagram showing the decomposition of DP3 into its business processes is shown in figure 48.

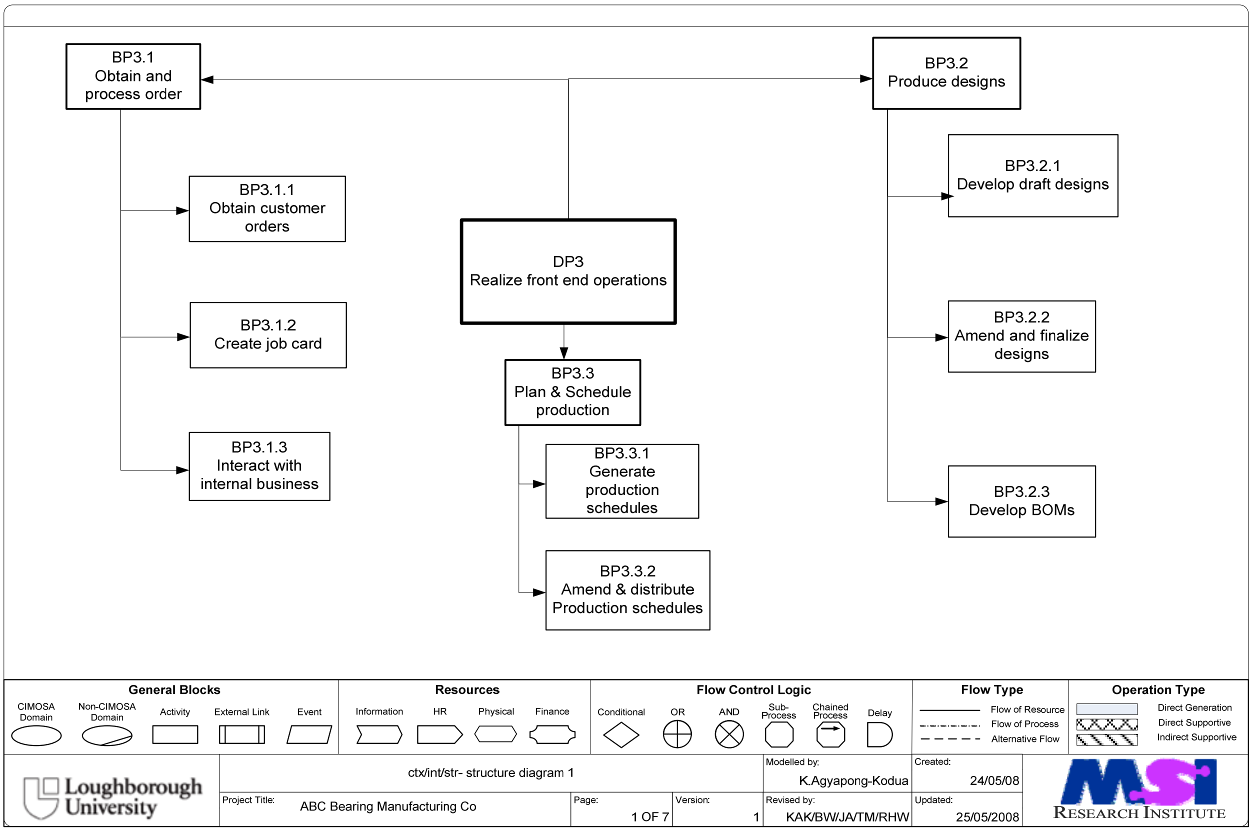


Figure 48: Structure decomposition of 'realize front end operations' (DP3)

From figure 48 it can be observed that the 'realize front end operations' domain process (DP3) can be decomposed into three main business processes, namely: 'obtain and process order' (BP3.1), 'produce designs' (BP3.2) and 'plan and schedule production' (BP3.3). BPs (3.1,3.2 and 3.3) have their own sub BPs as described in figure 48. BP3.1 is decomposed into 'obtain customer orders' (BP3.1.1), 'create job card' (BP3.1.2) and 'interact with internal business' (BP3.1.3). These three sub business processes have responsibility for 'obtaining and processing' customer orders. The 'produce designs' business process (BP3.2) is also decomposed into three sub BPs: 'develop draft designs' (BP3.2.1), 'amend and finalize designs' (BP3.2.2) and 'develop BOMs' (BP3.2.3). The last observed business process belonging to DP3 also has two sub business processes, 'generate production schedules' (BP3.3.1) and 'amend and distribute production schedules' (BP3.3.2). Each of these sub business processes are composed of elemental activities responsible for the realization of their BPs.

Another structure diagram describing the decomposition of 'produce and deliver products' domain process (DP4) is shown in figure 49.

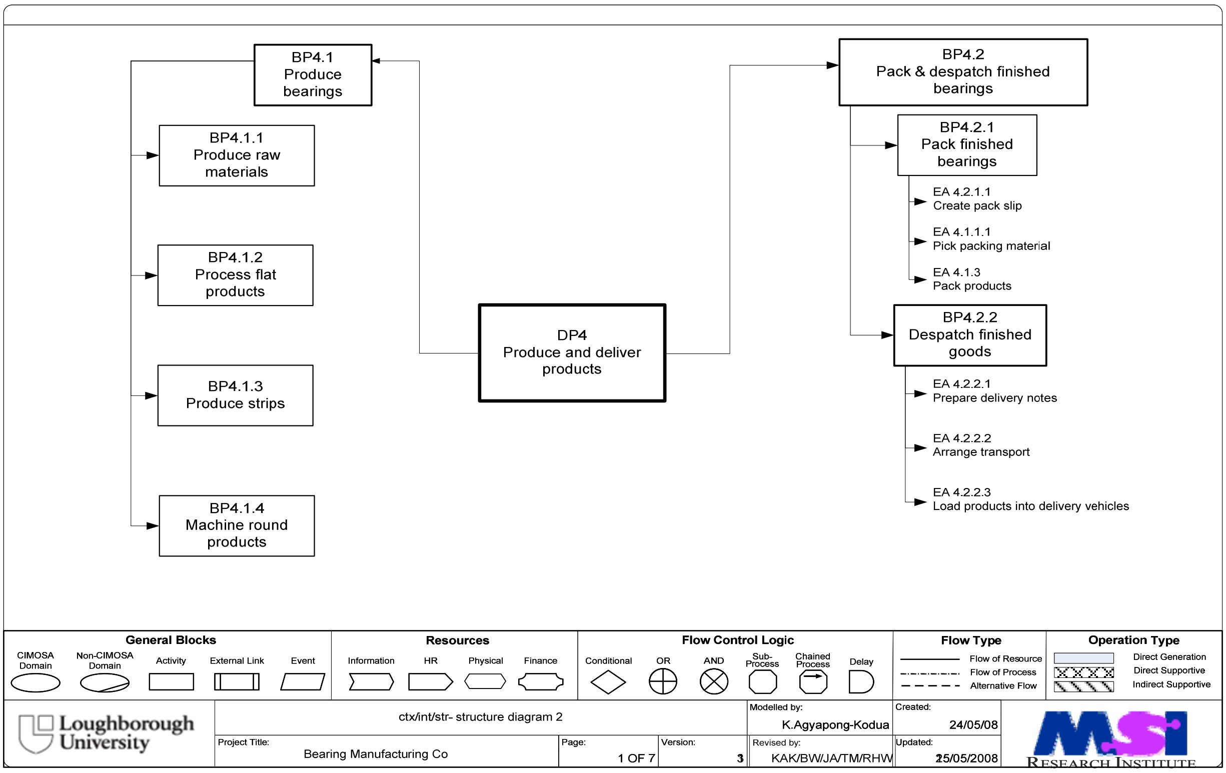


Figure 49: Structure diagram for 'produce and deliver' (DP4)

As shown in figure 49, DP4 is decomposed into two main business processes: 'produce bearings' (BP4.1) and 'pack and despatch bearings' (BP4.2) business processes. A number of sub business processes existed which supported the production of bearings and packing and despatch of the finished bearings. A knowledge of these processes led to a further decomposition of BP4.1 and BP4.2 into their sub BPs. As shown in figure 49, BP4.1 was decomposed into four main subs BPs. These are 'produce raw materials' (BP4.1.1), 'produce flat products' (BP4.1.2), 'produce strips' (BP4.1.3) and 'machine round products' (BP4.1.4). BP4.2 is also decomposed into 'pack finished bearings' (BP4.2.1) and 'despatch finished bearings' (BP4.2.2).

Finally, the 'manage business' domain process (DP5) was decomposed into six main business process. These are 'manage demand uncertainties' (BP5.1), 'manage human resources' (BP5.2), ‘manage finance’ (BP5.3), ‘manage purchases’ (BP5.4), ‘manage inventory’ (BP5.5) and ‘control quality’ (BP5.6). Each of these business processes has responsibility for other sub business processes as shown in figure 50.

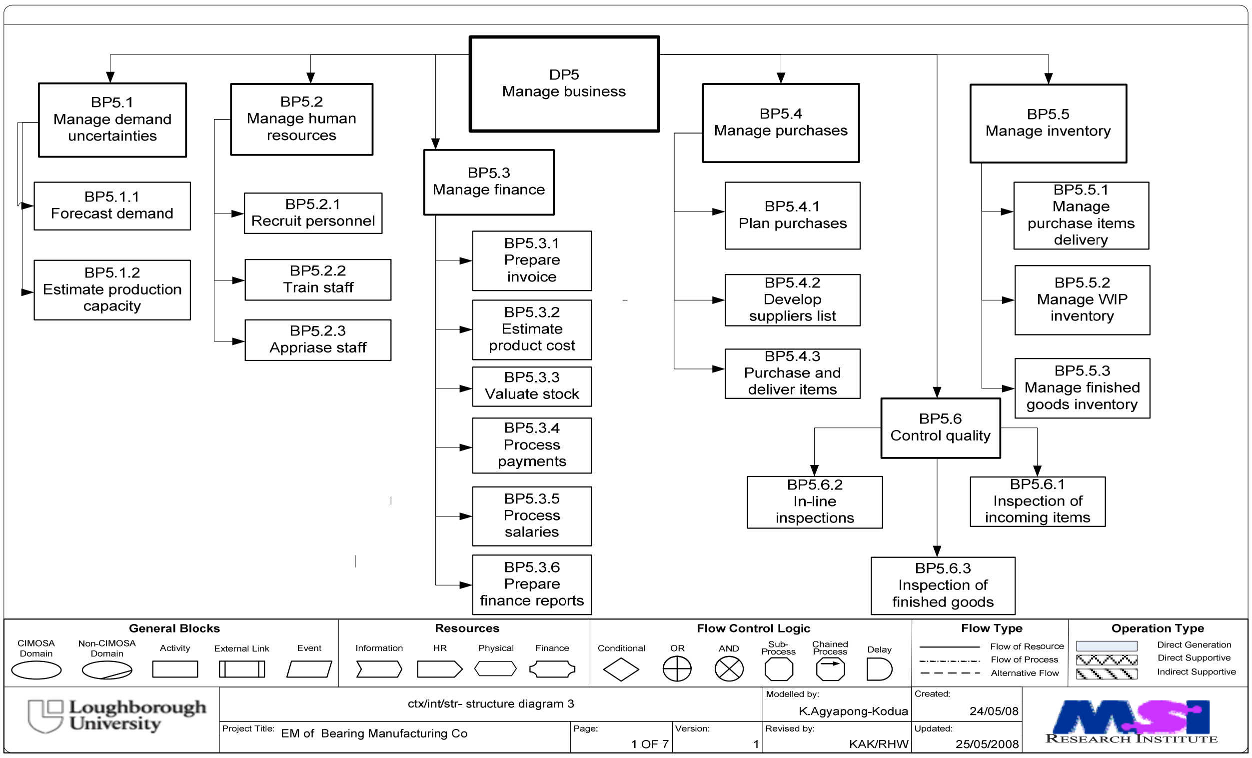


Figure 50: Structure diagram for DP5

At the next stage of the enterprise modelling exercise of ACAM Ltd, a decision was taken to further understand the process interactions that existed between the sub business processes of DP3 and DP4. Efforts were concentrated on further decompositions of DPs 3 and 4, because discussing with the Production managers of ACAM Ltd, it was concluded that the company was essentially interested in knowing how front end and production activities impacted on cost and values generated by the company. This decision matched well with the research objectives since in most cases the desire was to understand the implications of the ‘direct value adding’ activities on cost and value generation. In terms of understanding the influence of ‘front end’ and production activities on cost and values, sub-interaction diagrams of DP3 and DP4 were created. This was to further help provide a backbone for understanding the impacts of dynamics on sub processes. A sub interaction diagram showing how material and information flow between BP3.1, BP3.2 and BP3.3 is shown in figure 51. Instances of interaction of these BPs with external DPs such as DP1, DP2, DP4, DP5 and DP6 are also shown in the figure.

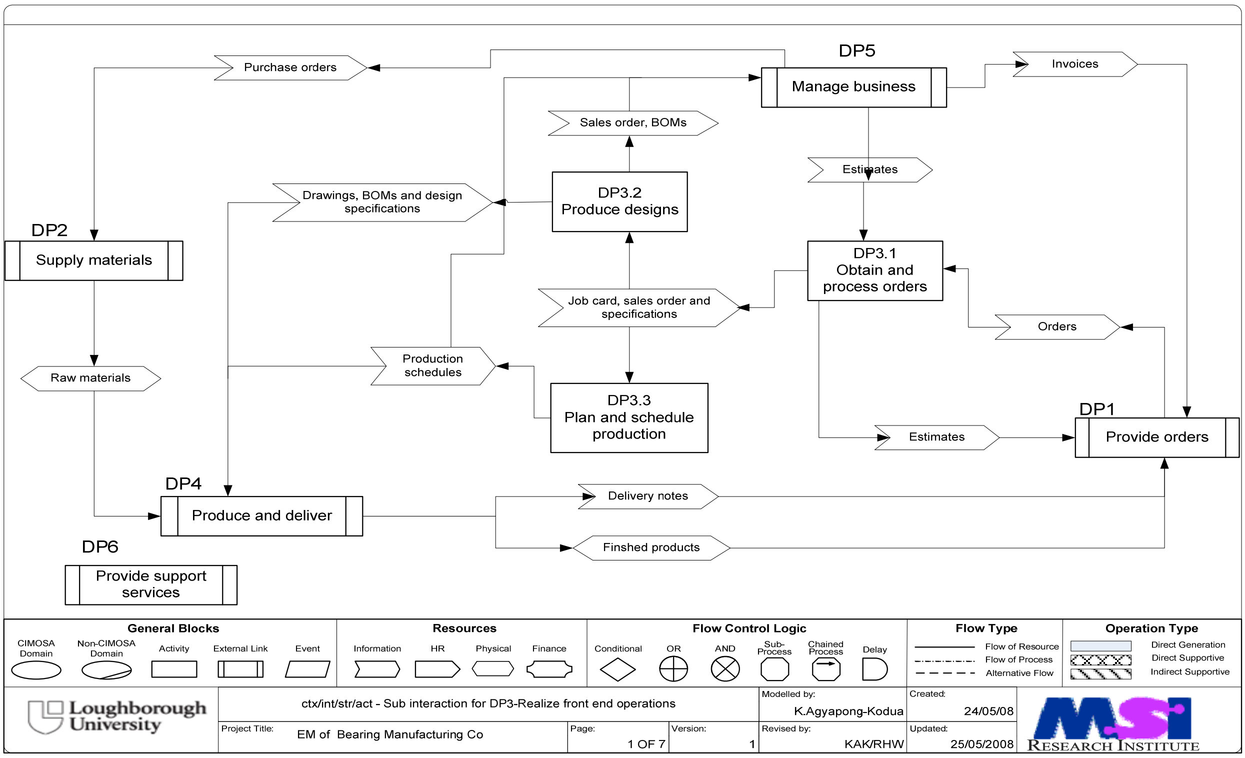


Figure 51: Sub-interaction diagram for DP3

A careful study of the sub interaction diagram shown in figure 51 shows that orders are received by the 'obtain and process orders' (BP3.1) from the external domain process belonging to the customer domain. By realizing BP3.1, sales orders are generated and transferred unto a job card which becomes the major input information for 'produce designs' (BP3.2) and 'plan and schedule production' (BP3.3) processes. Bill of materials (BOMs) derived from the realization of BP3.2 are transferred to DP5 for purchases and estimates to be prepared and sent to suppliers and customers respectively. Product drawings, BOMs and design specifications are also derived through BP3.2 and transferred to DP4. Upon receipt of purchase orders, suppliers supply raw materials to DP4 for further processing.

A second sub interaction diagram showing the flow of materials and information between BP4.1 and BP4.2 is shown in figure 52. A study of figure 52 shows that production schedules and job cards flow from DP3 to BP4.1, the 'produce bearings' business process. Physical materials also flow from DP2, suppliers, to BP4.1. Based on the job card specifications which includes the production schedule, bearings are produced by fulfilling BP4.1. These finished bearings together with the job card and production schedules are sent to BP4.2, 'pack and despatches' finished bearings. BP4.2 which is the final business process for DP4, packages finished bearings and despatch the finished bearings to customers. When the despatch is done, a despatch note is sent to the ‘manage business’ domain process (DP4).

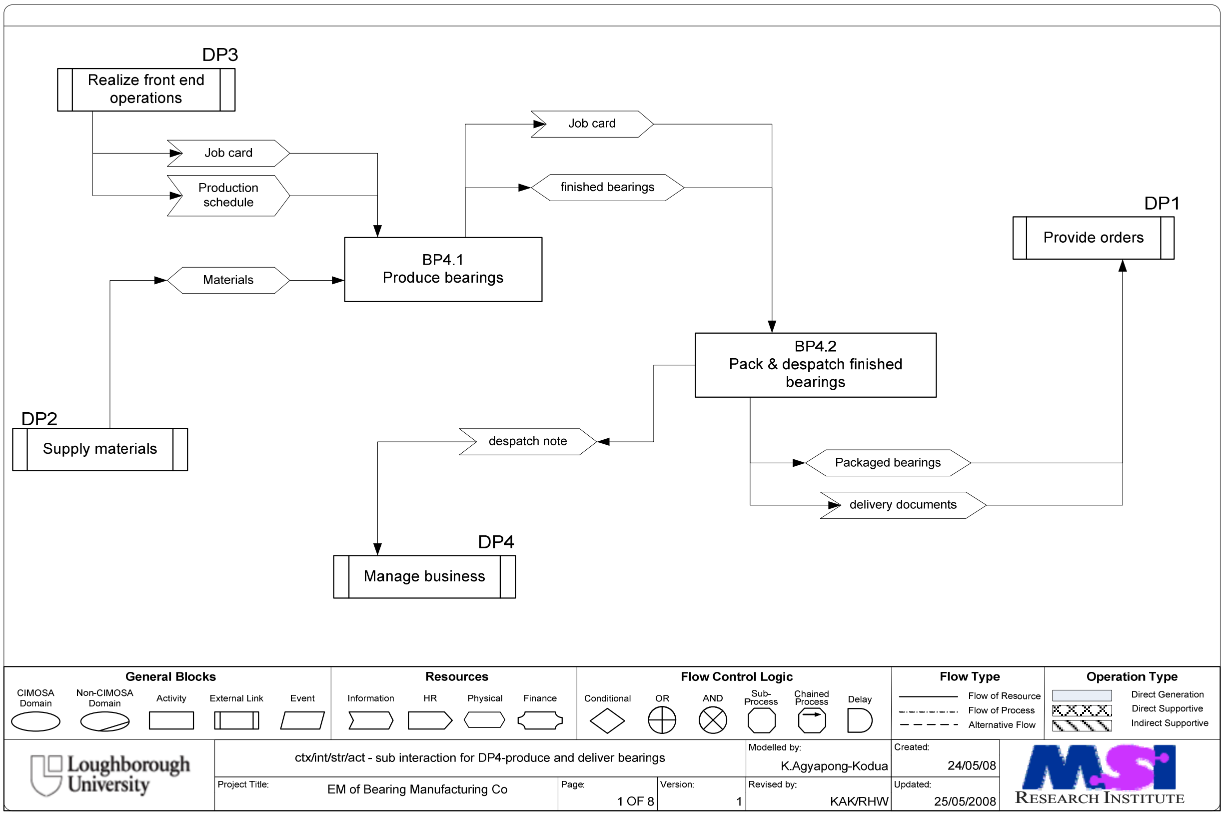


Figure 52: Sub-interaction diagram for DP4

Knowledge gathered from the creation of the sub interaction diagrams showed that BP4.1 and BP4.2 were the main production business processes. Thus to fully understand implications of production activities on cost and value generation, there was the need to further create interaction diagrams describing the various flows that exist between the sub business processes of BP4.1 and BP4.2. These further elemental interaction diagrams were called ‘sub-sub’ interaction diagrams. Figure 53 shows the sub-sub interaction diagram describing the flows that exist between sub processes of the ‘produce bearings’ (BP4.1) and ‘pack and despatch finished bearings’ (BP4.2) business processes. From the sub-sub interaction diagram shown in figure 53, it can be noted that the ‘produce raw materials’ business process (BP4.1.1) receives production schedules, job cards, drawings and BOMs from DP3. Resins, colours and bearing clothes are supplied to BP4.1.1 from the suppliers domain process, DP2. BP4.1.1 produces materials for flat, round and strip products. These materials become inputs to the ‘produce flat products’ (BP4.1.2), ‘produce strips’ (BP4.1.3) and ‘machine round products’ (BP4.1.4) business processes. Progress reports are sent externally from BP4.1.1 to DP5. Finished products are transferred from BPs 4.1.2, 4.1.3 and 4.1.4 to ‘pack finished bearings' (BP4.2.1) business process. Packaged products are then sent to the 'despatch finished bearings' business process (BP4.2.2) for them to be delivered to the customer domain process (DP1).

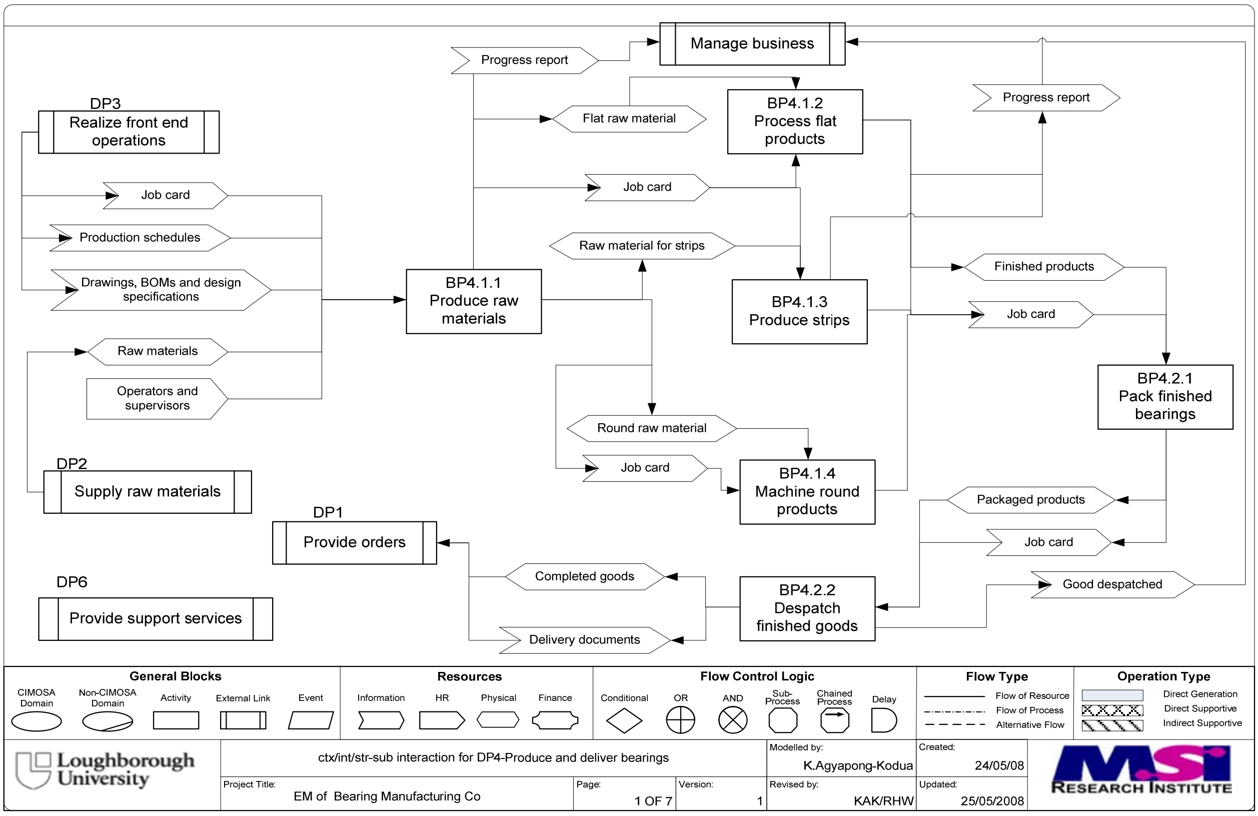


Figure 53: Sub-sub interaction diagram for BP4.1 and BP4.2

Activity diagrams for each of the BPs described in the sub-sub interaction diagrams can be created to illustrate how BPs are decomposed into their elemental activities. This was considered irrelevant considering the modelling objectives for the second case study. This is because, fundamentally, the CIMOSA models created are to serve as a backbone for understanding process interactions and the various flows among business processes so that dynamic analysis of factors which impact on cost and values generated by processes can be understood and based on the understanding derived, provide solutions for managing complexities and dynamics in manufacturing processes. The sub-sub interaction diagram was adequate to provide the basis for understanding the cause and effects structure of the company.

6.4.2 Creation of dynamic models of the case company

The sub-sub interaction diagrams created enabled understandings to be gained about the various flows and interactions that exist between key production business processes. However because of ongoing change in the case company and also the number of variables which influence the realization of processes, it was considered necessary to model process variables which impacted on aspects of the business processes depicted by the sub-sub interaction diagram. This led to the transformation of essential portions of the static models (mostly the interaction diagrams) into causal loop models capable of supporting dynamic qualitative analysis of process implications on cost and values.

Studying the top level interaction diagram (figure 47) of the second case study company, it was noted that a number of interactions exist between the six enterprise domains described by the context diagram. However a more careful study of the top level interaction diagram revealed that there was no direct interaction between ‘provide orders’, DP1 and ‘supply raw materials’, DP2. Also there was a unidirectional interaction between ‘supply raw materials’, DP2 and ‘produce and deliver bearings’, DP4. Similarly a unidirectional interaction exist between ‘produce and deliver bearings’, DP4 and ‘provide orders’, DP1. However bidirectional interactions exist between: ‘provide orders’, DP1 and ‘realize front end operations’, DP3; ‘provide orders’, DP1 and ‘manage business’, DP5; ‘realize front end operations’ and ‘produce and deliver bearings’, DP4; ‘produce and deliver bearings’, DP4 and ‘manage business’, DP5; ‘manage business’, DP5 and ‘supply raw materials’, DP2. Identifying the directions of flows and interaction between domain processes led to the creation of a ‘top level causal structure’ diagram (see figure 54) which was considered to be the starting point for the derivation of causal loop models from enterprise models. The top level causal diagram shows a simplified illustration of the domain processes which interact with each other and their direction of interaction. The top level causal structure diagram served as the parent model upon which specific process parameters were extracted and modelled in detail.

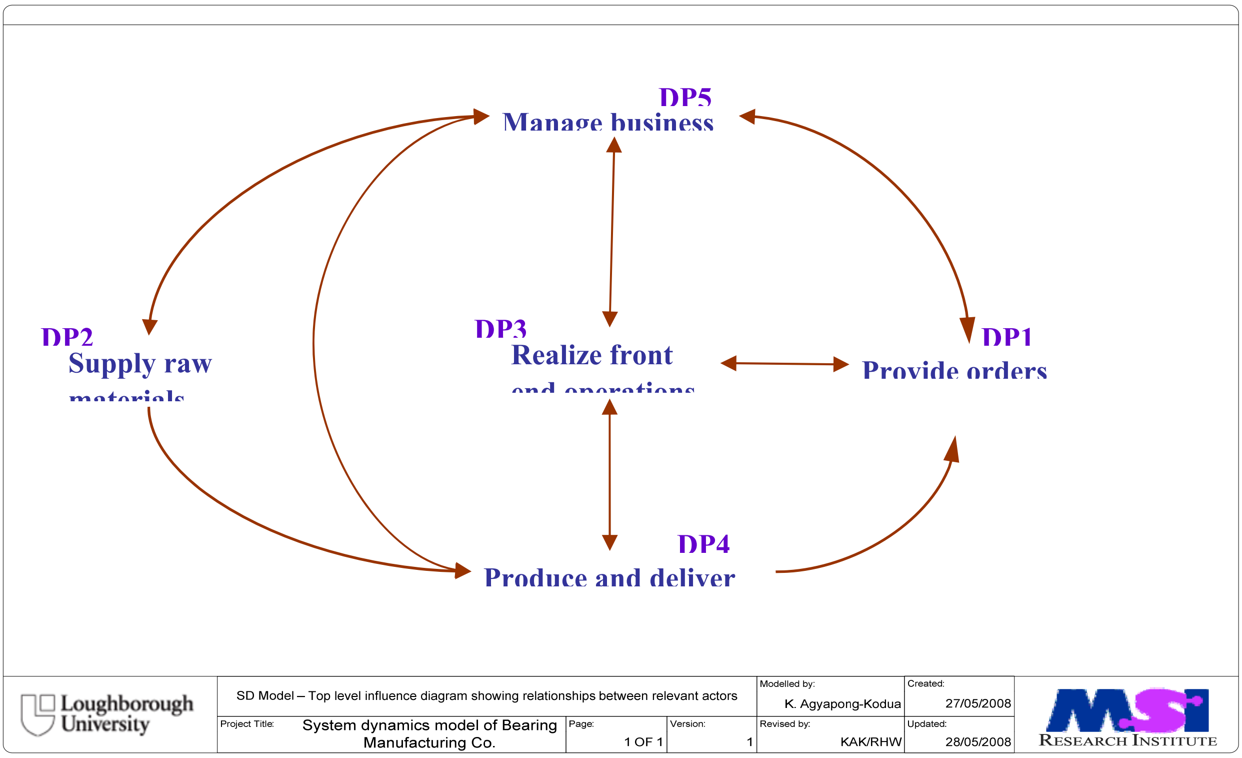


Figure 54: Top level causal structure of domain processes

Creating causal loop models from this perspective enables reasoning about possible causal factors to be placed in the context of the processes under consideration, thus limiting the possibility of modelling variables whose effects are outside the scope of the modelling exercise.

An initial causal loop model describing how the customer orders influence purchases and supply of raw materials is shown in figure 55. Customer demand is influenced by a number of factors but because these factors are external to the main business domains, investigations were not carried out to establish the actual variables influencing customer requests. However internal sales records showed that customer demands were received through e-faxes, emails, post and telephone. About 92% of these customer requests turned out to become sales orders. Thus in general terms, the increase in customer demand increased the number of sales orders produced. The preparation of sales orders is performed through BP3.1.1 (create sales order/job card) which belongs to DP3 as shown in figure 55. An increase in the number of sales orders created will increase the material requirements as well as the number of different bearings required.

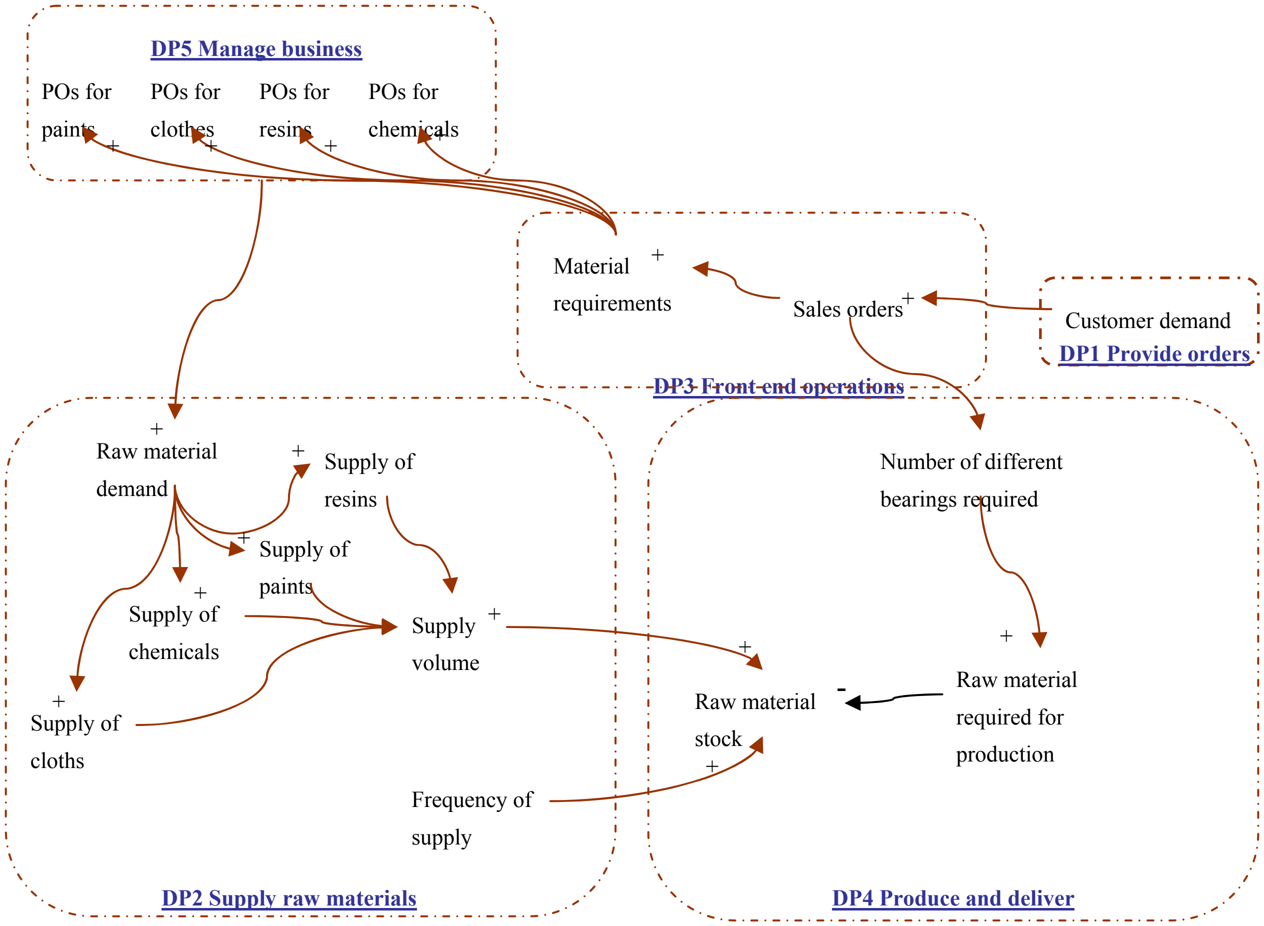


Figure 55: Initial CLM illustrating factors affecting raw material stock

Increase in material requirements implies that the number of individual material components will increase. From their material purchase records, normally four main raw materials are purchased. These are broadly classified as paints, clothes, resins and other chemicals. Thus an increase in material requirements mean an increase in the purchase orders (POs) of these components. Collectively as the number of POs raised by the 'manage purchases' business process (BP5.4) increases, the total raw material demand also increases. This demand triggers the supply of the materials specified by the POs. In effect the total supply volume increases as shown in the CLM in figure 55. However the actual raw material stock is influenced by a number of factors which include the supply volume and supply frequency. Internally, the raw material stock is negatively influenced by the consumption of material through production processes. This is expressed in the form of material required for production in the ' produce and deliver' domain process (DP4).

A more detailed description of the causal influences of the 'produce bearing' business process (BP4.1) is shown in figure 54. A study of the sub-sub interaction diagram showing the process interactions of BP4.1 and BP4.2 shows that in the 'produce and deliver' domain process (DP4), raw materials are processed to meet the material requirements for producing flat products (BP4.1.2), strips (BP4.1.3) and round products (BP4.1.4).

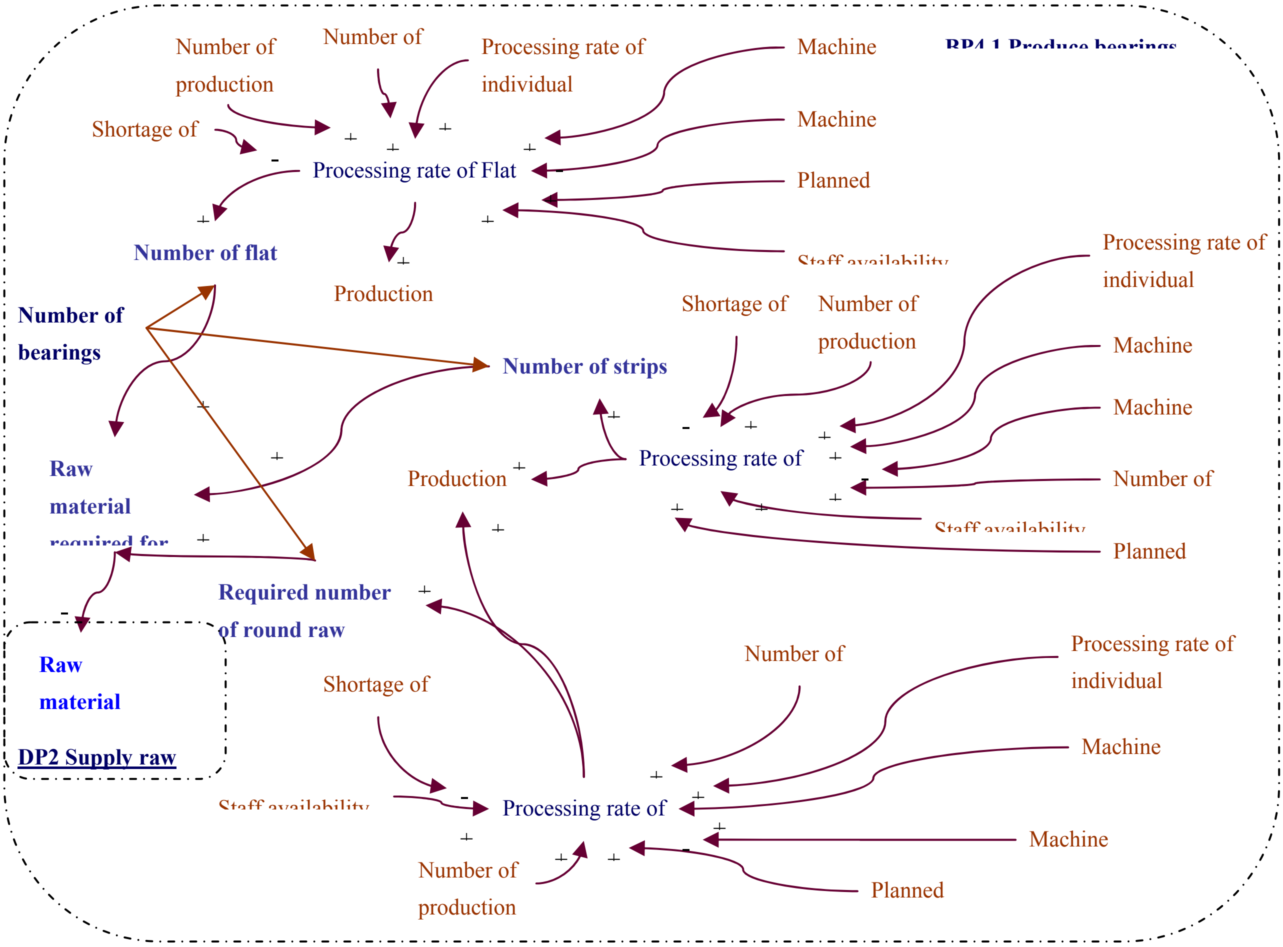


Figure 56: Initial CLM for bearings production (BP4.1)

Therefore the total raw materials required will be equivalent to the sum of the total raw materials for flat, strips and round products, whose quantities are grossly influenced by the total number of bearings derived from the sales orders. As shown in figure 56, the total number of flat, strips and round products are dependent on the processing rates of the production shops in charge of producing these components. The processing rates of the three shops are themselves influenced by a number of factors such as: number of activities, resource requirements, resource capabilities and competence, material availability, machine availability, among others.

Another initial CLM created to describe the influences of process variables on the ‘pack and despatch of bearings’ business process (BP4.2) is shown in figure 57. As shown in the figure, the actual numbers of flat, strips and round products realized is dependent on the processing rate of the various production shops responsible for the making of these products. Other factors which influence the processing rate of the shops are described in figure 57. Thus in the CLM for the 'pack and despatch' (BP4.2) process, the number of products packaged is dependent on the total products finished.

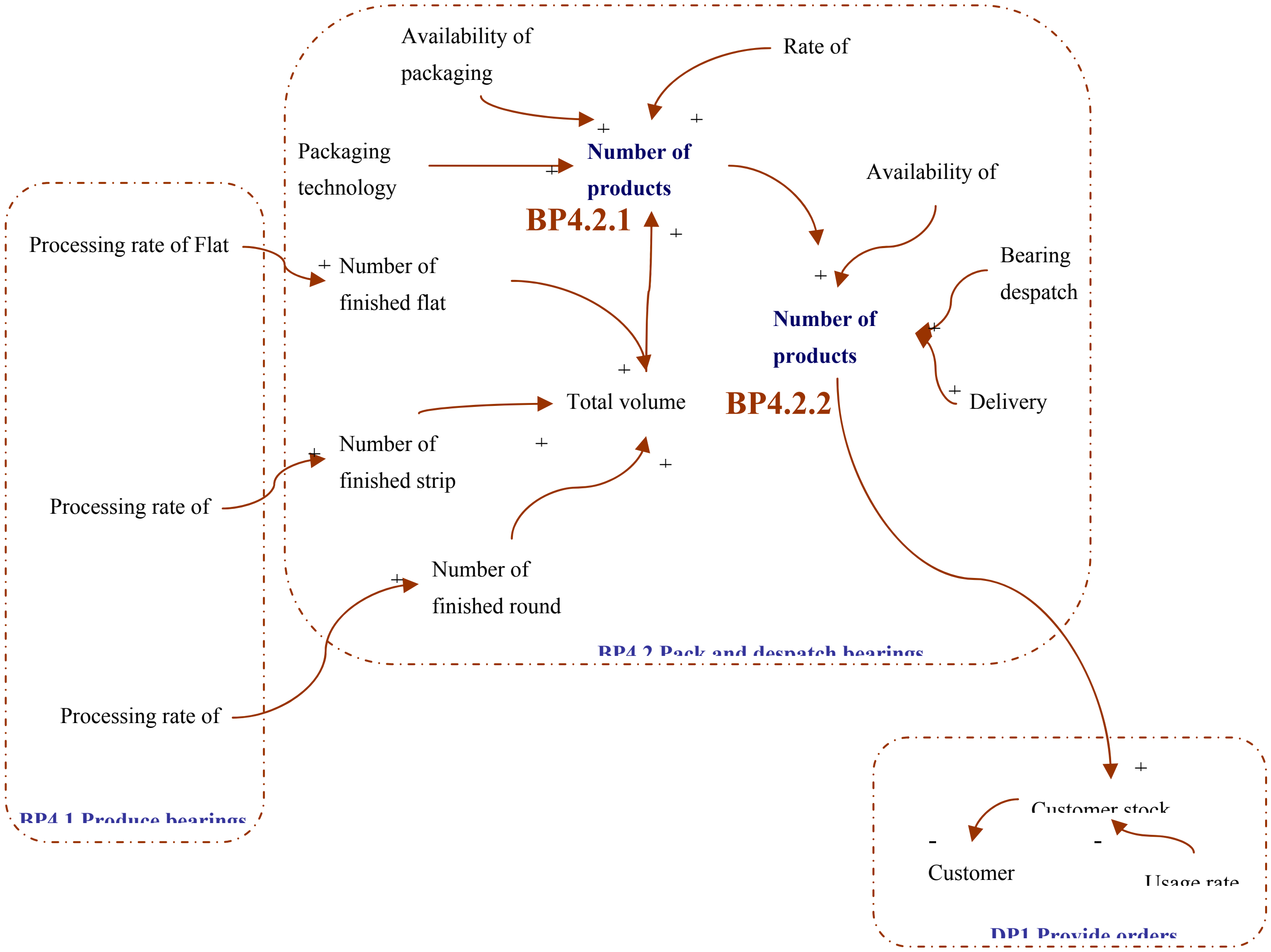


Figure 57: Initial CLM for 'pack and despatch bearings' (BP4.2)

Other factors include the availability of packaging materials and the rate of packaging. The increase in number of packaged products increase the number of bearings despatched. However other factors such as delivery rules, availability of despatch vans and internal despatch priorities positively affect the number of bearings despatched.

6.4.3 Creation of structured causal loop models (SCLMs)

The CLMs created in the section 6.4.2 was helpful in describing qualitatively the causes of dynamics in selected key business processes of ACAM Ltd. The cause and effects structure was used to denote the factors which influence various aspects of the production. Changes in the factors identified influence other factors which are causally linked. This influence can be positive or negative depending on the polarity stated on the model. Because primarily CLMs consist of variables describing causes and effects, the tendency of indicating variables which are 'correlated' but not ‘causally related’ is high. In effect CLMs can represent anything. As a result, the author is of the view that if the objective behind the development of a CLM is to support decision making, then initially created CLMs must be ‘structured’ to be able o provide useful contributions towards analytical decision making. The structured causal loop model (SCLM) must accurately define the physical and behavioural structure of the system being studied. Thinking about developing SCLMs, a set of rules were designed to help reorganize the variables defined in the initial causal loops created. The starting point was to identify variables with measurable and operational meanings. Starting from this point enable other variables to be connected in such a way that estimation of the ‘operational variable’ can be determined through the ‘factual analysis’ of the connecting variables. Whilst doing this, care is taken to ensure that the resultant SCLMs consist of variables which are causal, deterministic, time variant, directed and signed. In addition to these requirements, based on recommendations for the creation of useful CLMs provided by Burns (Burns 2001), the following formulations are disallowed:

1. self-loops involving a single quantity
2. loops involving exclusively information paths or auxiliary variables
3. more than one connector joining any two quantities and
4. connectors which have more than one originating quantity or more than one destination quantity.

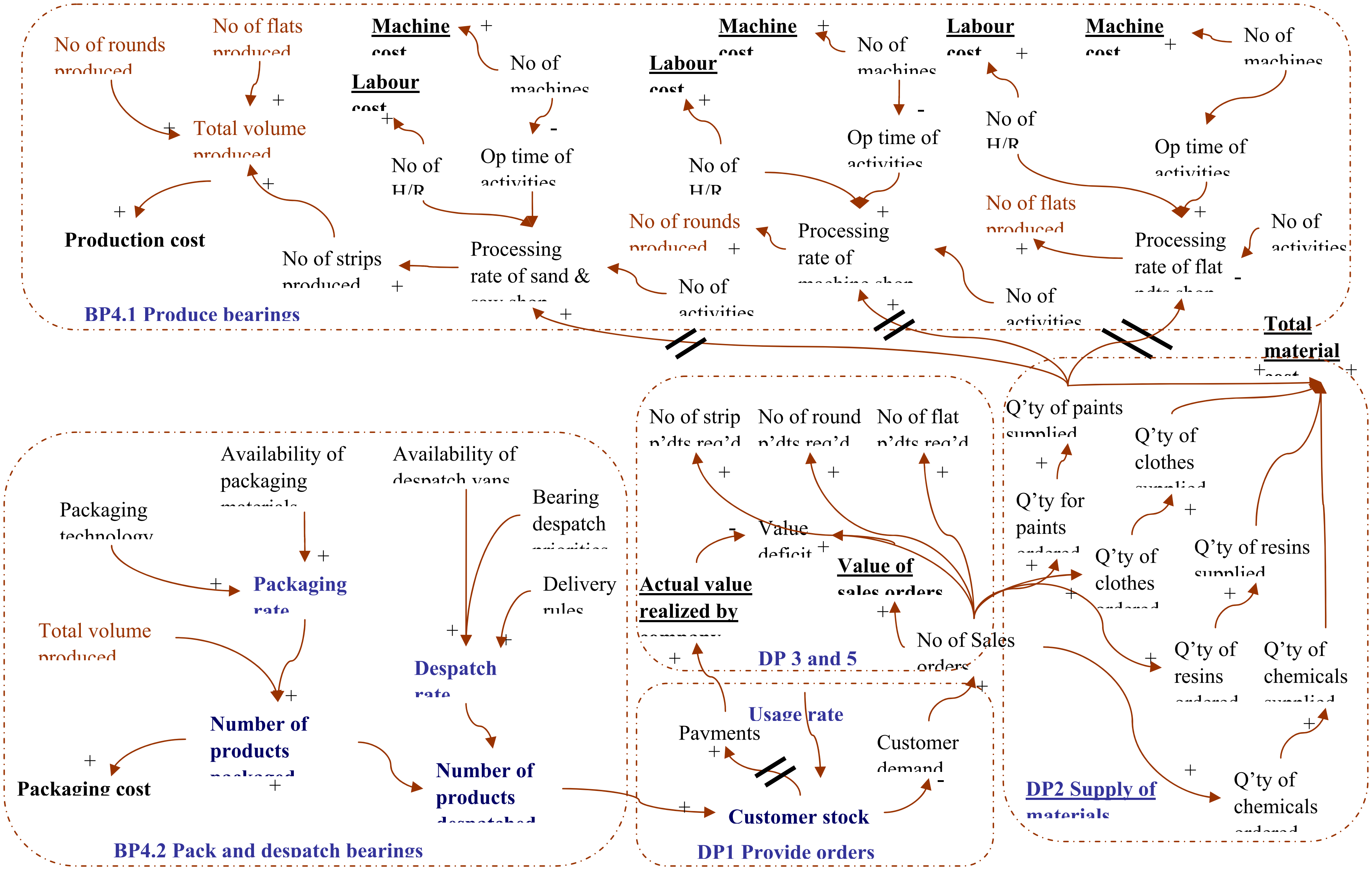


Figure 58: Structured causal loop model with cost and values information

Another objective pursued whilst deriving the SCLMs from the initially created CLMs was that the SCLM must also show the influence of process variables on the generation of cost and values so that the effect of changes in process variables on cost and values can be measured and controlled where necessary. With the quest to achieve SCLMs of relevance to cost and value modelling, the initially created CLMs (see figures 56,57 and 58) were revised based on the requirements described above.

Figure 59 is an extension of the initial CLMs presented in figures 56, 57 and 58. It was derived through an extensive study of the previously created CLMs. Comparing figures 56 and 57, it can be seen that to be able to quantify customer demand, other factors need to be taken into consideration. Since finished bearings were supplied to meet customer needs, it can be deduced that customer demand increases when customer needs increase. To quantify customer needs, customer stock levels are taken into consideration. A negative polarity is indicated because as customer bearing stock level reduces, customer demand increases. Customer stock level is affected by a number of factors. Again, for the purpose of creating a structured causal loop model, the broad range of factors such as customer bearing failure rate, machine breakdowns, preventive maintenance schedules, customer stocking policies and other influencing factors are described simply as customer usage rate. In practice ACAM Ltd operates directly with most of the engineering departments of their customers and are able to predict their maintenance cycles. Although ACAM Ltd is not in favour of stocking bearings, their historic patterns of sales are able to predict the bearing usage rate of their customers. In a more complex model, customers will have to be classified based on their usage rates, so that distinct analysis can be made for each customer. One critical thing derived from customer demand is the number of sales orders prepared by ACAM Ltd front end business (DP3) process. Traditionally, it has been verified that about 92% of customer enquiries become sales orders so it is possible to estimate the number of sales orders generated within the six months period. One other critical information from customer stock level is ‘payments received’ by ACAM Ltd. Although this link is not vivid, it is implied that since bearings are supplied before payments are made by customers, the quantity of bearings required to be paid by a customer, is the difference between the ‘paid stock of bearings’ and the ‘unpaid received stock of bearings’. Most often there are some delays in payments. The actual value realized by ACAM Ltd is the total payments received from customers. But for budgeting purposes, ACAM Ltd estimates the total sales value from the number of different sales orders received. The estimated value of sale orders almost always exceeds the actual payments received from customers, so a ‘value deficit’ is created.

From the number of sale orders received, useful production and supply information can be deduced. This is reflective in the information presented on job cards and production schedules. On the production schedule the expected number of strips, round and flat products are indicated. The difference between the expected number of products and the actual manufactured products is the backlog ACAM Ltd needs to deal with. The actual production volume is affected by real production variables such as processing rates of the production shops, materials available, human resource, machine availabilities and bearing type. Based on the number of sales orders, the designers estimate the quantity of materials required. These quantities are compared with existing stock levels of materials to enable specific material orders to be raised. Historic data exist for number of material orders raised over the six months period. In some cases, the actual materials supplied did not match exactly with the quantity of materials ordered. Reasons provided by the Production Managers included the unavailability of materials in the suppliers domain, counting errors and wrong deliveries, among others.

The total material cost is estimated by the cost of the total materials supplied. There is also a difference in actual cost of materials and material cost paid by ACAM Ltd. This is due to the payment arrangements and delays between ACAM Ltd and some of their suppliers.

In the 'produce bearings' domain the factors which were specified in figure 56 were simplified and reorganized to provide a background for quantitative analysis of the production requirements in the shops. The key factors influencing the production rate of the shops was observed to be the number of activities required to fulfil specific orders. Taking into consideration the operation time of these activities, the number of bearings produced over time can be estimated. The operation time is a historic data which takes into account human resource and machine availabilities, breakdowns and all necessary adjustments in the shops. To help estimate the machine and labour cost, the number of machines and human resources required for the activities in the shops are shown. The labour, machine, material and storage cost influence the total production cost. If these cost components are expressed in units related to number of products realized then production cost can be deduced from the production volume.

In the 'pack and despatch' business process, it was also understood that packaging technology, availability of packaging materials were factors which affected the packaging rate. In the same way delivery rules, despatch priorities and availability of despatch vans affected the despatch rate. Packaging cost can be estimated by deriving the unit cost per product packaged from the resources and materials required for packaging. Finally the increase in the number of products despatched increase the customer stock.

As can be seen from the SCLM, efforts were made to express the otherwise descriptive variables into variables with operational and measurable meanings whilst taking care not to violate the rules for the creation of effective CLMs. To gradually transform the qualitative model into a quantitative model, at the next stage of modelling, the variables specified by the SCLM were classified into stocks, flows and auxiliaries.

6.4.4 Creation of stock and flow models

The conversion of structured causal loop models into 'stock and flow' models require further understanding of the variables in the model and their associated links. The first step in the conversion process is to identify the **stocks** in the model. Stocks are identified by studying the SCLM to observe which of the factors possess a sense of accumulation. This is confirmed by noting the links which flow into those variables. Further verifications can be made by identifying the units of measure. In addition the following questions can be asked whilst trying to identify stocks:

'which of the factors accumulate?'; 'can it be stocked somewhere else and used later?'; 'if time stops, can it be measured?'; 'is there a level?', etc. In addition one may also look out for terminologies like buffers, inventory level, compartments, reservoirs, balance sheet, integrals, states, stocks, prevalence, etc.

Once stocks are identified, all other factors are either flows or converters. The difference is depicted through the nature of the outgoing dependencies. The only means a stock could change is through the influence of a flow. Hence a measure of the flow is the unit of the stock per unit time. To identify a flow dependent variable, questions which can be asked include:

'if the stock is measured with unit *y*, can the flow be measured with unit *y* per unit time. To identify flows one may also look out for terminologies like rates, throughput, derivatives, flows, cash flow, infection, incidence, income statement items, reaction rates, mobility, mortality rates, etc.

Converters hold values for constants, defines external inputs to the model, calculates algebraic relationships, and serves as the repository for graphical functions. They are linked to the model through connectors. A description of these modelling elements is shown in figure 59. Input converters are defined as all factors which are affected by nothing (no other factors) whilst output converters are factors which do not affect anything.

Figure 59: Elements of stock and flow models

Based on these definitions and distinctions, Table 30 was created to help specify the stocks, flows and converters in the SCLM shown in figure 58.

List of relevant modelling variables	*Stocks*	*Flows*	*Converter*
Customer stock	x		
No of sales orders			x
usage rate		x	
Payments			x
Actual value realized			x
Value deficit			x
Sales value			x
Volume of materials ordered			x
Volume of materials supplied			x
Material cost			x
Volume of products required			X
Processing rate of shops		x	
Number of activities, machines and human resource			x
Operation time of activities			x
Stock of bearings produced	x		
Labour, machine, storage, production cost			x
Packaging rate		x	
Volume of products packaged	x		
Volume of products despatched	x		
despatch rate		x	
Packaging cost			x
Delivery cost			x

Table 30: Classification of stock and flow variables

To ensure that:

- **a.** no stock led to another stock directly
- **b.** the level of a stock was changed only through inflows or outflows
- **c.** no flow led to another flow;

the model was redefined and new factors introduced. The resultant stock and flow model was enhanced and created with the iThink continuous event simulation tool.

6.4.5 Creation of iThink models

So far in the system dynamics modelling process described in this Chapter, structural and descriptive behavioural models have been generated. To support quantitative decision making, it is necessary to convert the initially created SCLM to simulation models. Literature has shown that iThink simulation models naturally match unto CLMs better that discrete event simulation models. However, the systematic transformation process described in this Chapter is to help provide a platform for transforming qualitative CLMs to quantitative simulation models.

The iThink model consists of three layers: interface, map and model. Figure 58 shows a top level model in the interface layer, showing the interactions between process elements captured from the map layer.

Figure 60: Model interfaces

The details of the model segments shown in the interface layer are displayed in the ‘map layer’. The map layer basically shows the stock and flow diagrams. For simulation purposes, these stock and flow diagrams are transposed into the ‘model layer’ and mathematical relationships among modelling elements are established. Detailed mathematical equations linking process variables are shown on the ‘equation layer’. Although all the model elements were connected together in the iThink tool, to help simplify understanding, the models have been shown in this thesis in different sectors representing process segments described by the interface model.

Referring to Table 30 and the SCLM presented in figure 58 and adding additional process variables which will enhance the algebraic relationship between process variables, the iThink simulation model for various DPs was created. A snapshot of iThink model for 'produce and deliver' domain process (DP4) is shown in figure 61.

Figure 61: iThink model of DP4

Also model elements influencing aspects of 'supply materials' (DP2), 'realize front end operations' (DP3) and 'manage business' (DP5) is shown in figure 62.

Figure 62: iThink model of aspects of DP 2, 3 and 5

The last iThink model shown in figure 63 shows how some model elements impacting on cost consumption and value generation were brought together for analysis.

Figure 63: Cost and value model elements in iThink

6.4.6 Simulation results and analysis

Initial data was inputted into the model to generate the ‘current state’ results of the company. It is possible to derive various forms of results based on parameters which are modelled. For example if the effect of ‘customer demand’ on actual value generated by ACAM Ltd needs to be analysed, then in the results mode, ‘customer demand’ and ‘actual value’ are dragged unto the ‘graph plate’. Graphically the impact of customer demand on value generated and material cost is shown in figure 64. The result shown in figure 64 helps to explain the causal relationship between customer demand, value generate and material cost. Because of the nature of the production system, the relationship is not linear. Many factors are connected and thus the outcome is described by the graph in figure 64. A study of figure 64 shows that in ACAM Ltd, customer demand falls gradually from the beginning of the accounting year. Significant impacts are made on actual value realized. Because of the random nature of payments received from customers, actual value realized is largely different from ‘expected value’ which is essentially dependent on number of sale orders for a given month. As shown on the graph, there is a gradual rise in value which means more payments are received at the beginning of the year and the peak of ‘actual value realized’ is in the fifth month. As customer demand reduces, there is a sharp fall of value realized until it reaches its lowest level in the seventh month.

Figure 64: Results showing the impact of customer orders on value realization

Another set of result showed the effect of constant sales orders on volumes of strip, paints and chemicals supplied and total storage cost. It was expected that when customer orders are steady, volumes of materials supplied will be constant, but the model assisted in understanding quantitatively the impact of material supply policies on ACAM Ltd production system. The graph showed that purchasing was not synchronized with customer orders. When this was verified from the Managers of ACAM Ltd, they explained that the supply of materials are forecasted based on previous production orders achieved. As actual production order achieved differ largely from customer orders, actual number of sale orders did not directly impact on their volume of material supply.

Figure 65: iThink model results of supply of materials

In a related result showing the impact of number of sale orders on despatch volume, total products manufactured and packaged volume, it is evident that sales orders are not ‘pulled’ through the production system (see figure 66).

Figure 66: Results for total products manufactured and despatched

Other results showing current operations of ACAM Ltd on total process cost, machine cost, movement cost and storage cost is shown in figure 67. Carefully studying the results shown in figure 67 reveals that process cost is not constant.

Figure 67: Effect of modelling variables on process cost

Figure 68 shows that payments are inversely proportional to ‘value deficit’ but as supply increases customer stock increases but despatch increases and falls along the months.

Figure 68: Effect of variables on payments

6.5 Observations about system dynamics modelling of cost and value dynamics

It was observed through this research that the process of capturing elements impacting complexities and dynamics on cost and value generation demanded adequate data collection and thorough understanding of the processes being modelled. The close collaboration of the authors and the staff of the case company was necessary for the successful data collection, validation and analysis. In the case of the company under investigation various causal loop models describing the operations and change enactors in the company have been created. Specific portions of the causal loop models were transformed into iThink simulation models for further analysis in terms of a) replicating and understanding historic enterprise behaviour and responses; b) predicting future enterprise behaviours and impact on performance indicators and c) experimenting alternative decisions before implementation to save cost and errors.

In carrying out this research the following observations were made:

1. The causal loop modelling technique was helpful in predicting the possible effects of potential change parameters in the company. Manufacturing elements which impacted on cost could fairly be modelled and controlled. The operation of the company was better understood in the process of modelling with the causal loop technique. The method was not very rigorous but fairly simple to understand. This is the reason why it can easily be misunderstood and interpreted wrongly. It was also observed that identifying key variables was not simple. It demanded thorough understanding of the business process. A clear limitation of the causal loop modelling technique which was observed was that each of the loops could be further modelled in detail. The challenge involved in that is the end model becomes complex and difficult to understand. As a result the idea behind creating the model could be lost. The ability to determine at what point to end the ‘decomposition’ of the variables becomes a key issue to the modeller. Another observation was that until the models are clearly explained by the Modeller it is quite difficult to comprehend as some variables and links could have multiple meanings. That is why for each of the models created attempt was given by the authors to provide explanation in words to outline the meanings of the cause, effects and links involved in the model. Although links and possible effects of causes were observed it was not possible to know the extent of the change which was happening in the company. This gave way to the utilization of the iThink software to capture the extend of the change.
2. The transformation of the causal loop models to iThink software was not straight forward. It demanded further understanding of the relationship between the variables. The relationship had to be expressed mathematically to suitably demonstrate how changes in the variables will impact on the ME. Although literature had attempted to explain the transformation process, it is not simple and easy to apply to manufacturing set ups. The key issue is being able to extract stocks, flows, convertors and other elements of the software from the causal loop model. It demands reformatting the causal loop model into what has been termed as ‘structured causal loop models’ before transformation is possible. The structured causal loop

models were helpful but contained some assumptions until they were utilized in the iThink software. As could be observed from this chapter, the two modelling techniques were used supportively to derive the results presented. It is therefore required and essential to begin the iThink simulation model from the causal loop modelling technique since it provides a strong foundation for analysis. Also they contain minimal formal notation symbols as compared to the iThink modelling tool. However the price for this abstraction is the lack of exactness.

3. It was observed that many factors impacted on cost and value generation. Hence the generation of a generic cost and value model will required the collection of lots of data and experiments. The system dynamics tool served as a strong modelling technique to capture most of the salient factors in the company. To the expert in modelling, it was an excellent way of illustrating the factors which could be controlled and monitored to reduce cost and improve value.
4. Suitable experiments could be conducted to analyse optimal performance in terms of cost and values generated by the company. The critical ordering point was established and the alternative deployment of an extra machine was experimented. The results was indicative of the real life results the company anticipated. Hence it is possible to generate from these system dynamics models, the outcome of possible decisions before implementation. Decisions result in actions and actions generate cost as well as values. How these are matched effectively will show how profitable the company will be. Modelling MEs by this approach has the enhanced benefit of capturing all or at least some of the factors creating dynamics in the company. When this is achieved companies are not surprised by changes and are able to predict likely consequences of events before they happen. Hence for most MEs operating in dynamic markets it is beneficial to deploy these techniques.
5. Although the author believes that further work is needed to investigate the interplay between causal loop and iThink modelling techniques, it was observed that the causal loop modelling technique provides a suitable backbone model which usefully encode sets of needed factors which can be used to facilitate the design and building of simulation models based on system dynamics principles.

To summarize, the system dynamics modelling techniques in the form of causal loop and iThink simulation models were able to capture dynamic properties of a case ME impacting on cost and values. Therefore in a dynamic business environment with lots of uncertainties, this technique offers support for planning of businesses and most importantly the reorganization of resources to meet changing conditions. Experiments that test the validity of models before their use were also done and used to support decision making regarding higher profit generation and competitiveness in price. The causal loop model was a suitable foundation for building the simulation model in iThink and illustrating the dynamic changes that are possible in the ME. Also the likely performance of MEs can be experimented and tested with dynamic variables before their implementation. Despite the rich knowledge base provided by the causal loop models, they were not parametric and hence could not be used for quantitative analysis. They were thus supported by the iThink software to completely achieved the aims of the research.

6.6 Conclusions on Chapter 6

Dynamics impacting on cost and values in MEs have been modelled using system dynamics modelling techniques. Following this modelling approach enabled complex structure and dynamics impacting on cost and value to be captured. Also the interaction between key system parameters was observed. The efficient modelling of these interactions was necessary since it provided a thorough understanding of the system behaviour and provided a basis for assessing the system performance under various operating conditions. The models supported the company in measuring their state of performance under increasing customer orders. Also it emphasized the need to increase sales operations to increase customer orders.

It holds that it is possible to deploy system dynamics modelling techniques in a manufacturing environment to assess the effect of various dynamics on the enterprise. This provides an excellent way of scientifically assessing the impact of decisions especially on key performance indicators including cost and value.

7. Unified application of the integrated multiproduct cost and value stream modelling technique

7.1 Introduction

Chapters 5 and 6 showed initial applications of the proposed integrated multiproduct cost and value stream modelling technique. A critical review of the results derived from the case studies in terms of the application of the modelling technique showed that different aspects of the technique were enacted and applied to solve specific company-based problems. By doing so, the strengths and limitations of the modelling technique were observed. Clearly two main routes were adopted. The first route related to the synergistic application of value stream mapping (VSM), CIMOSA modelling and Simul8 techniques. This was used to demonstrate how already published techniques such as VSM can be supported with enterprise and simulation modelling techniques to capture multiproduct related processes and complex aspects of manufacturing systems design for purposes of business process analysis and evaluation.

The second route described in Chapter 6 showed how process dynamics can be modelled and used as basis for understanding change and potential process improvement variables which can be manipulated when re-designing and structuring manufacturing processes for optimal performance. The key business drivers considered were low cost and high value generation. This was achieved through the coherent application of CIMOSA and system dynamics modelling techniques in the form of causal loops and think simulation models.

In this Chapter, a third case study is reported to illustrate how the modelling techniques reported in Chapters 5 and 6 were unified to form a comprehensive approach towards modelling multiproduct flow systems meeting the requirements specified in section 3.3. In the third case study, a consistent and systematic approach involving all aspects of the modelling technique (VSM, CIMOSA modelling, system dynamics and discrete event simulation) was applied in a fast growing ‘Engineer to Order’ Point of Purchase (POP) Manufacturing Company located in Loughborough, UK. The derived methodology was applied in the POP manufacturing company to help externalise understandings about their business processes and help solve specific industrial problems related to process designs. Because of the enormous amount of data and research findings in the case company, it was decided to report the research work in two phases comprising the derivation and utilization of static multiproduct flow cost and value stream models in Chapter 7 and the development and application of dynamic multiproduct flow cost and value stream models in Chapter 8.

7.2 Description of POP Manufacturing Company

POP Manufacturing Company was founded in 1968 as a small scale ‘moulded-parts manufacturing’ company with prime interest in plastic products. POP Manufacturing Company expanded its product range after it had gained large market shares in the supply of customised plastic products. This was mainly due to high investments in human resources of key designing and manufacturing skills as well as the introduction of Hi-Tec design tools and semi automated manufacturing systems. As a result of the expansion of POP Manufacturing Company, the Company has become specialised in the design and manufacture of quality, three dimensional point-of-purchase (POP) and shop equipment.

Currently about 50% of their finished goods are exported to more than forty countries across the globe with major clients being Boots and Superdrug Ltd. In addition, products from POP Manufacturing Company support key international brands such as L’Oreal, Rimmel, No.7, Maybelline, MaxFactor, Vodafone, T-mobile and Gallaher.

In a report presented by their Change Manager during the initial stages of the research work, the Manager expressed their well established concern of high inventory levels and resource underutilization leading to unused stock values of about £2.2m. This was alarming and it formed part of the reasons why there was urgent need to develop and instrument methods which could help prevent further inventory accumulation as well as reduce current levels of inventory.

The POP Manufacturing Company is led by a Managing Director who is supported by seven Directors. The seven directors are each responsible for managing one of the seven departments in the company. These departments are Key Accounts Management, Innovation and Product Development, Operations and Assembly, Finance, Design and Global Business Development. Key Accounts Department is another name for the Sales Department whilst Innovation and Product Development is used to refer to the department responsible for internal marketing activities. The Global Business Development department is responsible for international marketing activities and the Finance Directorate is responsible for cash management and all other human resource management tasks in POP Manufacturing Company. The primary ‘value adding’ directorates are the Operations and Assembly departments. But most often the operations of these departments are greatly influenced by design activities required to specify what needs to be manufactured.

7.3 Overview of POP Manufacturing processes

Figure 69 shows a flow chart depicting the general flow of information and materials through the production system of POP Ltd. The production system comprises of the sale teams who are responsible for identifying requirements of customers. This leads to the generation of production orders which becomes the main information source which dictate the pace of production. The production orders are released to the design and planning centres. Based on customer specifications on the production order, new designs are made or existing designs are modified. Bill of materials (BOMs) specifying the material requirements for manufacturing the designed product is created and distributed together with the designs, to relevant users. A planning group exist which plan the production order for primary manufacturing and assembly departments. Planning is manually achieved through the development of weekly or monthly job schedules. These job schedules appear as spread sheets which show details of jobs required and their expected delivery dates. Work orders and production documents are routed to the assembly floor and the respective manufacturing sections. Some of the orders require sub assembling of parts during manufacturing, whilst a larger percentage requires full assembly in the main assembly section.

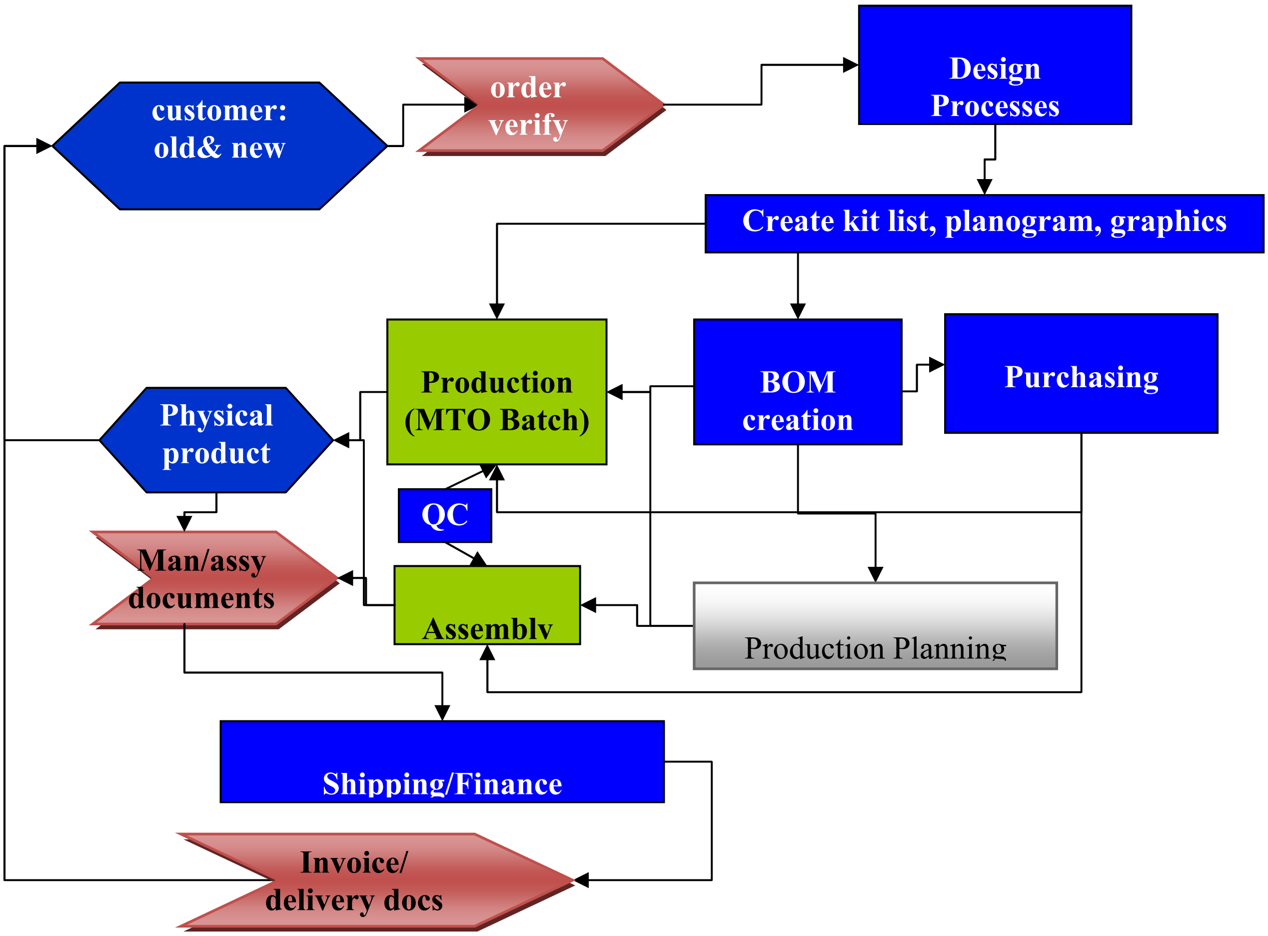


Figure 69: Generic closed loop operations at POP Ltd

The accounts department prepares final invoices and shipping documents. These documents together with the physical products are shipped to the customer as shown in figure 69.

7.4 Description of industry-based problems at POP Ltd

Research work in POP Ltd started after the MSI Research Institute of Loughborough University secured a contract to understudy the manufacturing processes of POP Ltd and see how best processes in POP Ltd can be enhanced and integrated to obtain best results. The initial MSI team was composed of three PhD researchers including the author, 2 MSc students and the Head of MSI Institute. Series of meetings were held between the MSI team and the internal POP Ltd project team to help establish understandings about POP Ltd business domains and the main research problems to be addressed in the company. Four main research themes in the areas of supply chain modelling, human resource modelling, human competence modelling and cost and value stream modelling were agreed upon. Each of these themes had their specific objectives and deliverables related to the challenges of POP Ltd production system as described by the Change Manager and they were carefully selected based on the expertise and research focus of the MSI team members. Chapters 7 and 8 report on the core work of the author in the area of multiproduct cost and value stream modelling.

Following a meeting with the Managers of POP Ltd, it was realized that, primarily, the company designs and manufactures several customized point of purchase products. These products are customized because they are produced to fit unique shapes and dimensions of customer's stores. In addition, once contracts are established, POP Ltd will have to supply replacement kits when ever needed. Another critical aspect which added to the complexity of the market was that when new products are launched by customers, display units or kits related to the new products will have to be designed and produced to meet customer requirements. Most often new products of customers are launched without prior notice to POP Ltd. This leads to POP Ltd dealing with vast variety of products.

In a report from the Change Manager, it was identified that in POP Ltd, all new products require designing. Detailed product and process designs are required to effectively assist production operations. For very complex and absolutely new designs, there might be the need to design tools and product parts which sometimes go beyond the competencies of the designers as well as the capabilities of their design tools. The slightest design error affects the quality of BOMs which are generated and hence there is a high tendency of producing wrong parts which most often do not match up during assembling. One other challenge mentioned by the Managers was that customer orders are unpredictable and hence it is difficult to organize their manufacturing systems to meet growing customer requirements. There were seasons of high and low demands. Orders varied from complete units, to repair or replacement kits. Each of these product types requires different combinations of resources and processing times. How to organize the production system to manage such complexities were not simple from their perspective.

Another clear challenge reported by the Managers was the lack of flow in their production processes. In most cases, the assembly shop had to wait several days because components from other primary manufacturing shops and purchase stores were not ready. The main difficulty is that, many times these missed components are not recognized until required for assembly. As a result, sub assembled parts have to wait for several days until all needed parts are ready before final assembly can be done. This was explained to be the main course of production delays and excessive lead times. The other side of the problem was that in some cases, excessive parts are produced leading to over stocking and high work in progress. These parts cannot be used because other parts which need to be assembled together may not be available. This has led to the accumulation of stock to the value of £2.2m. These problems were attributed to the lack of proper planning schemes and tools.

In their attempt to solve the problem, the company has invested in an ERP software called AVANTE, but unfortunately they have experienced great disappointments since the problems are pending. An internal team was therefore formed to see to the implementation of lean principles in the company, as it was conceived that the adoption of lean thinking might provide solutions to their menace. At the time of the research, the internal team had introduced 5S and created process maps of some of their processes but no solutions had been provided. The MSI team's intervention was therefore important to the company and was considered essential for the provision of industrial-based solutions.

7.5 Generation of multiproduct cost and value stream models of POP Ltd

After the first two meetings with the Managers of POP Ltd, attempts were made to understand the problems described by the company managers. This was necessary from the team's point of view so that the problems described could be aligned to individual research competencies and interest. By doing so, the list of challenges which were deemed relevant to the scope of cost and value stream modelling were considered to be:

1. The investigation and possible redesign of POP Ltd production system to ensure 'production flow', reduced lead times, low process inventories and hence low process cost and high product value generation.

2. The development of a virtual support tool to help manage product variability and support planning of production systems for efficient resource utilization and economic manufacturability of products.

Observing the description of problems mentioned by the Managers and with previous experience in systems dynamics modelling, it was easy to identify how the problems mentioned were interrelated. However it was understood it could introduce further problem if the author were to jump into hasty conclusions. Therefore it was decided that the already developed systematic and scientific approach to modelling cost and value streams in production systems would be adopted to help analyse and evaluate business processes in POP Ltd. To help address the cost and value stream related problems in POP Ltd, the author decided to use the derived multiproduct cost and value stream modelling methodology, so that its effectiveness can be tested in such a dynamic engineer-to-order manufacturing environment. In line with the specified requirements in section 3.3 and the needs of POP Ltd, it was further decided that the research outcomes would consist of:

1. A comprehensive multi-product static cost and value stream model

This will demonstrate how analyses of multiple product flows can be achieved and hence used as the basis to manage product variability. By achieving this, business processes responsible for various product groups will be understood and analysed. Potentially, wastes in process executions and improvements will be identified. This method will be based on use of an already established modelling technique which consists of the unification of VSM and CIMOSA modelling formalisms. The significant difference relative to current best practice of mapping processes will be the ability to generate product based Business process Oriented Configurations (BOCs). A number of static analyses depicting the current state of the business will be conducted for the processes modelled. Most importantly, understanding of processes will be verified such that the static model becomes the backbone for further business process analysis in POP Ltd.

2. A dynamic multi-product cost and value stream model with simulated applications

To enable the testing of alternative business ideas which might positively impact on the business profitability and competitiveness, the static value stream model will be enhanced into a virtual dynamic simulation model so that results can be visualised before their implementation. By adopting this approach, potential results of the impact of alternative manufacturing and planning policies such as pull, push, lean, agile, etc on cost and value generation can be deduced and discussed so that best decisions are made before resources are committed to the decision. The dynamic multiproduct flow cost and value stream models will assist in identifying potential means of introducing ‘flow’ in the production system; reducing inventory and production lead times, minimizing impacts of product complexities and variance, reducing cost and improving values for better business process efficiencies

When these outcomes are achieved, POP Ltd will have a comprehensive cost and value stream tool suitable for analysing the problems mentioned in Section 7.4. In addition experiments related to alternative product flows and resource allocations can be conducted to optimize the various business processes, thereby deriving a ‘to-be’ value stream model of great benefit to POP Ltd. In terms of redesigning specific portions of POP Ltd processes, the technique will provide basis for testing and selecting suitable manufacturing paradigms for appropriate segments of the value chain.

7.5.1 Data collection at POP Ltd

To help derive multiproduct flow dynamic cost and value stream models of POP Ltd, the proposed modelling methodology as specified in figure 21 (section 4.6) was followed. This implied that at the initial stages of the research, company data from primary sources were gathered so that based on the understanding derived from the data gathered and established enterprise modelling formalisms, a graphical model representing the ‘big picture of POP Ltd’ can be determined. Initial data acquired from the Change Manager who was the main actor from POP Ltd was an organizational chart depicting the various departments and human resources deployed in those departments (see Appendix B1). In addition a factory layout was obtained from the Manager to help identify where the offices and production shops were located. To help understand how customer orders are received and converted to production orders, it was first decided to meet the Sales Manager for a formal interview and discussion. In stages, all the managers and supervisors of the concerned departments were interviewed. By interviewing these knowledge holders, a clear picture of how processes were realized was obtained. In addition how processes interacted with each other were identified. Example products were selected and followed through the entire process network to understand the various flows and interactions that exist between processes. A textual description of all the processes studied was prepared and submitted to the Change Manager for verification and correction. After the verification of the report, the author was of the view that knowledge about POP Ltd’s processes were fairly accurate and hence an enterprise model externalizing understandings and current state operations of the company could be created. Whilst awaiting the response of the report from the Change Manager, further specific data related to cost and value estimations were requested from the sales department, production shops and account department.

One of the data types requested was the product types produced over three to six month periods. This data was to help identify the seasonal variations in demand as more than one period of data could usefully inform aspects of seasonal variation. This data was to help understand customer orders and values these orders give to the company. It was again to form the basis of classifying products and focussing on relevant product classes. When the need for this data was discussed with the Change Manager he requested that the sales department helps generate a sales report specifying the different product types delivered to customers covering the period June 2007 to November 2007, inclusive.

To understand how these product types match unto the business processes of POP Ltd, it was considered necessary to have data describing the historic workflows through identified business processes involved in realizing the different product types described by the sales data. It was initially difficult to determine how products are routed through the production processes, but it was realized that after ‘top-level’ production plans are prepared by the planning department, each production shop prepares job schedules which describe the type of products required to be produced in the shop. So previous production schedules was reviewed and matched with the sales data already provided. This gave a formal description of the product-process relationships which were vital for the development of multiproduct flow value streams.

The next data requested was operation times, make spans, production lead times, product delivery dates and resources involved in realizing the products mentioned in the sales report. Some of these information was available on their old production plans except that the Change Manager confirmed that they were not very accurate. Thus a decision was taken to do time studies on a few of the product types described in the sales data. Delivery dates was obtained on the sales data, production lead times were specified on the assembly capacity plan. After a careful examination of these data and the few time studies conducted, a discussion was held with the Change Manager and the internal project team to help indicate in perspective the operation times, make spans and lead times of some of the operations. Other accounting data such as overheads, production cost, prices of products, rates of pay, material cost, depreciation, etc were requested from the accounting department but the for the sake of confidentiality, figures used in this Thesis are not the exact accounting figures. The logic, ratios and difference between accounting figures were maintained in order to give a precise representation of the company.

7.5.2 Development of Enterprise model of POP Ltd

After the Change Manager verified the content of the initial report describing the authors understanding of the processes at POP Ltd, it was decided at the next stage of the research to create an enterprise model which best represents graphically the 'as-is' processes and flows in POP Ltd. This was to help share ideas about the processes that existed in POP Ltd as well as provide a backbone for the derivation of the multiproduct flow cost and value stream models. After reviewing the company organization charts, production flow charts and data gathered through the interview of relevant sectional managers in the company, a table was created to help specify the observed processes and their associated sub processes in the company. This was necessary to help discussions on our perceived business, manufacturing and engineering environments of POP Ltd. This was also to serve as the starting point for the creation of the enterprise model for POP Ltd. As a result of the experience gathered in the second case study, efforts were made to explain the CIMOSA modelling terminologies and decomposition formalisms before showing the spreadsheet to the responsible managers for verification. This was to avoid the likely interpretation of domains as departments and the tendency of other departments feeling less valuable in the attainment of the company goals. A day training was therefore conducted on CIMOSA modelling and associated multiproduct flow value stream modelling terminologies. Usually in the established method of using tables to help structure business process, two main stages are required. The initial table identifies all established departments, sub sections and stakeholders in the company. By identifying the domain objectives, roles and processes which spanned across departmental boundaries, the second stage involves recomposing and defining domains and business processes to match their objectives in the company. The second stage classification of domains and business processes in POP Ltd is shown in Table 31. The first stage classification of domains and their processes obtained after interacting with the Managers of the company and conducting shop floor visits is shown in Appendix B2.

Studying the process descriptions provided in Table 31, it can be noted that nine enterprise domains were observed in 'the manage and realize POPs' processes. These processes were further described graphical by using the CIMOSA modelling templates as shown in figure 70.

CIMOSA process decomposition of POP Ltd						
Derived Enterprise Domains (DMs) and associated processes						
Enterprise overall objective: Manage and realize POP products						
No.	**Enterprise Domains (DM)**	**Domain objectives**	**Main Domain Process (DP)**	**Business Processes (BPs)**	**Sub BPs**	**Comments**
1	**Customers**	To provide orders, receive products on time and make payments to POP Ltd	Provide orders	**No further decomposition required**	**No further decomposition required**	**Non-CIMOSA domain**
2	**Suppliers**	To receive orders and supplier material and components to POP Ltd on time	Supply materials	**No further decomposition required**	**No further decomposition required**	**Non-CIMOSA domain**
3	**Front end business domain**	To obtain customer orders, convert customer requirements into designs and associated BOMs to support production activities	Realize front end operations	1. Obtain and process order	1. Obtain customer orders	**CIMOSA domain**
					2. Interact with designers	
				2. Generate designs	1. Create planograms and kit lists	
					2. Generate BOMs	
					3. Develop graphic designs	
					4. Create product designs	
				3. Develop prototypes	1. Develop rapid prototypes	
					2. Inspect prototypes	
4	**Produce and deliver products domain**	To produce various components, assemble, pack and coordinate the delivery of finished POPs to customers	Produce and deliver	1. Make products	1. Make prints	**CIMOSA domain**
					2. Vacuum form parts	
					3. Produce moulded parts	
					4. Make wooden parts	
					5. Heat bend parts	
				2. Assemble & pack products	1. Release products	
					2. Batch assemble POPs	
					3. Lean assemble POPs	
					4. Pack finished POPs	
				3. Despatch finished POPs	1. Prepare delivery notes	
					2. Arrange transport	
					3. Load delivery trucks	
5	**Business Management domain**	Manage order fulfilment and support processes	Manage business	1. Manage human resources	1. Recruit personnel	**CIMOSA domain**
					2. Train personnel	
				2. Manage finance	1. Prepare invoice	
					2. Receive payment	

					3. Estimate product cost	
					4. Valuate stock of materials	
					5. Make payments	
					6. Prepare internal finance reports	
					7. Prepare external finance reports	
					8. Conduct internal audits	
				3. Prepare production plans	1. Plan production	
					2. Prepare shop level production schedules	
					3. Adjust production plans	
				4. Prepare purchase plans	1. Update stock list	
					2. Develop purchase plans	
					3. Update suppliers list	
				5. Plan supply chain	1. Manage purchase items delivery	
					2. Manage inventory	
					3. Manage finished POP inventory	
					4. Manage transport systems	
				6. Manage projects	1. Define projects	
					2. Control project schedules	
					3. Complete project schedules	
				7 Control quality	1. Inspect incoming items	
					2. Inspect and test in-process parts	
					3. Generate reports	
6	**Subcontractors**	To produce and supply subcontracted parts to POP Ltd	Produce subcontracted parts (metal parts and tools)	**No further decomposition required**	**No further decomposition required**	**Non-CIMOSA domain**
7	**Retail projects**	To produce retail products	Produce retail parts	**No further decomposition required**	**No further decomposition required**	**Non-CIMOSA domain**
8	**Support Services domain**	To provide IT support, equipment and facilities maintenance	Provide support services	**No further decomposition required**	**No further decomposition required**	**Non-CIMOSA domain**
9	**Product and process improvement domain**	To provide continuous review of POP Ltd processes, manufacturing methods, and enhancement of customer-based products	Provide process and product improvements	**No further decomposition required**	**No further decomposition required**	**Non-CIMOSA domain**

Table 31: Process decomposition table for POP Ltd

A context diagram showing the nine enterprise domains observed to be relevant to the 'manage and realize POP products' in POP Ltd is shown in figure 70.

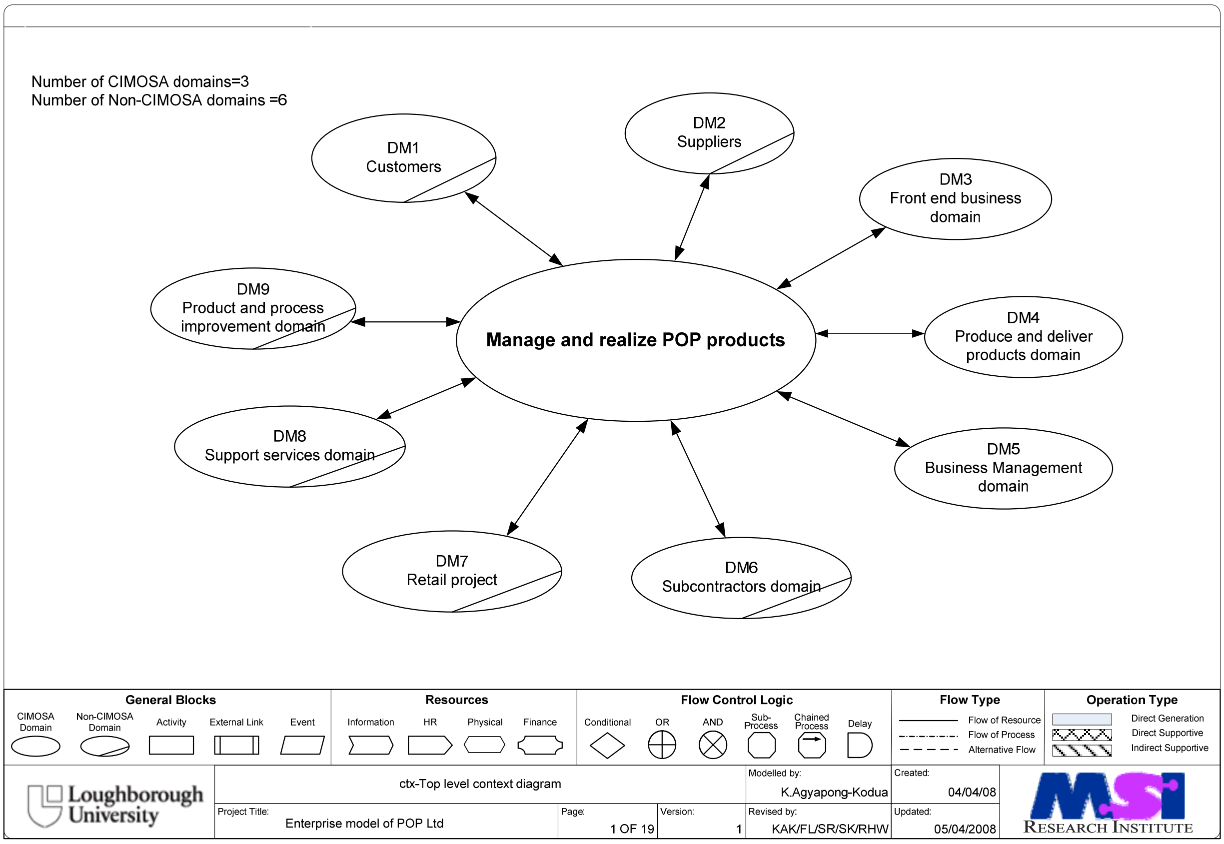


Figure 70: Context diagram of POP Ltd

As explained in the previous chapters, after creating context diagrams, enterprise domains are decomposed into their respective Domain Processes (DPs) and utilized in an interaction diagram to show the various flows and process interactions that exist between DPs. Figure 71 shows the top level interaction diagram showing the process interactions that exist between the various DPs. From the top level interaction diagram, it can be seen that customer orders are received through the 'provide orders domain process (DP1). These orders are released to the 'front end domain process (DP3). In the front end domain process, customer orders are converted to design data and order specifications which are transferred to 'produce and deliver (DP4)' and ' manage business (DP5) domain processes respectively. The design data so created consist of planograms, product designs, kit lists, tool designs and graphic designs. The order specifications on the other hand refer to a a list of documents including BOMs, delivery dates and other product information. In the 'manage business domain process' (DP5), the order specifications are converted to production plans and 'shop floor travellers' and purchase orders for materials and sub parts. The production plans and shop travellers are routed back to the 'produce and deliver products' domain process (DP4). In response to the purchase orders sent from DP5 to the 'supply raw material' and 'produce sub contracted parts', raw materials, parts and finished subcontracted parts are delivered to DP4. After parts supplied are checked in DP4, DP5 makes payments to suppliers and subcontractors.

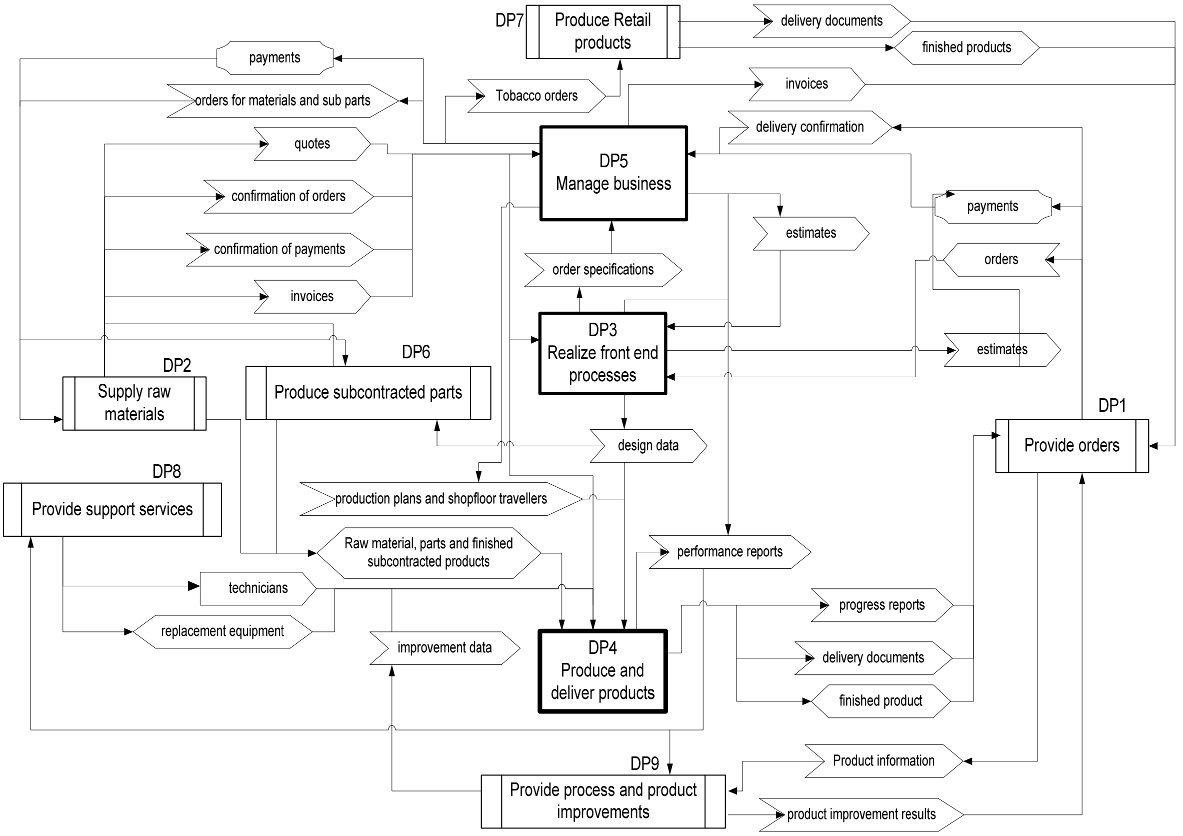


Figure 71: Top level interaction diagram of POP Ltd

DP4 produces and assembles various products based on the design data received and delivers finished POP products to customers. The finished products are accompanied with delivery documents and manuals. Whilst executing these processes, performance reports are prepared and delivered to the 'provide support services domain process' (DP8). DP8 arranges and replaces all necessary equipments, IT and software as per process requirements. In addition current product information and process performance reports are monitored by the 'process and product improvement domain process (DP9).

At the next stage of the enterprise modelling exercise for POP Ltd, three structure diagrams were created to describe the decomposition of DPs 3, 4 and 5. Decompositions of DPs 3, 4 and 5 resulted in 46 business processes. Parts of these business processes are shown in the structure diagram for DP4 (see Figure 72) . The structure diagrams for DPs 3 and 5 showing the remaining BPs are shown in Appendix B3.

The decomposition of DP4 resulted in three main top level business processes (BPs): 'make components' (BP4.1), assemble and pack products (BP4.2) and despatch finished goods (BP4.3). These BPs are further decomposed into sub-BPs which have responsibilities for their top level BPs. For example BP4.1 is decomposed into 'make prints' (BP4.1.1), 'make wooden parts' (BP4.1.2) and 'heat form parts' (BP4.1.3). Because of the long chain of processes in BP4.1, the sub-BPs (BPs 4.1.1, 4.1.2 and 4.1.3) were further decomposed into elemental BPs as shown in figure 72.

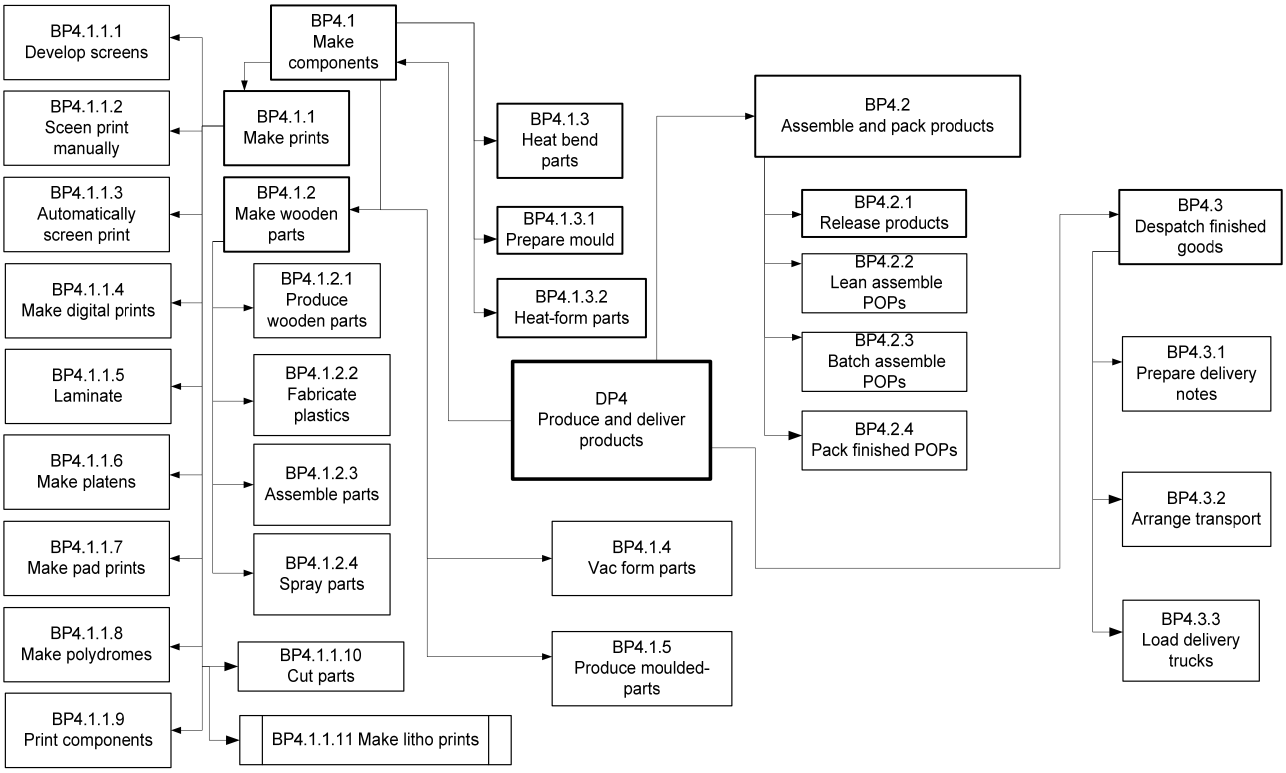


Figure 72: Structure diagram for DP4

Further sub and sub-sub interactions diagrams were created to depict the interactions that exist between the respective BPs described by the structure diagrams. For the sake of clarity and inadequate space, these diagrams have been shown in Appendix B3.

After the BPs were identified, because the intended purpose of further decomposition is for cost and value stream analysis, a spreadsheet was designed to collect actual activities required to fulfil the identified BPs. In addition to identifying the stepwise activities, the template was used to capture the operational times of each activity, delays, resources required, information and materials necessary to complete the BPs. This was done for each of the BPs and the result is shown in Appendix B4. An example activity diagram representing the 'as-is' activities required to fulfil 'make digital prints' (BP4.1.1.4) is shown in figure 73.

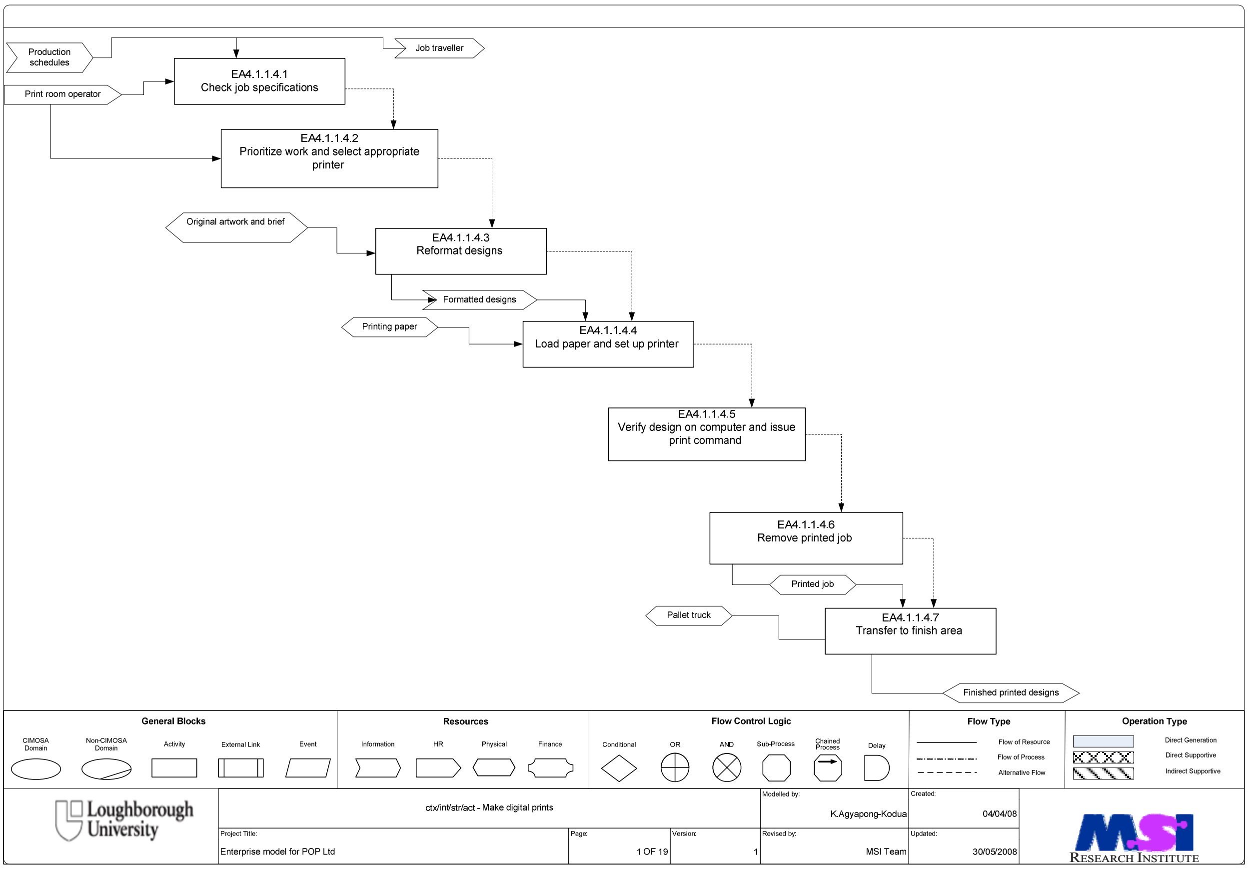


Figure 73: Activity diagram for ‘make digital prints’ (BP4.1.1.4)

The enterprise model for POP Ltd enabled a thorough understanding of the processes involved in the production of parts at POP Ltd. This implied that with an appropriate chain of processes identified to be responsible for the realization of particular products, configurations of business processes can be modelled for the different products. As a result of this need, products were matched with their respective processes and used as the basis for determining process-based-product types. The next section explains how this was achieved in POP Ltd.

7.5.3 Process-based product classification

Literature has shown various methods of classifying products (see section 4.3). To limit the impact of product complexities, at the first stage of the classification exercise, products which are routed through the same processes were classified as one group. This was achieved by creating a matrix of ‘value adding BPs’ and matching them with the products. From the sales data for the period June 2007 to November 2007 (not shown), products were matched with their respective BPs. The Change Manager assisted in sorting out these sales data since most of the products had been produced before the commencement of the research in POP Ltd. In all a total of 3725 different products were analysed. By using the production records and also with support from the Change Manager, the products were classified into their production batches, product types and their respective process routes. Table 32 shows the results of the first stage process-based product classification. The classification was based on Business Processes (BPs) related to the 'realize front end operations' (DP3) and 'produce and deliver products' (DP4). Although normally, in modelling multiproduct flow cost and value streams, process classifications are based on 'direct value adding processes', it was considered necessary in this case to include the front end business processes of 'obtain and process order' (BP3.1), 'create designs' (BP3.2) and 'develop prototypes' (BP3.3). this was because these processes made significant difference in how downward processes were designed and realized. 'Despatch finished POPs' (BP4.3) was not included in the list of processes for classification purposes, because obviously all the products were despatched. During the first stage of the classification, it was observed that out of the 3,725 products, components of 385 products went through all the identified business processes. This class of products which required essentially all the business process was called 'standard units'. The next type of products required all processes apart from some design and prototype processes, such as: create graphic designs (BP3.2.3), create product designs (BP 3.24), develop prototypes (BP3.3.1) and inspect prototypes (3.3.2). This set of products was called 'repeat units'. Because they are repeat orders, graphic and product designs already exist and prototyping of parts is not required. The next set of products did not require 'planograms' and new BOM creation. In addition product and graphic designs were not required. Final product assembly processes were also not required. This class of product was termed 'rerun or update kits'. The last group of products based on similarity of processes was called 'graphic only kits'. These were products which required mostly graphic design and printing processes. Details of products belonging to these product classes are not shown for the sake of size and confidentiality.

Data related to the process times for each of the products was further reviewed. The review showed that within the same product class, further classifications of products were necessary considering total processing times. This was considered necessary to limit the complexities involved in grouping products of large processing time variations together. This is particularly so if the end goal of the classification exercise is to also test the possibility of instrumenting pull or lean in the production systems. A 'total work content' for each of the product types was defined to be the total operation time required to complete all the processes as if performed by one person. With reference to Duggan (Duggan 2003), a work content criteria was defined as 'the total work content of the downstream process steps for each part in the product family should be within 30% of each other'. Based on this definition, the products were reclassified into six sub groups. Table 33 shows a summary of the final derived product families.

Process based product classification																				
Product groups (Stage 1)	**DP3 Realize front end operations**								**DP4 Produce and deliver**											
									Make components (BP4.1)											
	Obtain and process order (BP3.1)			**Generate designs (BP3.2)**				**Develop prototypes (BP3.3)**		**Make prints (BP4.1.1)**										
	Obtain customer orders (BP3.1.1)	Update POTS (BP3.1.2)	Interact with designers (BP3.1.3)	Planogram (BP3.2.1)	BOMs (BP3.2.2)	Graphic design (BP3.2.3)	Product designs (BP3.2.4)	Prototypes (BP3.3.1)	Design inspect (BP3.3.2)	Screen dev't (BP4.1.1.1)	Screen print-manual (BP4.1.1.2)	Auto Screen Printing (BP4.1.1.3)	Digital Printing (BP4.1.1.4)	Lam'tion (BP4.1.1.5)	Platens (BP4.1.1.6)	Pad Printing (BP4.1.1.7)	P'droming (BP4.1.1.8)	Comp't Printing (BP4.1.1.9)	Cut (BP4.1.1.10)	Litho Print (BP4.1.1.11)
Standard units	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Repeat units	X	X	X	X	X					X	X	X	X	X	X	X	X	X	X	X*
Rerun or update kits	X	X	X			X	X			X	X	X	X	X	X	X	X	X	X	X*
Graphic based kits	X	X	X			X							X	X					X	

Product groups (Stage 1)	**Process based product classification continued**											
	DP4 Produce and deliver											
	Make components (BP4.1)								**Assemble and pack (BP4.2)**			
	Make wooden parts (BP4.1.2)				Heat bend parts (BP4.1.3)		BP4.1.4	BP4.1.5				
	Wood work (BP4.1.2.1)	Plastic fab (BP4.1.2.2)	Assemble parts (BP4.1.2.3)	Spray parts (BP4.1.2.4)	Prepare mould (BP4.1.3.1)	Heatform parts (BP4.1.3.2)	V'forming (BP4.1.4)	Mouding (BP4.1.5)	Release products (BP4.2.1)	Lean assy (BP4.2.2)	Batch assy (BP4.2.3)	Package (BP4.2.4)
Standard units	X	X	X	X	X	X	X	X	X	X	X	X
Repeat units	X	X	X	X	X	X	X	X	X	X	X	X
Rerun or update kits	X	X	X	X	X	X	X	X				

Graphic based kits												

Table 32: Process based product classifications

A range for determining work contents of the same product family was defined by (Duggan 2003) as :

$$\textbf{Range} = \frac{(Highest - lowest)}{highest} \textbf{ x 100} \qquad \textbf{(14)}$$

All products classified as low standard units were within 30% of the average work content for that product family. Products classified as 'high standard products' were above 30% of the average work content of the 'low standard units'.

Product families		**Average work content**
Standard units	High	31298
	Low	21297
Repeat units	High	12274
	Low	6387
Rerun or update kits		5622
Graphic only kits		3362

Table 33: Work content based product families

7.5.4 Static cost and value stream model of POP Ltd

It was realized from the product classification exercise that products can suitably be classified based on similarity of processes and also on the work content requirements of the products realized through the same processes. Classifications based on similarity of processes and work contents made it possible to bring together products of similar process requirements, hence reducing the complexities associated with managing high variety products. Results from the process classification exercise showed that the products realized by POP Ltd can be divided into six product families: high standard units, low standard units, high repeat units, low repeat units, update kits and graphic only kits.

Based on these classifications, cost and value stream models were created for the different product families. This was achieved in stages. The first stage involved creating a top level cost and value stream model for the product families. This involved identifying the network of business processes and the associated values and cost they provide to the business. In addition process realization times and outputs are indicated on the model. Queue sizes, queue times and resources required are shown on the model. The static model was created based on earlier conceived methods and constructs described in Chapter 5. At the next stage of the modelling exercise, the static cost and value stream model was used as the reference for conducting further static analysis on the business processes of POP Ltd. A top level static cost and value stream model consisting of the top level Business

Process Oriented Configuration (BOC) for generating values and cost for the six product families is shown in figure 74. The static cost and value stream model shown in figure 74 describes how information, material and resources are transferred among the top level DPs. Initial values of materials representing the material prices for each of the product families is shown at the material inventory point. Also average production volumes deduced from the sales record is shown on the model. The processing and waiting times for the different product families is shown as a range, for example 2days to 3 months is shown as the waiting time for raw material inventory. This range takes into consideration the least and maximum waiting time in that inventory. Details of how values were estimated for the top level DP is explained in section 7.5.4.1.

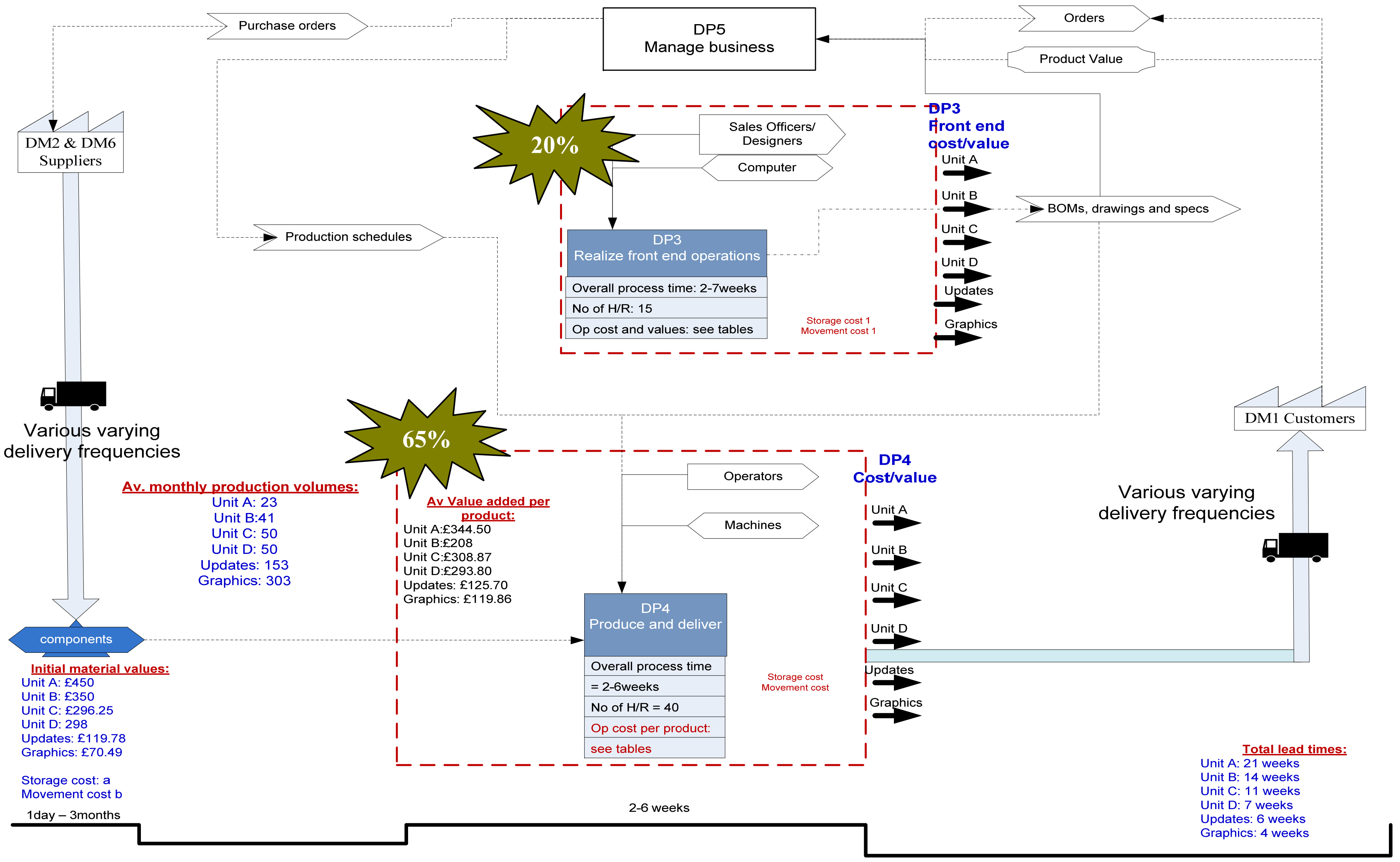


Figure 74: Top level cost and value stream model

7.5.4.1 Derivation of sub models and estimation of values and process cost generated

A number of parametric static analysis was conducted based on the models created. It was estimated that the 'value added' by the production system to raw materials and components, in transforming them into finished goods meeting customer requirements, is the difference between the selling price of the finished goods and the total purchased price of the raw material and components required for the production of the goods (Agyapong-Kodua, Ajaefobi et al. 2009). Meyer et al (Meyer, Creux et al. 2007) has shown that, for multiple product flow systems:

Value added = $p_o - p_i$

$$\text{Value added (for m and n numbers of flows)} = \sum_{i=1}^{m} po_i - \sum_{k=1}^{n} pi_k \qquad \text{------------ (15)}$$

p_o: value of output product
p_i: value of input product
m: number of output product flows
n: number of input product flows

The total value added by the processes of POP Ltd is the sum of values provided by 'Front end domain' (DM3), 'Produce and deliver domain' (DM4), 'Manage business domain' (DM5), 'Support services domain' (DM8) and 'Product and process improvement domain' (DM9). Because the focus of the research is on estimating 'direct value' through physical manufacturing processes, a decision was taken to limit the cost and value analysis to processes within the 'Produce and deliver domain' (DM4). This implies that direct material value addition will consist of three business processes: 1. 'make components' (BP4.1); 2. 'assemble and pack' (BP4.2) and 3. 'despatch finished POPs' (BP4.3). The value of input product (p_i) is the purchase price of all materials and components required for the manufacture and assembly of POPs. p_i was obtained from the price list provided by the purchasing department for the BOMs specified for the different product types. Although detail specific value analysis can be conducted based on the individual material requirements, it was more convenient considering the number of products analysed, to estimate an average historic price for materials and parts required to produce the different product families. The total value of output product (po) is the sum of the sales value for different products families realized over a specific time frame. This data was deduced from the sales and accounting records obtained during the initial stages of the research. Based on these definitions, the value added by the production system during the production of different POP product families was estimated as shown in Tables 17, 18 and 19.

As shown in Table 34, the different production volumes for the six months was considered and multiplied by the unit sales price to determine the monthly sales value for that product type. In the same manner average material prices for the different product types was considered and multiplied by the respective production volumes to determine the initial material values. This was estimated for ‘high and low work content standard units’. From the figures shown in Table 34, it can be estimated that the production system added values of £74,200 and £78,400, representing 118% and 91.4% for Units A and B respectively.

Standard Units												
	High (Unit A)						Low (Unit B)					
Months	Prod vol	Unit Material value (£)	Value of input Materials (Pi) (£)	Unit sales price (£)	Sales value (Po) (£)	Value added (Po-Pi)	Prod Vol	Unit Material value (£)	Value of input Material (Pi) (£)	Unit sales price (£)	Sales value (Po) (£)	Value added (Po-Pi)
Jun-07	23	450	10350	980	22,540	12,190	33	350	11550	670	22,110	10,560
Jul-07	20	450	9000	980	19,600	10,600	43	350	15050	670	28,810	13,760
Aug-07	46	450	20700	980	45,080	24,380	25	350	8750	670	16,750	8,000
Sep-07	14	450	6300	980	13,720	7,420	55	350	19250	670	36,850	17,600
Oct-07	23	450	10350	980	22,540	12,190	57	350	19950	670	38,190	18,240
Nov-07	14	450	6300	980	13,720	7,420	32	350	11200	670	21,440	10,240
Total	140		63,000		137,200	74,200	245		85,750		164,150	78,400

Table 34: Estimation of values derived from standard units

From Table 34, the total value realized through the sale of Units A and B are £137, 200 and £164,150 for production volumes of 140 and 245 respectively. Hence the average value per every type of Unit A is £980 and Unit B is £670.

To estimate values generated through the sale of Units C and D, production volumes for the six months was used to multiply the average unit sale values for the months and compared with the material values as described in Table 35.

Repeat unit												
	High						Low					
Months	Prod vol	Unit Material value (£)	Value of input Materials (Pi) (£)	Unit sales price (£)	Sales value (Po) (£)	Value added (Po-Pi)	Prod vol	Unit Material value (£)	Value of input Material (Pi) (£)	Unit sales price (£)	Sales value (Po) (£)	Value added (Po-Pi)
Jun-07	42	300	12600	700	29,400	16,800	63	298	18774	750	47,250	28,476
Jul-07	47	210	9870	800	37,600	27,730	54	298	16092	750	40,500	24,408
Aug-07	52	350	18200	822	42,744	24,544	45	298	13410	750	33,750	20,340
Sep-07	55	322	17710	798	43,890	26,180	43	298	12814	750	32,250	19,436
Oct-07	49	280	13720	802	39,298	25,578	51	298	15198	750	38,250	23,052
Nov-07	55	305	16775	700	38,500	21,725	44	298	13112	750	33,000	19,888
Total	300		88875		231,432	142,557	300		89,400		225,000	135,600

Table 35: Estimation of values derived from repeat units

Unlike standard units, significant differences existed in the material and sale prices of the different repeat units produced for the months. Therefore, different average material prices and sale values were estimated and used for subsequent analysis. Studying the results shown in Table 35, it can be deduced that the average value added by POP Ltd for the sale of Unit C product families is 160% and 152% for Unit D product families. Material prices generally, for these types of product families was about 30%-50% of the total value realized. This partly explains why over stocking leads to high inventory cost in POP Ltd and hence low profit generation. Also the total average monthly sale value generated from the sale of repeat units is £456,432.00 as compared with the average total sales value of £301,350.00 for standard units

The last form of top level value generation analysis was performed on ‘update and graphic only kits’. In a similar manner, production volumes, material prices and sale prices were used to estimate the values that was added by POP Ltd whilst meeting customer requirements. Table 36 shows the results derived from the value estimations performed on ‘update and graphic only units’.

	Update kits						**Graphic based kits**					
Months	Prod vol	Unit Material value (£)	Value of input Materials (Pi) (£)	Unit sales price (£)	Sales value (Po) (£)	Value added (Po-Pi)	Prod vol	Unit Material value (£)	Value of input Material (Pi) (£)	Unit sales price (£)	Sales value (Po) (£)	Value added (Po-Pi)
Jun-07	148	102	15096	250	37,000	21,904	348	62	21576	150	52,200	30,624
Jul-07	146	110	16060	302	44,092	28,032	284	55	15620	280	79,520	63,900
Aug-07	163	80	13040	290	47,270	34,230	269	101	27169	198	53,262	26,093
Sep-07	164	130	21320	400	65,600	44,280	269	68	18292	302	81,238	62,946
Oct-07	144	95	13680	333	47,952	34,272	262	72	18864	313	82,006	63,142
Nov-07	155	200	31000	298	46,190	15,190	389	69	26841	298	115,922	89,081
Total	920		110,196		288,104	177,908	1821		128,362		464,148	335,786

Table 36: Estimation of values derived from kits

Results shown in Table 36, confirm that very high values were achieved through the sale of high quantities of kits. Essentially in estimating the unit value contribution for kits, it was realized that the sale of one update kit has a value of £313.16 whilst a unit graphic only kit contributes £254.89 value. Hence values realized by POP Ltd is dependent on unit sale prices as well as production volumes. For example because of the high production volumes of kits, the total average monthly value obtained through the sale of kits is £125,375.33 for an average monthly production volume of 457 products. By dividing the average value added with the initial material values, the percentage increase in value is 161% and 262% for update and graphic only kits respectively.

At the next level, since the objective of the research is to use values and cost generated by business process as a basis for recommending process improvements, it was decided to estimate actual values added and cost generated by the individual business processes required to produce the six product families. The end result of these estimates together with the process cost incurred as a result of the realization of the business processes was indicated on the sub-level cost and value stream model created for the various product types. Up to this point, analysis was limited to the direct value adding processes identified as the core manufacturing processes, ‘produce and deliver POPs’ (DP4).

To estimate values added by DP4, ‘value estimation indices’ were defined and used for determining the amount of value generated through the realization of DP4. Average percentage estimates were used. Based on the definition of value proposed through this research, value estimation indices were determined through a cooperate exercise with the accounting department. Basically it involved determining the resource values of the company and estimating in proportion how different sections contribute to the overall resource value of the company. It is a reflection of the percentage resource inputs in sections of the company. Technically these are representations of cost percentages, but based on the authors view of value as defined in section 3.2: ‘the degree of value realized through a process is dependent on resources associated with the realization of the process. Resources, here, refer to humans, machines and technology necessary to realize the product or service’. Other means of estimating value ratios require determining the ratio of number of components produced by the different BPs to the overall number of components. Other methods require determining the portion of weight of parts contributed by the different BPs. Although these methods exist, based on the authors earlier propositions on value (see section 3.2) it was necessary to maintain the value ratios proposed through the resource-based approach. Another view which was harnessed through this research was that, for sub-business processes, their values can be compared with the selling prices of subcomponents they produce. For example, market prices of similar vacformed products can be compared with values generated by the vacform process. Where value indices and hence value estimation at the business process level is impossible, these similar market prices of components are used to compare with process cost so that decisions of make or buy can be explored. This is however not applicable at the Domain process level of POP Ltd since DPs in POP Ltd realize a broad range of products. Hence the value estimation was limited to the value indices whilst at the business process level market prices of components were analysed. In most companies, data already exist, especially when valuation exercise have been done previously. In POP Ltd, the accounts department indicated that the production department (primary manufacturing, assembly and packing) contributed to 65% of the total value of POP Ltd. Table 37 shows the overall value contributions of the respective enterprise domains in POP Ltd.

Top level internal value estimation index			
Domain Number	**Domain Description**	**Value ratios**	**Domain Processes**
1	Customers	0%	Not needed
2	Suppliers	0%	Not needed

3	Front End Business	20%	Not needed
4	Produce and deliver	65%	DP4.1 Make components DP4.2 Assemble and pack products DP4.3 Despatch finished goods
5	Business Management	10%	Not applicable
6	Subcontractors	0%	Not applicable
7	Retail project	0%	Not applicable
8	Support services domain	2.50%	Not applicable
9	Product and process improvement	2.50%	Not applicable
		100%	

Table 37: Value estimation indices of POP Enterprise domains

Based on these indicators, value added on product families by DP4 was estimated as 65% of the total monthly values added by POP Ltd. Results showing the values added by DP4 on realizing Units A, B and C is shown in Table 38.

	Standard Units						**Repeat units**		
	High (Unit A)			**Low (Unit B)**			**High (Unit C)**		
Months	Value added (£)	Value added by DP4 (£)	Average value per product through DP4 (£)	Value added (£)	Value added by DP4 (£)	Average value per product through DP4 (£)	Value added (£)	Value added by DP4 (£)	Average value per product through DP4 (£)
Jun-07	12,190	7,924	**344.50**	10,560	6,864	**208.00**	16,800	10,920	**308.87**
Jul-07	10,600	6,890		13,760	8,944		27,730	18,024.5	
Aug-07	24,380	15,847		8,000	5,200		24,544	15,953.6	
Sep-07	7,420	4,823		17,600	11,440		26,180	17,017	
Oct-07	12,190	7,924		18,240	11,856		25,578	16,625.7	
Nov-07	7,420	4,823		10,240	6,656		21,725	14,121.25	
Total	74,200	48,230		78,400	50,960		142,557	92,662	

Table 38: Estimation of values generated by DP4 for standard and repeat units

From Table 38, it can be observed that Unit A offers a higher unit value addition to POP Ltd’s overall value realization as compared to Units B and C. Similar estimations were made for Unit D, Update kits and Graphic only kits and the results is shown in Table 39.

Repeat units			**Kits**					
Low			**Update kits**			**Graphic based kits**		
Value added (£)	Value added by DP4 (£)	Average value per product through DP4 (£)	Value added (£)	Value added by DP4 (£)	Average value per product through DP4 (£)	Value added (£)	Value added by DP4 (£)	Average value per product through DP4 (£)
28,476	18,509	**293.80**	21,904	14,238	**125.70**	30,624	19,906	**119.86**
24,408	15,865		28,032	18,221		63,900	41,535	
20,340	13,221		34,230	22,250		26,093	16,960	
19,436	12,633		44,280	28,782		62,946	40,915	
23,052	14,984		34,272	22,277		63,142	41,042	
19,888	12,927		15,190	9,874		89,081	57,903	
135,600	88,140		177,908	115,640		335,786	218,261	

Table 39: Estimation of values generated by DP4 for repeat units and kits

Results shown in Tables 38 and 39 are further expressed graphically to depict the range of value realizations for the various product families (see figure 75).

Figure 75: Values generated by DP4

In principle, the values generated by DP4 were essentially derived through the realization of business processes belonging to DP4. From the previously constructed enterprise model of POP Ltd, it was observed that DP4 can be decomposed into three business processes, which are ‘make components’ (BP4.1), ‘assemble and pack products’ (BP4.2) and ‘despatch finished goods’ (BP4.3). Next level cost and value stream models were again constructed for the products realized through these processes as shown in figure 76. To further estimate values added by these business processes, the value estimation indices for these business processes were visited. Accounts records show that ‘make components’ (BP4.1) contributed to 80% of value generation in POP Ltd, whilst ‘assemble and pack products (BP4.2) and despatch finished goods contributed 10% and 2.60% respectively. In the case of DP4, allowance was made for the provision of external parts and this was allotted 7.40%. These percentages were used to estimate values generated for the different product families through BPs 4.1,4.2 and 4.3. As explained previously, in addition to estimating value indices, market prices of similar products realized by the BPs were compared with the values predicted by the value indices. Comparing the prices of similar products realized by the BPs, there was not much difference, hence the results deduced from the value indices approach was maintained and used for further business analysis. Table 40 shows the value estimation ratios for BPs 4.1 – 4.3 and the corresponding value ratios for their sub-sub BPs.

Business process level internal value estimation index			
Domain Processes	**Value ratios**	**Business processes**	**Value ratios**
BP4.1 Make components	80%	BP4.1.1 Make prints	20%

		BP4.1.2 Make wooden & plastic parts	5%
		BP4.1.3 Heat bend parts	5%
		BP4.1.4 Vacform parts	35%
		BP4.1.5 Produce moulded parts	35%
			100%
BP4.2 Assemble and pack products	10%	BP4.2.1Release products	1%
		BP4.2.2 Lean assemble POPs	50%
		BP4.2.3 Batch assemble POPs	45%
		BP4.2.4 Pack finished POPs	4%
			100%
BP4.3 Despatch finished goods	2.60%	Not needed	
* External	7.40%	Not needed	

Table 40: Value estimation indices of BPs 4.1, 4.2 and 4.3

Based on these indices, the value added by BPs 4.1 and 4.2 for the different product families are as shown in Table 41.

Product family	BP4.1	BP4.2
Unit A	£275.58	£34.44
Unit B	£166.38	£20.82
Unit C	£247.08	£30.90
Unit D	£235.02	£29.40
Update Kits	£100.56	£0
Graphic only kits	£95.88	£0

Table 41: Values added by BP4.1 and BP4.2

To fully appreciate the importance of the value estimations, detailed cost estimations were made for each business process belonging to DP4. This was to help understand the economic benefits attainable in fulfilling identified business processes in POP Ltd. The proposition maintained in this estimation exercise is that process parameters such us operation times, queue size, setup times, movements, delays, lead times, resource availabilities and all the lean metrics specified in published literature as essential for reducing waste, contribute to the generation of cost. Hence process cost estimates were based on conventional lean VSM parameters. The contrast is that in most published literature, such process parameters have been used in estimating values added by processes. But in reality, these parameters contribute to cost generation. Thus in essence, economic value generation depends on a number of other external factors which may be beyond the control of the company but process cost can be reduced such that the net profit or value obtained by the company is high.

In estimating process cost of the business processes in 'produce and deliver POPs' (DP4), current cost engineering methods and equations as proposed by Son (Son 1991) and demonstrated in the first case study (chapter 5) were deployed. Based on equations 3 -10, process cost for each of the business processes belonging to DP4, was estimated. To help provide a background for the estimations method adopted, an example process cost estimate for Unit A and Update is shown in Tables 42 and 43 respectively. The estimate was fundamentally supported by the process details specified on the static cost and value stream maps presented in figures 71-74. The total direct process cost for a business process was estimated as the sum of cost related to labour, machine utilization, storage, movement. A minimum labour rate of £5.65 was used for all estimates of labour cost. The Accounts department assisted in assigning machine utilization rates. This was based on agreed accounting figures adopted by the company. Since the authors findings was to be understood and applied by process owners of POP Ltd, it was decided that these accounting figures will not be changed. As of the time of the research, there was no records on movements and also no extensive analysis had been done on queue sizes and queue times. Since essentially the data used for these analysis referred to processes which had been realized in the past, it was decided that by conducting simulation of actual product flows, queue sizes and queue times can be observed and used as for estimating storage cost. Storage cost was therefore considered to be zero during the initial cost estimations.

Estimation of process cost for Unit A

Sub business processes	Sub-sub business processes	Average operation time (mins), t	Prod vol, v	Labour cost (£)= txvx5.65/60	Machine rates per min (£), r	Machine utilization cost (£) = rxtxv	Movement cost (£)	Storage cost (£)	Total direct process cost (£), P	Average direct process cost per unit (£) = P/v
BP4.1.1 Make prints	BP4.1.1.1 Develop screens	78	140	1,028.30	0.116	1,266.72	0	0	2,295.02	16

(20%)	BP4.1.1.2 Screen print manually	96	140	1,265.60	0.020	268.80	0	0	1,534.40	11
	BP4.1.1.3 Auto screen print	50	140	659.17	0.083	583.10	0	0	1,242.27	9
	BP4.1.1.4 Make digital prints	6	140	79.10	0.116	97.44	0	0	176.54	1
	BP4.1.1.5 Laminate	8	140	105.47	0.050	56.00	0	0	161.47	1
	BP4.1.1.6 Make platens	1	140	13.18	0.127	17.74	0	0	30.92	0
	BP4.1.1.7 Make pad prints	1	140	13.18	0.117	16.34	0	0	29.52	0
	BP4.1.1.8 Make polydromes	60	140	791.00	0.020	168.00	0	0	959.00	7
	BP4.1.1.9 Print components	1	140	13.18	0.127	17.74	0	0	30.92	0
	BP4.1.1.10 Cut prints	1	140	13.18	0.027	3.78	0	0	16.96	0
BP4.1.2 Make wooden & plastic parts (5%)	BP4.1.2.1 Produce wooden parts	120	140	1,582.00	0.111	1,864.80	0	0	3,446.80	25
	BP4.1.2.2 Fabricate plastics	110	140	1,450.17	0.111	1,709.40	0	0	3,159.57	23
	BP4.1.2.3 Assemble parts	125	140	1,647.92	0.001	17.50	0	0	1,665.42	12
	BP4.1.2.4 Spray parts	40	140	527.33	0.117	653.52	0	0	1,180.85	8
BP4.1.3 Heat bend parts (5%)	BP4.1.3.1 Prepare mould	40	140	527.33	0.010	56.00	0	0	583.33	4
	BP4.1.3.2 Heatform parts	60	140	791.00	0.010	84.00	0	0	875.00	6
BP4.1.4 Vacform parts		20	140	263.67	0.117	326.76	0	0	590.43	4

BP4.1.5 Produce moulded parts		6	140	79.10	0.117	98.03	0	0	177.13	1
BP4.2.1Release products		15	140	197.75	0.000	0.21	0	0	197.96	1
BP4.2.2 Lean assemble POPs		23	140	303.22	0.117	375.77	0	0	678.99	5
BP4.2.3 Batch assemble POPs		30	140	395.50	0.117	490.14	0	0	885.64	6
BP4.2.4 Pack finished POPs		40	140	527.33	0.001	5.60	0	0	532.93	4
		931						Total	20,451.07	146

Table 42: Estimation of process cost for Unit A

Estimation of process cost for Update kits

Sub business processes	Sub-sub business processes	Average operation time (mins), t	Prod vol, v	Labour cost (£)= txvx5.65/60	Machine rates per min (£), r	Machine utili cost (£) = rxtxv	Move cost (£)	Storage cost (£)	Total direct process cost (£), P	Average direct process cost per unit (£) = P/v
BP4.1.1 Make prints	BP4.1.1.1 Develop screens	68	920	5,891.07	0.116	7,256.96	0	0	13,148.03	14
	BP4.1.1.2 Screen print manually	70	920	6,064.33	0.020	1,288.00	0	0	7,352.33	8
	BP4.1.1.3 Auto screen print	50	920	4,331.67	0.083	3,831.80	0	0	8,163.47	9
	BP4.1.1.4 Make digital prints	5	920	433.17	0.116	533.60	0	0	966.77	1
	BP4.1.1.5 Laminate	5	920	433.17	0.050	230.00	0	0	663.17	1
	BP4.1.1.6 Make platens	1	920	86.63	0.127	116.56	0	0	203.20	0
	BP4.1.1.7 Make pad prints	1	920	86.63	0.127	116.56	0	0	203.20	0
	BP4.1.1.8 Make polydromes	25	920	2,165.83	0.127	2,914.10	0	0	5,079.93	6
	BP4.1.1.9 Print	1	920	86.63	0.127	116.56	0	0	203.20	0

	components									
	BP4.1.1.10 Cut prints	1	920	86.63	0.127	116.56	0	0	203.20	0
BP4.1.2 Make wooden & plastic parts	BP4.1.2.1 Produce wooden parts	80	920	6,930.67	0.127	9,325.12	0	0	16,255.79	18
	BP4.1.2.2 Fabricate plastics	80	920	6,930.67	0.127	9,325.12	0	0	16,255.79	18
	BP4.1.2.3 Assemble parts	90	920	7,797.00	0.127	10,490.76	0	0	18,287.76	20
	BP4.1.2.4 Spray parts	30	920	2,599.00	0.127	3,496.92	0	0	6,095.92	7
BP4.1.3 Heat bend parts	BP4.1.3.1 Prepare mould	40	920	3,465.33	0.127	4,662.56	0	0	8,127.89	9
	BP4.1.3.2 Heatform parts	50	920	4,331.67	0.127	5,828.20	0	0	10,159.87	11
BP4.1.4 Vacform parts		20	920	1,732.67	0.127	2,331.28	0	0	4,063.95	4
BP4.1.5 Produce moulded parts		6	920	519.80	0.127	699.38	0	0	1,219.18	1
BP4.2.1Release products										
BP4.2.2 Lean assemble POPs										
BP4.2.3 Batch assemble POPs										
BP4.2.4 Pack finished POPs										
								Total	116,652.63	127

Table 43: Estimation of process cost for Update kits

Based on the above cost estimations, it can be summed that the process cost for BPs 4.1 and 4.2 are as follows:

Product family	BP4.1	BP4.2
Unit A	£130	£16
Unit B	£113	£13
Unit C	£108	£13
Unit D	£100	£13
Update Kits	£99	£0
Graphic only kits	£2	£0

Table 44: Summary of cost estimates for BPs 4.1 and 4.2

Cost estimates for 'despatch finished goods' (BP4.3) was omitted in this analysis because in POP Ltd, although it was obvious, the Managers confirmed that despatch of POP finished goods was not a major issue.

The resultant cost and value stream model for BPs 4.1 and 4.2 realizing the six product families is shown in figure 76.

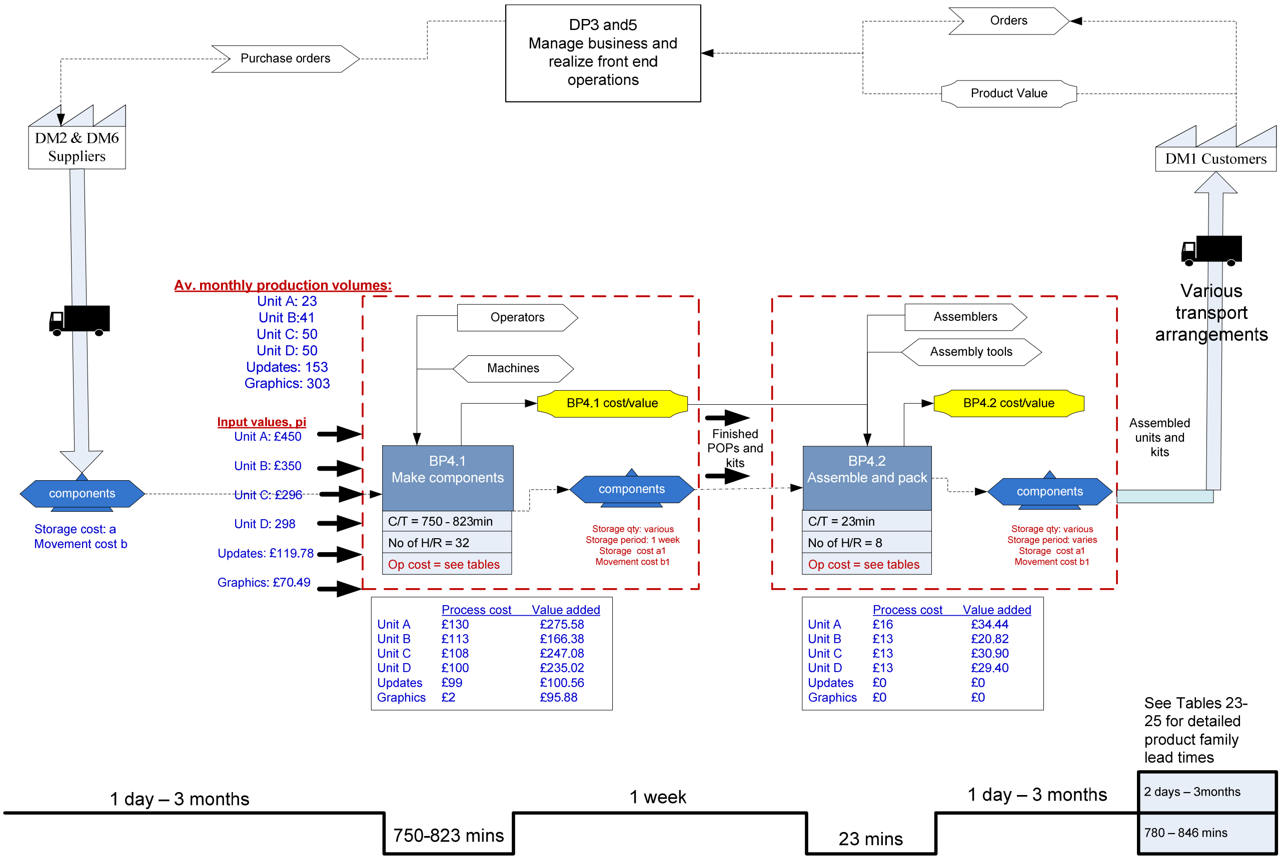


Figure 76: BP level cost and value stream model

This BP level cost and value stream model (figure 76) was linked to the parent model (figure 70) so that cost and values can be traced. As stated in chapter 5, the non-commercial improved MS Visio tool developed by the MSI Research Institute assisted in automatically linking sub models to parent models so that in-depth analysis can be performed.

Further analysis on the cost and value contributions of sub business processes belonging to BP4.1 and 4.2 were made by adopting the same estimation principles as described previously. To achieve average values generated for each product family, total values generated by the sub business process was divided by the total number of products processed through that business process. This was performed for all the product families. In addition market price information of similar products realized for these sub BPs were compared with the estimated values. The values estimated was found to be less than the market selling prices of similar components, hence the estimated process values were considered to be the limiting factor for efficiency estimation and was therefore used for further analysis. Referring to the value indices in Table 40 and the product values realized by BP4.1 and BP4.2 as shown in Table 44, average product values per unit for the different sub business processes was estimated and shown in Table 45.

Sub BPs	Unit A	Unit B	Unit C	Unit D	Update kits	Graphics
BP4.1.1	£55	£33	£49	£47	£20	£96
BP4.1.2	£14	£8	£12	£12	£5	£0
BP4.1.3	£14	£8	£12	£12	£5	£0
BP4.1.4	£96	£58	£86	£82	£35	£0
BP4.1.5	£96	£58	£86	£82	£75	£0
BP4.2.1	£0.34	£0.21	£0.31	£0.29	£0	£0
BP4.2.2	£17.23	£10.4	£15.44	£14.69	£0	£0
BP4.2.3	£15.50	£9.36	£13.90	£13.22	£0	£0
BP4.2.4	£1.38	£0.83	£1.24	£1.18	£0	£0

Table 45: Average product values for sub business processes

After deriving these average values, cost generated as a result of achieving these processes was estimated. A summary of these cost estimates for the different product families is shown in Table 46.

Sub BPs	Unit A	Unit B	Unit C	Unit D	Update kits	Graphics
BP4.1.1	£45	£38	£38	£36	£35	£12
BP4.1.2	£68	£58	£51	£47	£47	£0
BP4.1.3	£10	£10	£10	£9	£9	£0
BP4.1.4	£4	£4	£4	£4	£4	£0
BP4.1.5	£1	£1	£1	£1	£1	£0
BP4.2.1	£1	£1	£1	£1	£0	£0
BP4.2.2	£5	£5	£5	£5	£0	£0
BP4.2.3	£6	£5	£5	£5	£0	£0
BP4.2.4	£4	£2	£2	£2	£0	£0

Table 46: Process cost estimates for sub business processes

Thinking about the sub-sub BPs which exist in BPs 4.1 and 4.2, it was realized that ‘vacform parts’ (BP4.1.4), ‘Produce moulded parts’ (BP4.1.5), ‘Release products’ (BP4.2.1), ‘Lean assemble POPs’ (BP4.2.2), ‘Batch assemble POPs’ (BP4.2.3) and ‘Pack finished POPs’ (BP4.2.4) require no further decomposition to sub-sub BPs. Instead these processes are decomposed into their elemental Enterprise Activities (EAs). Hence at the next stage of modelling subsequent analysis and cost and value stream modelling of sub-sub BPs was conducted for only sub-sub BPs belonging to ‘Make prints’ (BP4.1.1), ‘Make wooden and plastic parts’ (BP4.1.2) and ‘Heat bend parts’ (BP4.1.3) processes. Referring to Tables 46 and based on the value indices shown in Table 40, average values generated by sub-sub BPs 4.1.1.1 - 4.1.1.10, BPs 4.1.2.1 – 4.1.2.4 and BPs 4.1.3.1 - 4.1.3.2 was estimated. The detailed values generated by these sub-sub business processes based on their respective value ratios is shown in Table 47.

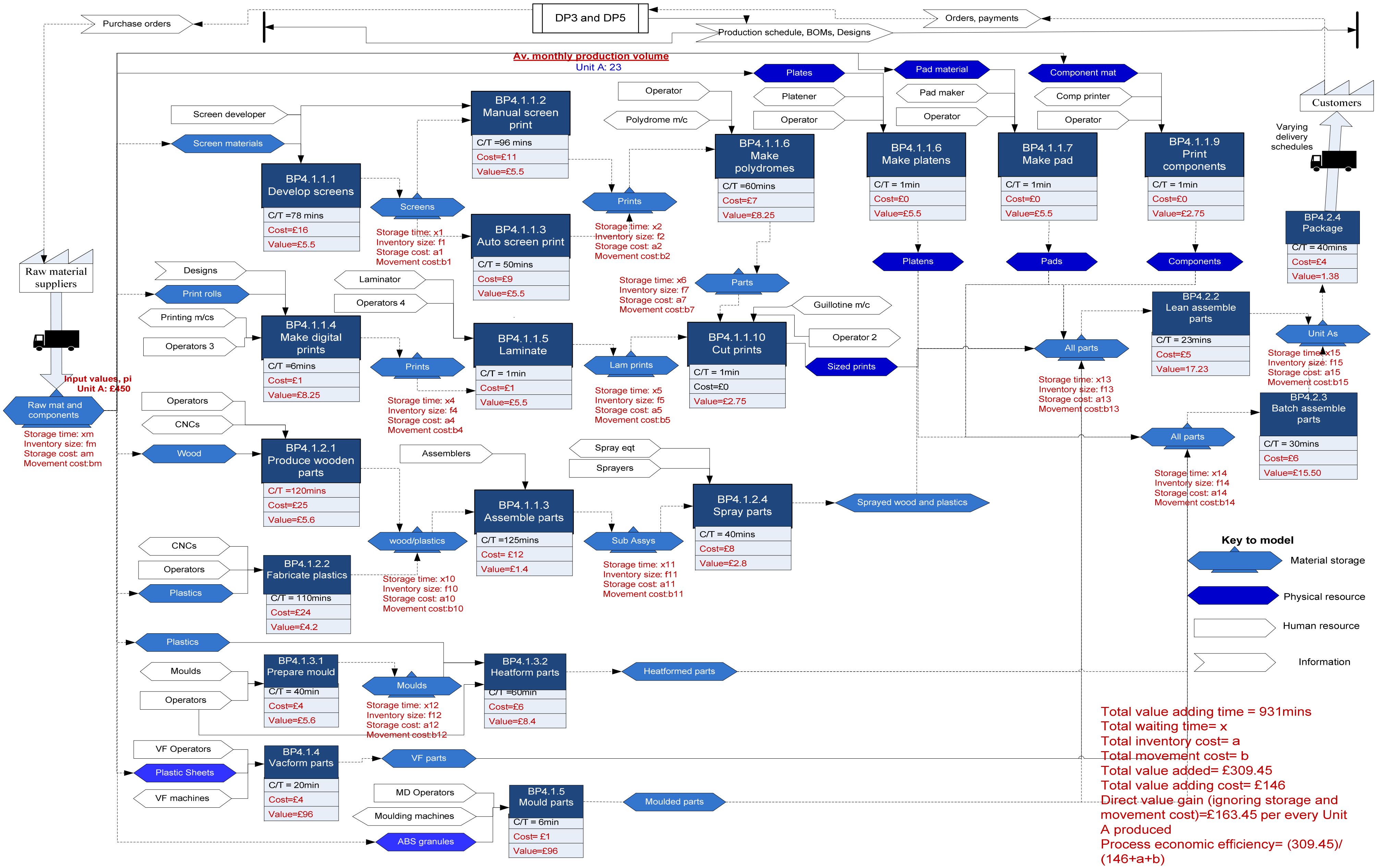
Values realized by sub-sub business process

Business processes	**Sub-business process**	**Value ratios**	Average value realized: Unit A (£)	Average value realized: Unit B (£)	Average value realized: Unit C (£)	Average value realized: Unit D (£)	Average value realized: Update kits (£)	Average value realized: Graphic only (£)
BP4.1.1 Make prints (20%)	BP4.1.1.1 Develop screens	10%	5.5	3.3	4.9	4.7	2.0	
	BP4.1.1.2 Screen print manually	10%	5.5	3.3	4.9	4.7	2.0	
	BP4.1.1.3 Auto screen print	10%	5.5	3.3	4.9	4.7	2.0	
	BP4.1.1.4 Make digital prints	15%	8.25	5.0	7.4	7.1	3.0	14.38
	BP4.1.1.5 Laminate	10%	5.5	3.3	4.9	4.7	2.0	9.59
	BP4.1.1.6 Make platens	10%	5.5	3.3	4.9	4.7	2.0	
	BP4.1.1.7 Make pad prints	10%	5.5	3.3	4.9	4.7	2.0	
	BP4.1.1.8 Make polydromes	15%	8.25	5.0	7.4	7.1	3.0	
	BP4.1.1.9 Print components	5%	2.75	1.7	2.5	2.4	1.0	
	BP4.1.1.10 Cut prints	5%	2.75	1.7	2.5	2.4	1.0	

									4.79
BP4.1.2 Make wooden & plastic parts (5%)	BP4.1.2.1 Produce wooden parts	40%	5.6	3.3	4.9	4.7	2.0		
	BP4.1.2.2 Fabricate plastics	30%	4.2	2.5	3.7	3.5	1.5		
	BP4.1.2.3 Assemble parts	10%	1.4	0.8	1.2	1.2	0.5		
	BP4.1.2.4 Spray parts	20%	2.8	1.7	2.5	2.4	1.0		
BP4.1.3 Heat bend parts (5%)	BP4.1.3.1 Prepare mould	40%	5.6	3.3	4.9	4.7	2.0		
	BP4.1.3.2 Heat form parts	60%	8.4	5.0	7.4	7.1	3.0		

Table 47: Estimation of values generated by sub-sub business processes of BPs 4.1.1 – 4.1.3

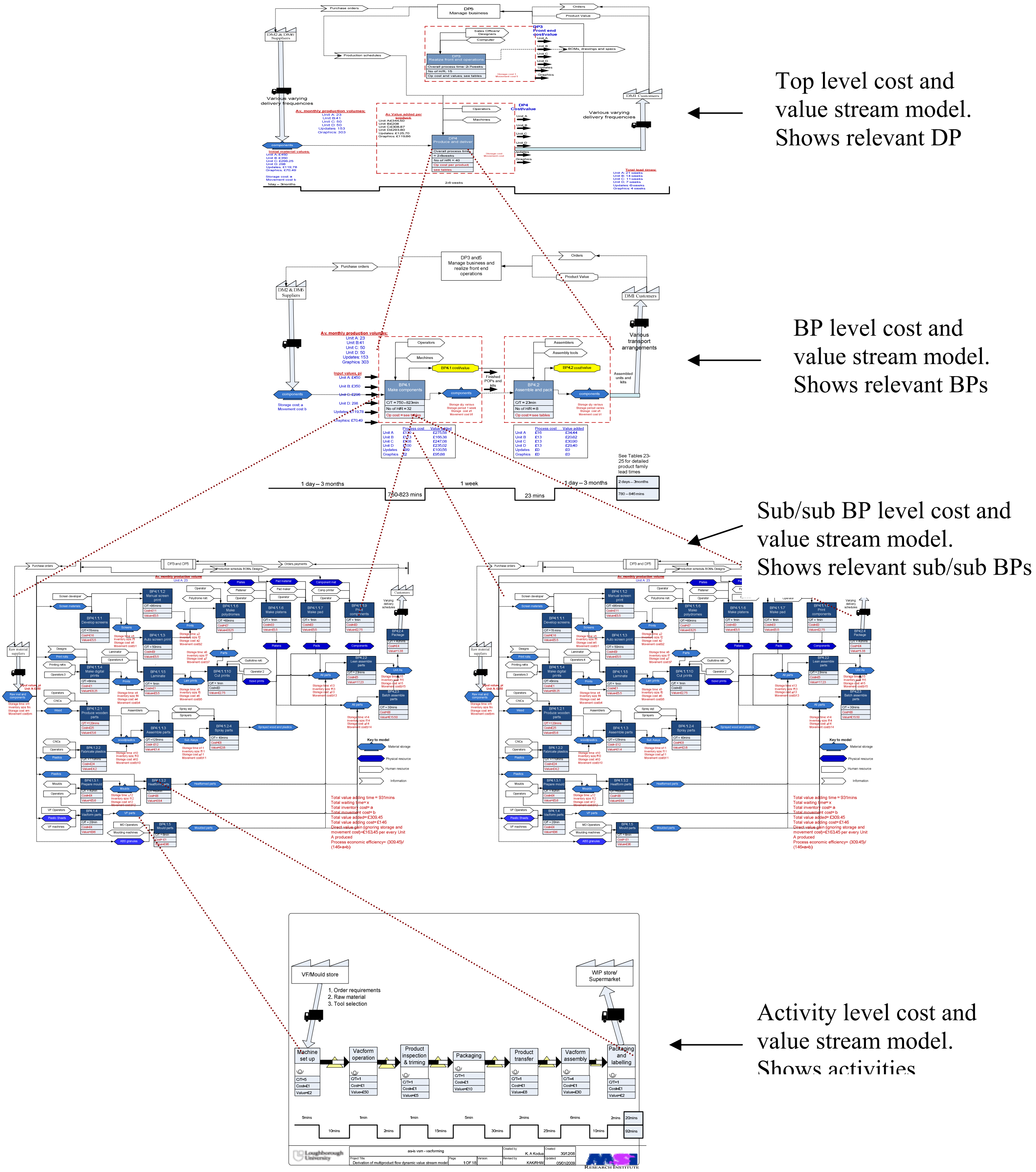
A model representing the cost and values implication of the flow of material, resources and information through the current state sub-sub business processes required to fulfil the production of Unit A is shown in figure 77. The cost and values shown on the model were derived from figures shown on Tables 45,46,47.



Total value adding time = 931mins
Total waiting time= x
Total inventory cost= a
Total movement cost= b
Total value added= £309.45
Total value adding cost= £146
Direct value gain (ignoring storage and movement cost)=£163.45 per every Unit A produced
Process economic efficiency= (309.45)/(146+a+b)

Figure 77: Sub-sub business process level cost and value stream model for producing Unit As

In principle further lower level cost and value stream models can be generated by observing the activities required to fulfil the sub-sub business processes. Creation of activity based cost and value stream models will depend on the intention and purpose of the modelling exercise. In reality since activity diagrams for the sub-sub business processes were created during the enterprise model development, it is fairly simple to develop activity based cost and value stream models. However in this exercise, because of the intended transformation of static models to dynamic simulation models, it was not necessary to create detailed activity based cost and value stream models. Activity based cost and value stream models were captured during the dynamic simulation modelling. exercise. The idea presented here is that, BPs are realized through the execution of sets of activities defined as elementary 'activity configurations'. Thus a hierarchical cost and value stream modelling scheme can be enacted where elementary activity based cost and value streams are connected to their sub-sub BP models, which are also connected to their BPs and then to their DPs and DMs. By adopting this approach, modelling elements can be captured in context and analysed within a frame work consistent with their application. An illustration of how top level cost and value stream models can be decomposed in stages to their finest level of activity cost and value streams is shown in figure 78.



Top level cost and value stream model. Shows relevant DP

BP level cost and value stream model. Shows relevant BPs

Sub/sub BP level cost and value stream model. Shows relevant sub/sub BPs

Activity level cost and value stream model. Shows activities

Figure 78: Illustration of hierarchical decomposition of process based cost and value streams

7.6 Analysis of static cost and value stream model of production system of POP Ltd

A number of static analyses can be performed on the results displayed in section 7.5.4.1. This is to form the basis for recommending improvement on relevant BPs in POP production processes. The analysis of results described in this section takes into consideration that essential information on inventories and movements in POP Ltd were not captured in the static model. For example movement and storage cost which are critical waste indicators were not captured in the model. This is because data used in the results generation are based on already achieved products and it was extremely difficult to estimate for the different products families, the inventory sizes, queue times and number of movements between processing stations. This limitation was overcame in the dynamic cost and value stream models as it was generated automatically when processing and completion times were assigned in the model. This approach was more suitable as it was easier for the Managers of POP Ltd to verify queue sizes, queue times as described by the simulation model.
Notwithstanding, essential process analysis was conducted on the results achieved through the static cost and value stream model. Some of the useful analyses are described in the sub sections that follow.

7.6.1 Cost and value analysis of BPs

A summary of the direct operational cost and values generated by key BPs realizing different product families is shown in figure 79. From the summary results, it can be seen that for Unit A, ‘vacform parts’ (BP4.1.4) and ‘produce moulded parts’ (BP4.1.5) generate high values. On the contrary, operational cost exceeds value generated for ‘develop screens’ (BP4.1.1.1), ‘screen print manually’ (BP4.1.1.2), ‘auto screen print’ (BP4.1.1.3), ‘produce wooden parts’ (BP4.1.2.1), ‘fabricate plastics’ (BP4.1.2.2), ‘assemble parts’ (BP4.1.2.3) and ‘spray parts’ (BP4.1.2.4) processes

Figure 79: Cost and values compared for Unit A production

Similar results were obtained for Units B, C and D. Studying the summary results of cost and values generated during the production of Update kits, it was noticed that in addition to the processes whose operational cost exceeded their values generated, for Units A,B,C and D, three more BPs produced parts at a higher cost than their values.

Figure 80: Cost and values compared for Update kits production

These additional processes are ‘ prepare mould’ (BP4.1.3.1), ‘heat form parts’ (BP4.1.3.2) and ‘make polydromes’ (BP4.1.1.8).

7.6.2 Comparison of values realized by product families

Based on ‘as-is’ operations of POP Ltd and six months sales record, figure 81 shows that for single products belonging to each of the product families, Unit A generates the highest value of 24% whilst Update and Graphic only kits generates the least unit value of 9%.

Figure 81: Unit value addition by different product families

Units C and D also provide reasonably high values of 22% and 21% respectively. This implies that when more orders of Unit A, C and D are produced, POP Ltd is likely to accumulate high values. However, a study of the production pattern of POP Ltd, shows that for the production period specified, graphic-only kits contributed 36% of the total value generated whilst Units A and B produced the least values of 8% each. This is because, within the period of study, POP Ltd produce high volumes of graphic only kits and less volumes of Units A and B. If this trend remains, then efforts will have to be made to reduce the cost involved in producing graphic only kits so that more profits can be realized.

Figure 82: Overall value addition by different product families

7.6.3 Value contribution by BPs

Summing the values realized by sub-sub BPs and assigning them to their corresponding top level BPs, it was observed that for all the product families realized 'vacform parts' (BP4.1.4) and 'produce moulded parts' (BP4.1.5) generated the highest values as shown in figure 83.

At a first glance it would appear that they are the most essential processes which should be focussed on since their cost concentrations are low. But further discussions with Managers of POP Ltd gave different indications as explained in section 7.7.

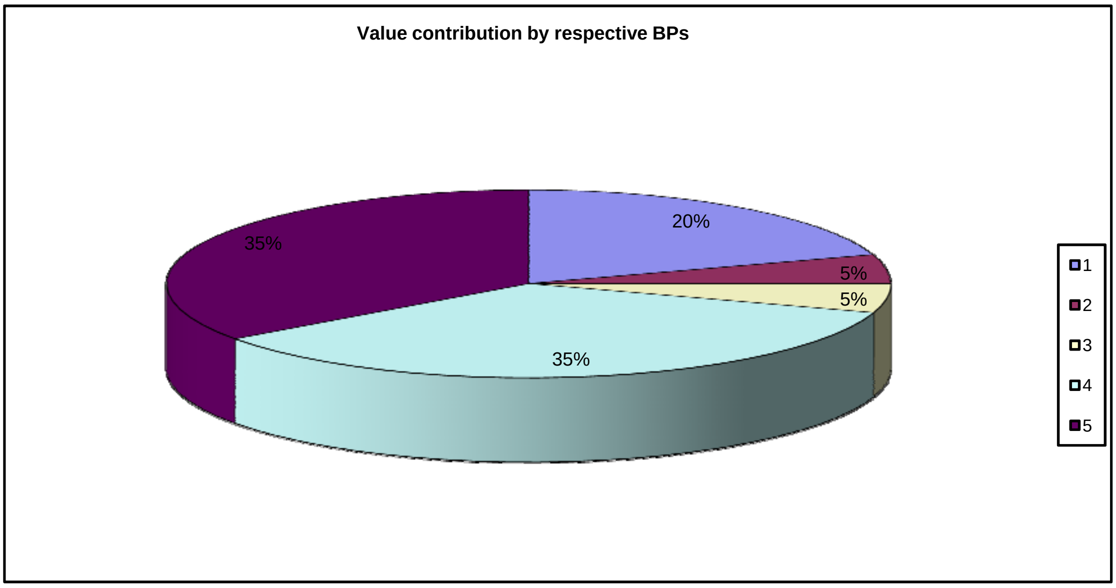


Figure 83: Value contribution by top level BPs

7.7 Observations and conclusions on Chapter 7

Chapter 7 has described how the multiproduct cost and value stream modelling technique was enacted to capture relevant process data, create models with data captured and analyse results derived from the model. The method demonstrated how multiple high volume product flows can be simplified through a process based classification. Process similarity ensures that products following similar process routes were grouped together. Further segregation of products with similar process properties was achieved through the work-content approach to process classification. This ensured that large varieties of products were grouped into six different product families, hence limiting complexities associated with managing large product types. Although there might be some differences in products belonging to the same family, these difference are considered to be minor and hence represents fairly the position of the product families.

The approach introduced a means of identifying networks of processes involved in the realization of specific product families giving room for detailed process-product based analysis, planning and improvements. This was necessary to distinguish process routes and hence provide a better means of analysing multiple products. Most importantly, because processes were decomposed from parent processes to their minute activities, rich understanding about how processes are interconnected and how materials, resources and information are transferred across process segments was achieved. This allowed a detailed analysis to be conducted on processes of interest.

One of the key outcomes of this chapter is the introduction of a method of estimating real values added by business processes. As explained in the literature review, current best practices in modelling value streams essentially maps lead times, cycle times and delays and use these metrics for specifying value added and non-value added processes. In this chapter, it has been seen that most often, process variables such as cycle times, delays, queue sizes and lead times rather affect process cost and not value. It was shown that real economic value achieved by a company is dependent on selling prices of products and production or sales volume. These two factors coupled with the value of resources required to achieve production provide a means of estimating values added by individual business process. Based on these indications, it can be said that in reality improving company values extends beyond internal company operations. Competitive prices, market trend, customer preferences and other factors which affect the sale of products affect value generation. However for higher profits, efforts must be made to reduce process cost by cutting down on operation times, resource and material cost, movements and storage cost. This is because these latter factors affect the cost of production and hence when they are reduced, high profits can be generated even if the values derived do not change. Process redesign is therefore vital to ensure that process metrics which have positive influence on cost are reduced. Chapter 8 describes how qualitative and quantitative modelling techniques are applied to support redesign of business processes to ensure low cost and high profits.

A hierarchical approach to modelling cost and values is described in this chapter. Essentially this approach to modelling cost and value streams ensured that processes are captured and connected to their parent sources so that the impact of one processes on the others can be understood. This approach ensures better understanding and a complete decomposition of processes, therefore providing a means of analysing cost and value generation through a bottom up approach or vice versa. Because the cost and value stream modelling technique depends an enterprise modelling scheme, for companies already involved in the use of enterprise models, the application of the cost and value stream modelling technique will be most suitable. However for companies without knowledge in the creation and application of enterprise models, it implies that additional work will be required to create enterprise models which will form the basis of the modelling technique. One added advantage through the use of this technique is that once first stage enterprise models are created, other benefits associated with the use of the enterprise models such as improved communication among functional entities in companies, instrumentation of business process reengineering, managing system complexities, among others can be obtained. The challenge however is that a lot of time is always required to be able to create a fairly representative enterprise model, which might delay the creation of multiproduct cost and value stream model. Detailed explanations of resource time required for creating models have been shown in chapter 10. However because the technique is built on state of the art enterprise modelling templates, it could serve as a backbone for the development of other system dynamics and simulation models.

However, an improvement in the technique will be perceived along the lines of decomposing only relevant processes of interest when the desire is to conduct cost and value stream analysis on business processes.

Comparing the modelling technique with best literature representation of VSM, it can be seen that additional constructs have been introduced. It was observed that between processes it was necessary to indicated what is transferred in between them. Thus a construct was introduced to represent physical resources which flow between processes. Also a construct was introduced to represent human resources required for process centres. Other construct borrowed from the domain of enterprise modelling to enhance the cost and value stream modelling formalisms include constructs for information and finance. However the static model does not show exactly the type of human resource or physical resource required by process centres. To indicate the type of inventory as well as queue sizes and queue times, a new constructs was also introduced. These new constructs enriched the cost and value stream model making it very informative and comprehensive. However modelling complexity is minimized because of the hierarchical decomposition approach adopted. Reasoning about cost and value streams in the third case study, it was observed that although Unit A requires the longest processing time, the sale of Unit A generate high values for POP Ltd. Hence it may be required on the basis of value sustainability to produce more of Unit A.

Collectively, graphic-only kits generated the highest production value. This basically is because of the high production volumes of graphics-only kits realized. Also among BPs identified in the production processes of POP Ltd, vacforming and moulding operations tend to posses the capability of maintaining high values for all product families in POP Ltd. Although in theory this was the case, the Managers of POP Ltd indicated that vacform and moulding processes are the highest produces of excess inventory and major contributors to overstocking in the company. Hence in the dynamic simulation models, this was investigated with the view to help reduce inventory produced by vacforming and moulding. It is therefore difficult to conclude that vacform and moulding processes offer the highest value contribution to POP Ltd. From the results presented, although storage and movement cost have not be added, it is however clear to indicate that it is expensive to ‘make wooden and plastic parts’ (BP4.1.2). This is because the cost realized by the sub-sub BPs exceeds the values they contribute. Also for all products apart from graphic-only kits, cost generated by ‘develop screens’ (BP4.1.1.1), ‘screen print manually’ (BP4.1.1.2) and ‘auto screen print’ (BP4.1.1.3) processes are higher than the values they bear. Hence potentially, these processes need to be redesigned for better cost or further investigations will be required to assess the possibility of buying parts or outsourcing these processes.

To derive ‘to-be’ models of POP Ltd with better cost and value indicators and also to experiment how production flow and production techniques such as push and pull can be introduced into POP Ltd production system, it was necessary to convert the static models into dynamic simulation models. In the static model, analysis on resource utilization and the contribution of resource efficiency on cost and value generation was not achieved. This was because of the enormous data that would have manually been dealt with. Generally, production systems must be designed to operate effectively at different workload. But alternative workloads and associated dynamic instances of processes cannot be visualized in the static model. Also noted is that cost and values are not static but influenced by process dynamics. These dynamics impact on the processes which intend determine whether cost and values are sustained. This latter is also not depicted in the static model. Also to satisfy the requirements of POP Ltd to redesign their processes to reduce process inventories, production lead times, introduce flow and improve resource utilizations, which are key cost improvement schemes, in Chapter 8, system dynamics and discrete event simulation models were created and used to test various alternative business scenarios which provided scientific background for recommending appropriate process and resource configurations.

8. Unified application of dynamic multiproduct cost and value stream modelling technique

8.1 Introduction

Chapter 8 is a continuation of the case application of the integrated multiproduct cost and value stream modelling technique involving the engineer to order POP manufacturing company, called POP Ltd, based in Loughborough, UK. A description of the problem domains of POP Ltd was given in Chapter 7. To help solve problems related to producing multiple POPs at low cost and high values, it was decided to develop:

1. a comprehensive multi-product static cost and value stream model capable of externalizing understand about direct value adding processes in POP manufacture. Also to use the model to estimate possible values and cost generated by business processes of POP Ltd. The static model was to provide a basis for static analysis of Business Processes (BPs) in POP Ltd.
2. a dynamic multiproduct cost and value stream model for simulation applications. The idea behind this objective is to help develop and test possible business scenarios such that best manufacturing strategies such as push, pull, leagile, etc with potential to reduce cost by increasing production flow, reducing inventory, reducing production lead times, increasing resource utilization can be experimented before implementation. This is pursued with the hope that products can be achieved at the lowest possible process cost and high values. Another aspect was to observe how process dynamic variables impact on cost and values and to use understandings gained from dynamic analysis of process variables to describe causes of process related problems in POP Ltd.

The first objective was achieved in Chapter 7 so Chapter 8 essentially focuses on the second objective. The outcome of chapter 7 was a static model useful for analysing cost and value streams of multiproduct flow systems. In Chapter 8, the static model was further enhanced with system dynamics modelling techniques in the form of causal loops and iThink continuous simulations. A methodology for transforming qualitative causal loop models into quantitative simulation models is introduced. This aspect is a continuation of work in system dynamics as described in Chapter 6. The iThink model provides cumulatively, strategic solutions or policies POP Ltd may have to adopt for effective business operations. For further incremental changes in process states, a discrete event simulation tool, Simul8, was applied to model all the direct value adding processes. Results from the Simul8 model provided specific solutions for key business processes in POP manufacturing.

8.2 Creation of dynamic cost and value stream modelling of POP Ltd production processes

To observe the impact of possible operations in POP Ltd on cost and value generation, the static cost and value stream models (figures 74-77) were enhanced with the system dynamics modelling technique. A ‘top level causal structure’ for the different product families was developed to explicitly describe the interactions and directions of ‘flows’ in the production process. This top level causal structure was based on the cost and value stream models showing the different integrated business processes for various product families. As described in Chapter 6, the creation of the top level causal structure is considered to be the starting point for the conversion of static cost and value stream models into system dynamics models. The top level causal structure for POP Ltd is shown in figure 112.

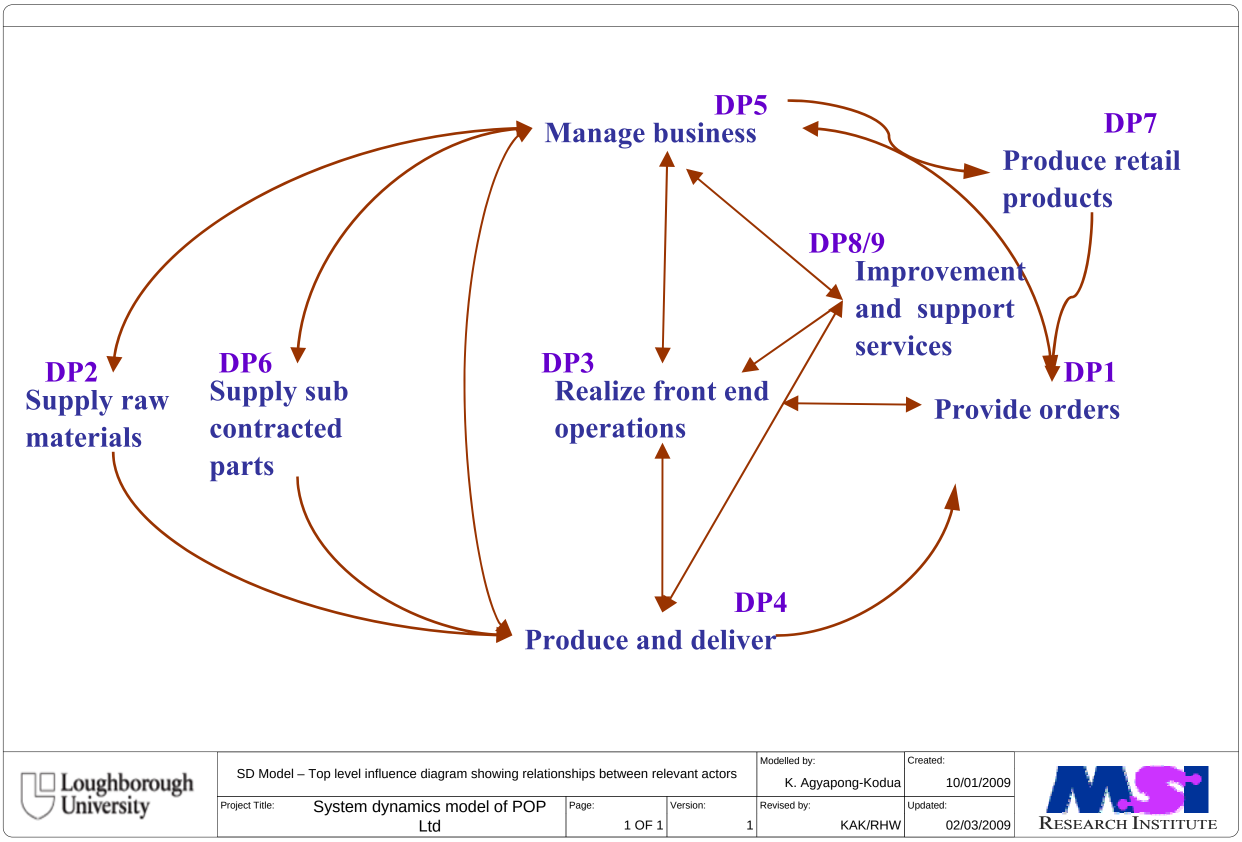


Figure 112: Top level causal structure for POP Ltd

From figure 112, it can be observed that unidirectional flows exist between DP4 and DP1, DP2 and DP4, DP6 and DP4, DP7 and DP1. Bi-directional flows however exist between DPs 1, 4, 5, 8, 9 and DP3. Following up on the static cost and value stream models previously created and shown in figures 74-77, detailed causal loop models (CLM) describing the general process structure and variables inducing process dynamics was created. The detailed CLM showing some key process variables which impact on cost and value generation is shown in figure 113.

From figure 113, it can be seen that ‘POP customer demand’ is influenced by a number of factors. This is an expansion of understanding on ‘provide customer orders’ domain process (DP1). Explanations given by the Sales Manager of POP Ltd proved that customer orders are increased normally by new product launches, contracts to refurbish existing units, contracts to supply update kits, new markets and new stores which require installation of new units. As these demand factors increase, POP Ltd acquires more sale orders. These sale orders are transformed into planograms in the design department. Planograms are higher level ‘design plans’ which specifies different designs and components required for customer orders. They are generated by a Designer normally called a Planogrammer. Planograms specify overall assembly dimensions for products ordered. In POP Ltd, planograms are the basic starting design documents. Based on the planograms, bill of materials (BOMs), graphic designs, product designs, structural designs and prototypes, where necessary, are created. BOMs lead to development of purchase orders for raw materials and parts that need to be subcontracted.

As shown on the CLM in figure 113, increase in number of BOMs increase the number of purchase orders (POs). In the ‘supply materials’ domain process (DP2), as number of POs increase, the supply of materials is expected to increase but this depends on other factors such as: supply agreements or policies, payment terms between suppliers and POP Ltd and available stock of materials. Similar factors influence supply of sub contracted parts but because subcontracted companies are also manufacturers, it largely depends on their internal production capacities and schedules. As supply of material increases, stock of goods in the raw material stores increase. The value of raw materials received is the total sum of the prices of materials received in stock. This normally includes the invoiced value of materials and delivery cost. This serves as an indication of the initial value of the materials yet to be converted by the internal manufacturing processes of POP Ltd. Specifically, six material categories are specified in POP Ltd. Therefore as supply of materials increase, stock of raw materials for printing, moulding, vacuum forming, woodwork and plastic fabrication and other accessories are increased. Other purchased and subcontracted stocks are also increased depending on the order requirements.

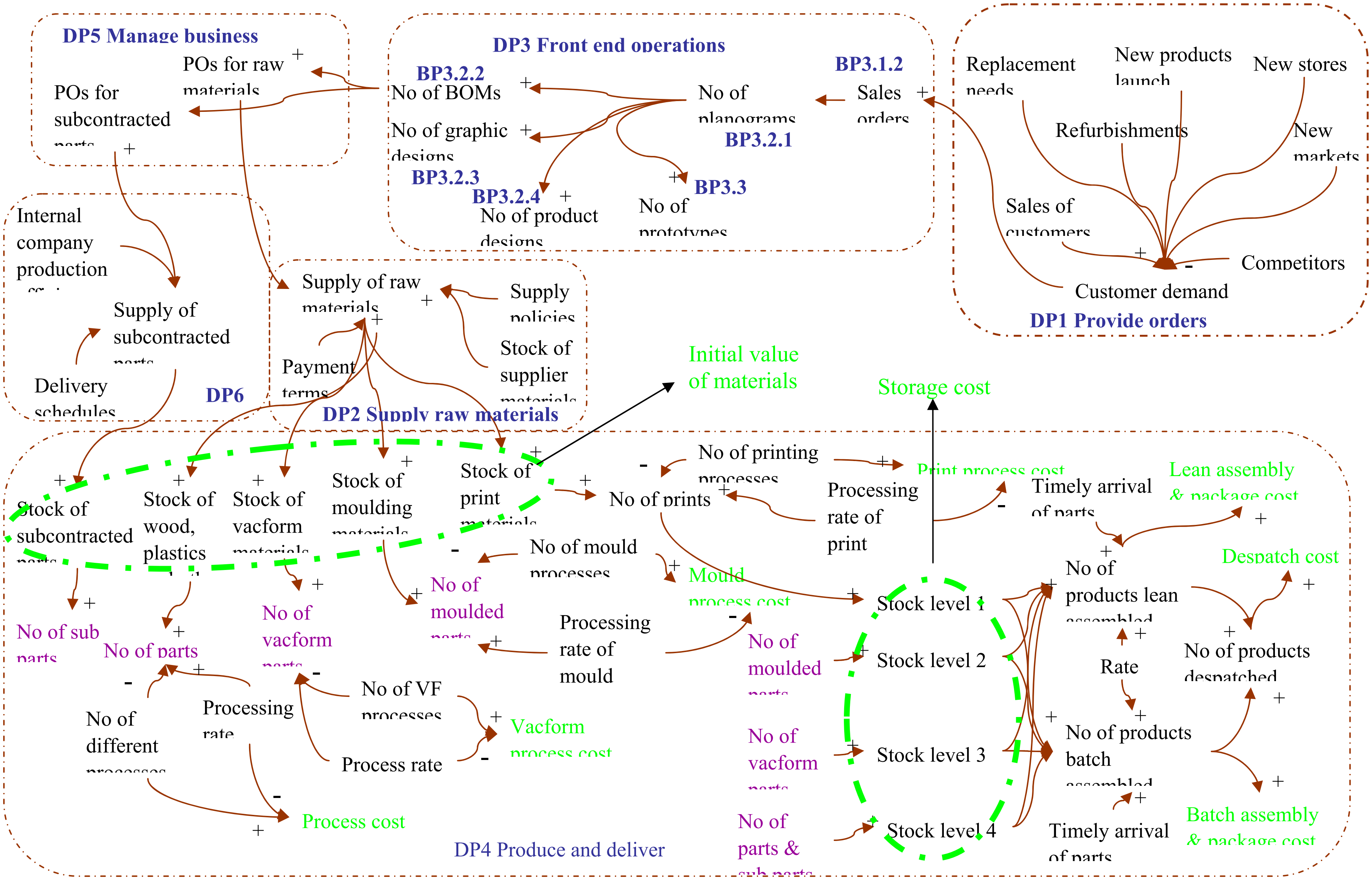


Figure 113: Detailed CLM models of DPs in POP Ltd

In addition to the availability of raw materials, raw materials will have to undergo a number of conversion processes before reaching finished states where they can be assembled together. These processes and their requirements differ from one another but more parts can be produced at high processing rates. High processing rates require appropriate coupling of 'right processes with right resources'. Although this later is not shown in the CLM model for the sake of simplicity, the conversion processes, resources and their rates of achievement, determine the process cost for the four shops. The total number of products assembled is dependent on the timely arrival of parts and the assembly process rate.

These also positively impact on the assembly process cost. In a similar way, package and despatch cost are influenced directly by the assembly process volume and cost of technology utilized.

Other causal loops describing the causes of high inventory levels, long production lead times, lack of production flow, high production cost and low value generation were created to help observe possible change variables which can be manipulated to affect POP Ltd production system so that better production outcomes can be derived. Referring to section 7.2 which documents the earlier problems stated by the Managers of POP Ltd, it was necessary to investigate the exogenous factors which impact on key process variables described in figure 113. This resulted in three 'problem descriptive' CLM models as shown in figures 114-116. In figure 114, it can be seen that inaccurate specification of customer orders lead to high errors in planograms. An explanation given by the Sales Manager showed that in some cases at the initial stages of transactions with customers, customers may not have an accurate idea of what they want. Other cases reported show that there are other times where documentation errors were created by sales officers who correspond with customers. In addition to these factors, the competence of planogrammers plays a critical role in ensuring that planograms are accurate.

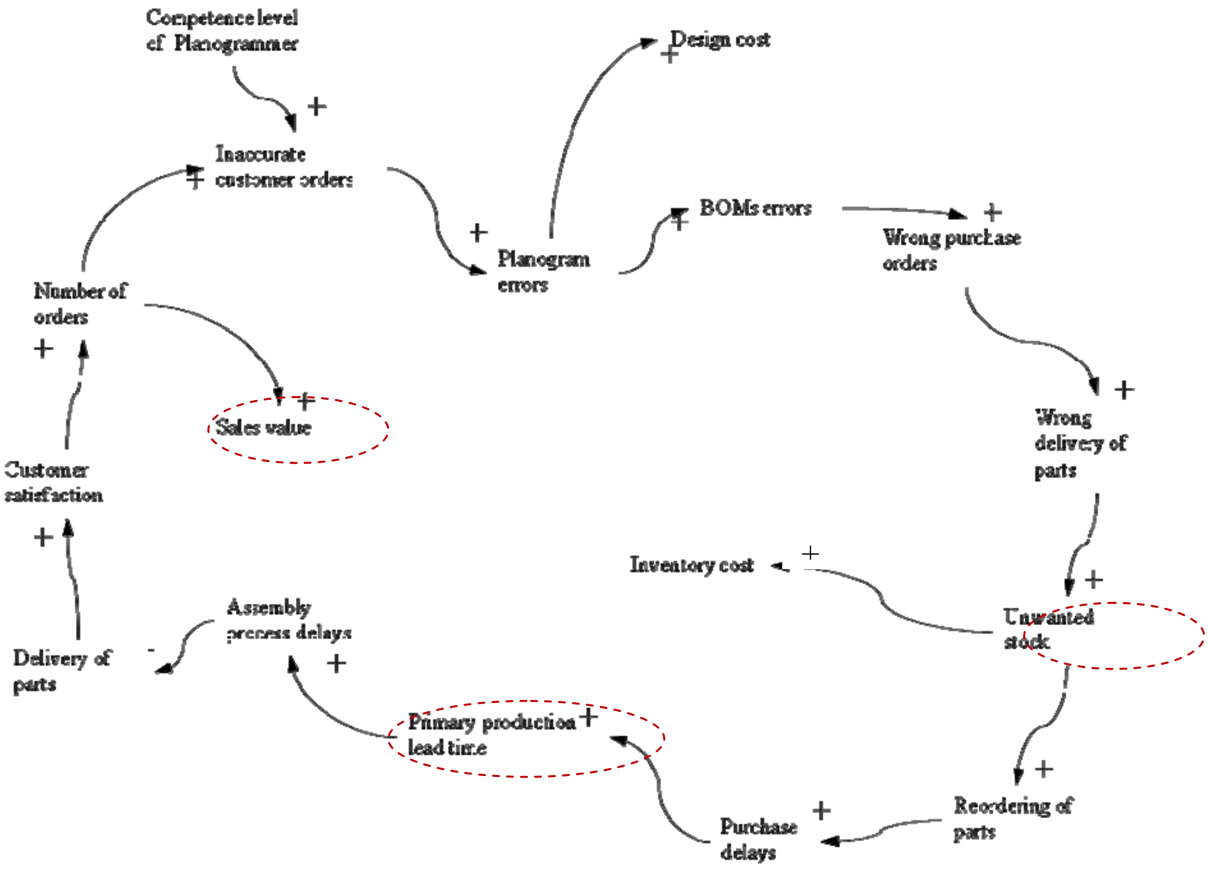


Figure 114: CLM describing some of the causes of delays and high inventories

Errors in planograms have serious consequences on POP Ltd business. They increase design cost and indirectly affect many other cost elements in the company. This is because planograms serve as the base document for the design, purchase and production activities. Errors in planograms potentially lead to errors in material specifications on BOMs. When these are not detected in time, it causes the purchase team to acquire materials or components which are not needed to fulfil an order. These unwanted materials or parts build up excess stock in their warehouses thereby increasing their inventory cost. Normally, in POP Ltd, wrong parts are only detected at the point of assembly. So such parts have to be reordered leading to long delays in purchases which causes long assembly lead times.

The CLM shown in figure 114 can further be developed to show how inaccurate planograms affect design activities which intend impact on production of wrong parts which lead to overstocking. This CLM is shown in figure 115. From the CLM shown in figure 115, it can been seen that wrong planograms affect the design of parts which are manufactured locally. When wrong part designs are created, it leads to wrong part production which has serious cost implications on the company because of the capital intensiveness of the production resources.

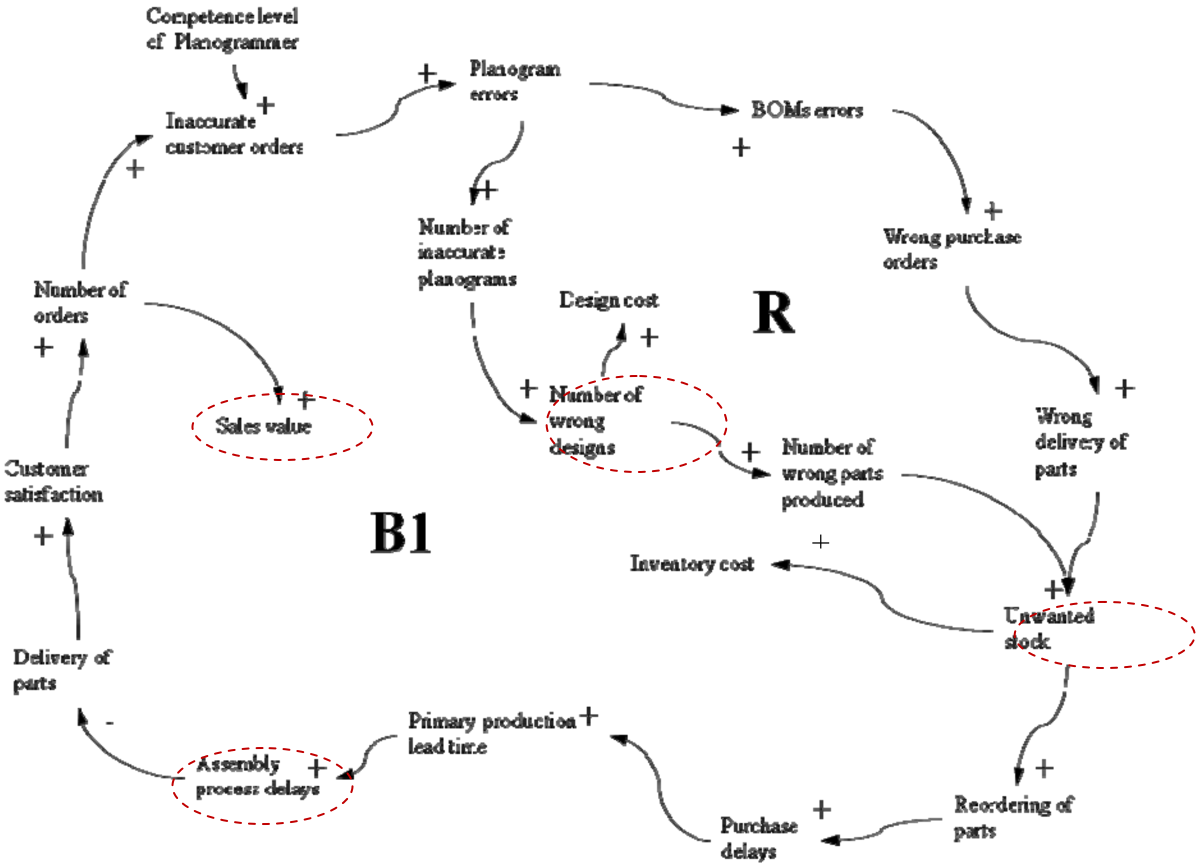


Figure 115: CLM showing the effect of design activities on inventory levels

Again these unwanted productions of parts build up inventory and add up to the cost of the company. When wrong parts produced are detected during assembly, new production orders have to be created whilst the remain parts lie on the assembly floor waiting for the primary manufacturing processes to be completed. This is one of the major causes of production assembly delays and inventory accumulation.

Another major factor observed to be affecting the smooth operation of POP Ltd production system is the ‘late changes in customer specifications’. These changes are caused by customers and they affect design, purchase and production requirements. Some of these changes are specified at a later time when all purchase and production processes are almost completed. Thus when there are changes, the earlier acquired or produced parts become waste and further instabilities are induced in the production planning systems. Long production lead times and high cost are the outcomes of these patterns as depicted in figure 116.

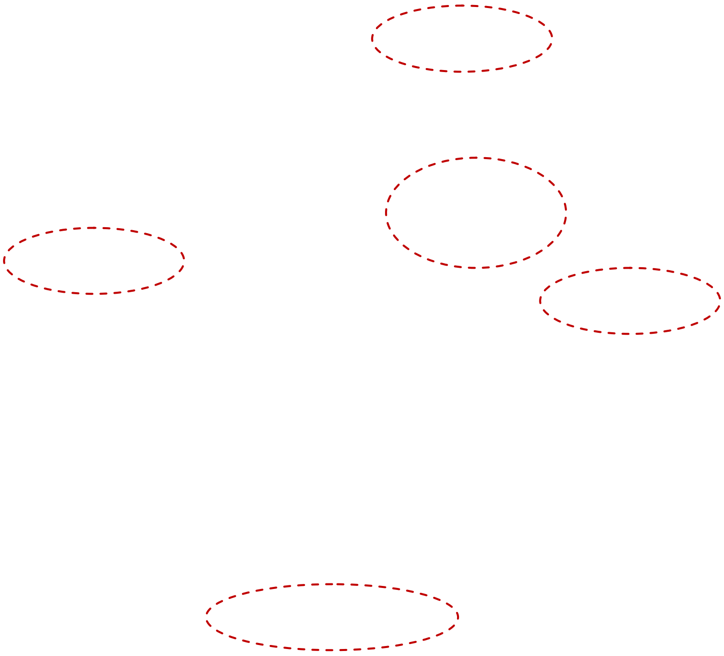


Figure 116: CLM showing effect of changes in customer specifications

When production lead times are beyond the acceptable levels for customers (this differs from one customer to the other), customers gradually lose interest in their products and consider other alternatives. This leads to the generation of low sale orders which affect the total sales value and hence the net profit generated by POP Ltd.

The Managers of POP Ltd were satisfied about the explanations given to the causes of their problems. Particularly they could now view the problems from an integrated point and hence knew that an integrated solution was the way out. This was contrary to the earlier views held by some of the Managers. In their earlier views, blames were assigned to the purchase department for late arrival of parts. Others also blamed the primary manufacturing departments for overproduction of wrong parts whilst the production department also blamed the design unit for their incompetence. It was therefore satisfying for the Managers to see how a cooperate approach was required.

As explained in Chapter 6, initial causal loop models can usefully be translated into iThink continuous simulation models using the '4-staged transformation mechanisms' specified in Chapter 6. This transformation mechanism requires:

1. creating initial causal loop models which best describe the factors depicting cause and effects of the system modelled;
2. transforming these initial CLM to structured causal loop models (SCLMs) which satisfy a set of system dynamics modelling requirements;
3. identifying stocks, flows and auxiliaries in the structured causal loop models (SCLM) and
4. translating the stock and flow model into ithink simulation models with parametric equations describing the behavioural structure of the system modelled.

As explained in Chapter 6, if the objective behind the application of CLMs is to support decision making, then CLMs must be 'structured' so that they form the basis for analytical thinking about decisions. Modelling formalisms which show how CLMs can be transformed into 'structured causal loop models' (SCLM) have already been explained in section 6.4.3. In essence SCLMs must be capable of describing the physical and behavioural attributes of the systems being studied. To attain this, variables must be revised to become measurable and operational whilst maintaining their robustness.

To provide a concise description of the state of POP production processes, knowledge gathered from the CLM describing the structural dependence of process variables (figure 113) and the problem descriptive CLMs (figure 114-116) were combined and enhanced to form a SCLM. This was necessary to enable the initial causal loop models to be transformed into simulation models. Bearing in mind also that one of the functions of a SCLM model is to support analytical decision making, it was necessary to redefine and reorganize the variables so that the resultant SCLMs consist of variables which are measurable, deterministic, time variant and operational. Attempts to create a SCLM which best mimics the production system of POP Ltd as well as describing the problems to be addressed resulted in the model shown in figure 117.

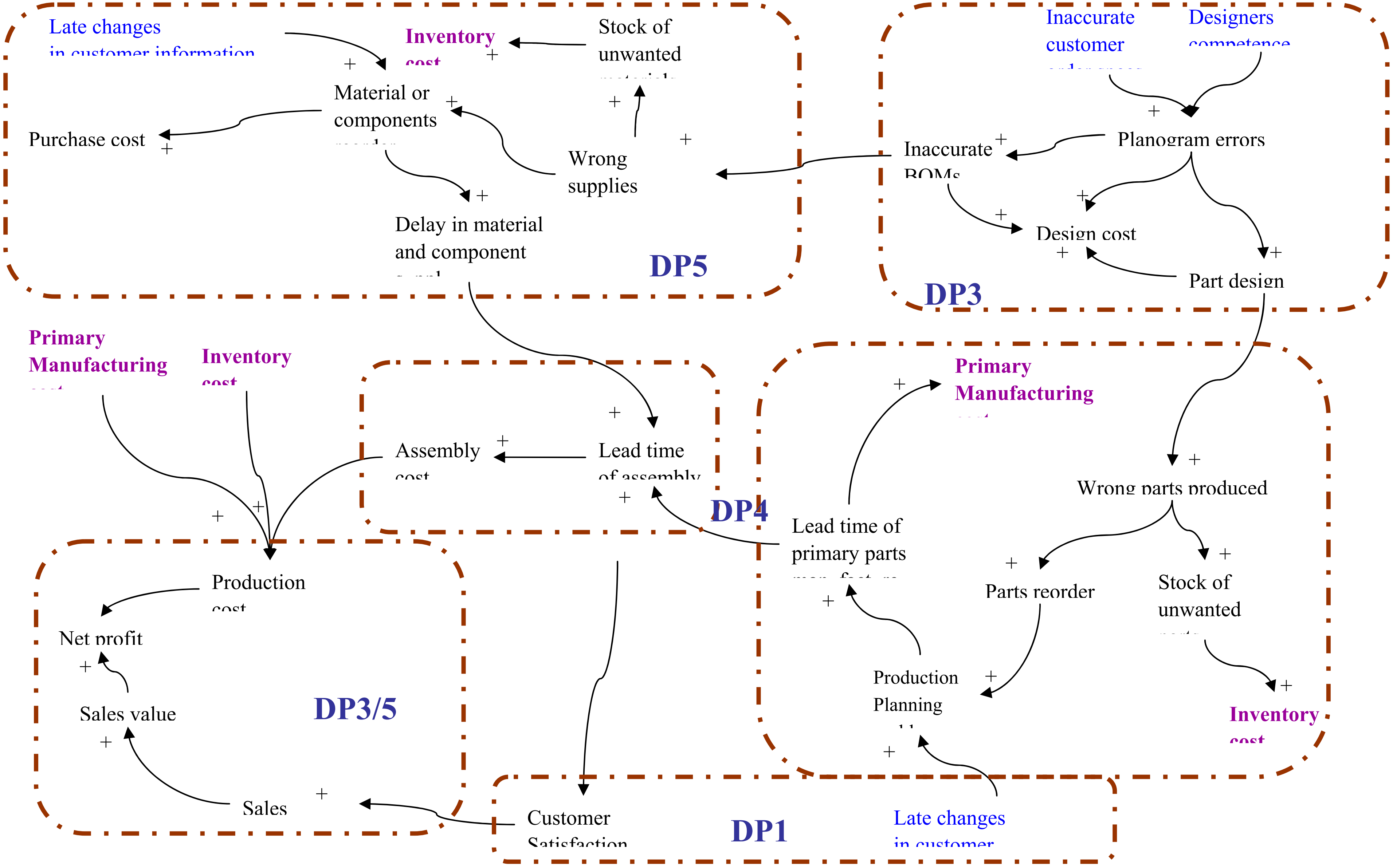


Figure 117: Resultant structured causal loop model (SCLM) of POP Ltd

Although the SCLMs provided insight and understanding to some of the causes of the process related problems in POP production system, it was necessary to convert these models to simulation models so that experiments related to potential improvements can be conducted. In addition the author was of the view that creating simulation models could help predicts future behaviours of the production system. Suitable policies could be experimented and verifiable conclusions drawn.

The formalism proposed in this thesis for transforming CLMs into iThink simulation models recommends that stock and flow models should be created after SCLMs have been developed. This normally implies classifying factors observed in the SCLM into stocks, flows and convertors and assigning the necessary modelling constructs to them. Experience gathered in applying this method in case study 2, showed that normally, whilst trying to deduce stocks and flows from how variables are connected and also having in mind possible mathematical equations that must link variables, new variables are introduced whilst existing variables are reorganized. This assertion was true in this case study too. Since partly the objective of the research is to be able to identify 'waste' and potential 'cost concentrations' which can be reduced, some new factors related to cost and values were added. Most essentially some of the process variables were summarized and organized in order to allow suitable mathematical and analytical analysis to be conducted on them. To maintain robustness and model usability, the names of some of the variables were changed whilst other new variables were introduced to allow connectors to express suitable mathematical or algebraic relationship between variables.

Normally creating stock and flow diagrams result in a static description of the process with static equations embedded in the process. However when these models are created with the iThink continuous simulation tool, stocks can indeed accumulate whilst flows cause changes in the stock levels and connectors manipulate and change flows. As explained in detail in Chapter 6, to avoid the Managers of POP Ltd losing interest in the models, the detailed connecting variables and mathematical expressions were hidden in the 'model and equation' layers of the iThink model. Instead a top level model captured from the map layer was shown to them from the interface layer. From a top level view, they were satisfied that the connecting variables and flows best depicted their company. Whilst describing the model to the Managers, efforts were made to only describe in detail the model excepts shown on the interface layer as well as the results derived from the experiments. The interface model showing the various process connectors is shown in figure 118.

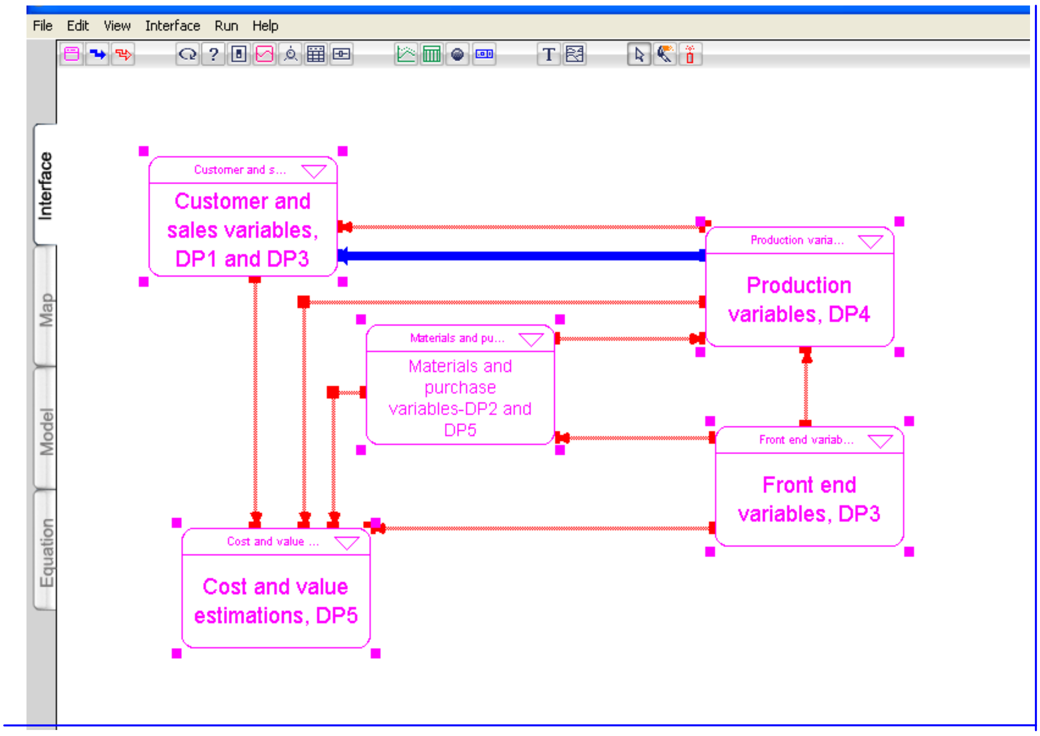


Figure 118: Interface model for POP Ltd

The detailed model thoughts in the form of a map were displayed in the 'map layer'. Since a structured approach was followed in deriving the iThink model, the map shown on the map layer is basically the same as the stock and flow model discussed previously. In the model layer, the maps were transformed into models with mathematical relations and values inputted. This led to models which were possible to simulate. The final derived simulation model depicting the relationships and process variables impacting on cost and values is shown in figure 122. The multi-layer model design approach made it possible for model complexity to be minimized and understanding of models were enhanced since their visual and algorithmic complexity was minimized and spread on different layers. Also in this thesis, the models have been presented in sector frames to enable easier description, where as in actual fact the sector models are all connected together. For example model elements related to the 'front end operations, DP3, is shown in figure 91. These model entities are the same as the variables used for the stock and flow models. To limit the tendency of connectors crossing each other, it is possible to create ghost images of actual model variables and pasting them at convenient places in the model, the associated connectors can be linked to them as shown in the case of the connection between 'number of accurate planograms' and 'designs'

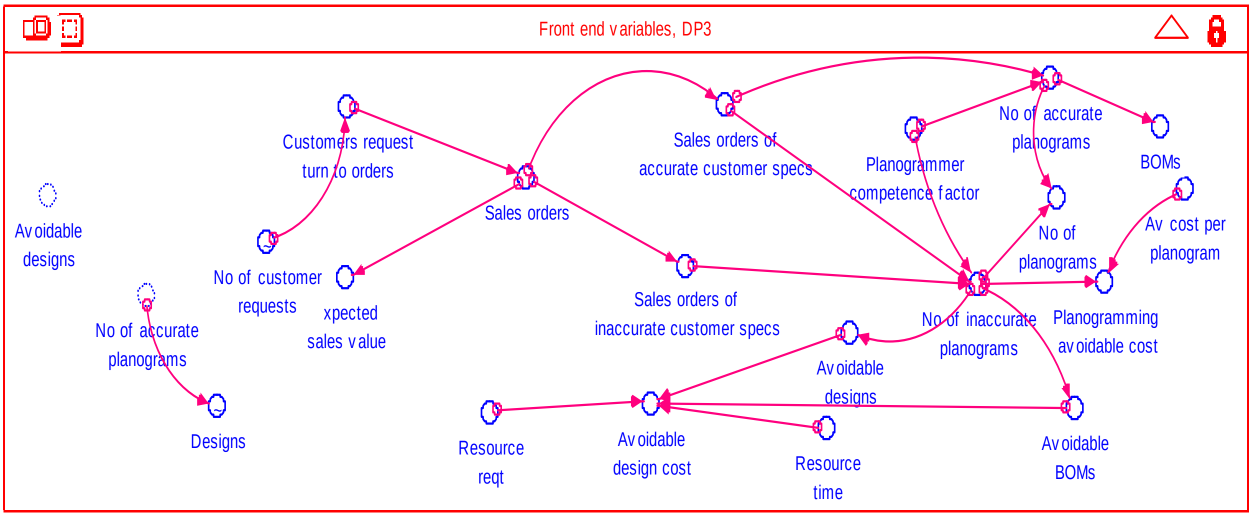


Figure 119: iThink model for 'front end operations', DP3

In a similar manner, the model elements representing 'material supplier' and 'purchase' variables are shown in figure 120. Figure 120 shows how 'avoidable material and purchase cost' are generated as a result of inaccurate customer requests and planogramming errors.

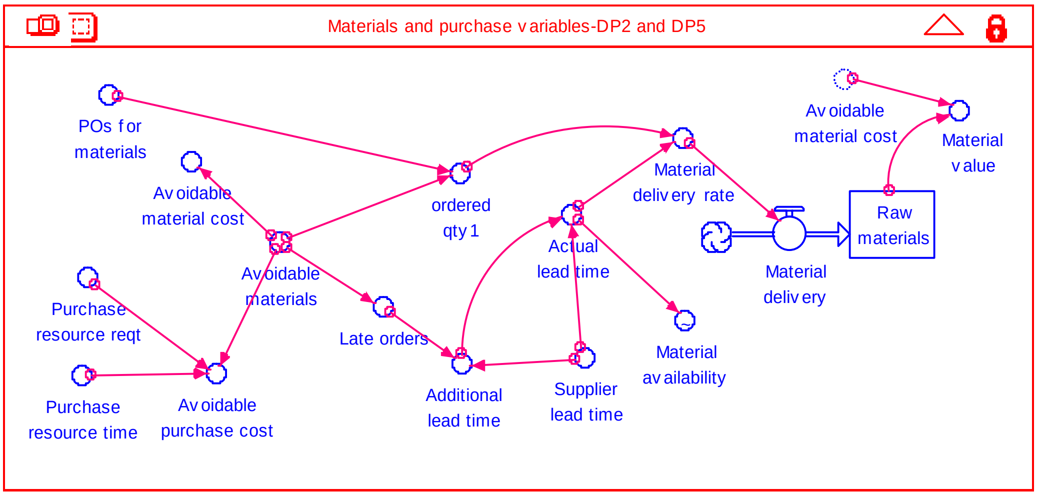


Figure 120: iThink model for 'material supply and purchase variables' (DP2 and DP5)

The latter part of the model shows how essential variables derived from the structured causal loops are instrumented to estimate a number of production performance indicators including cost, number of assembled products as well as inventory levels at strategic stations.

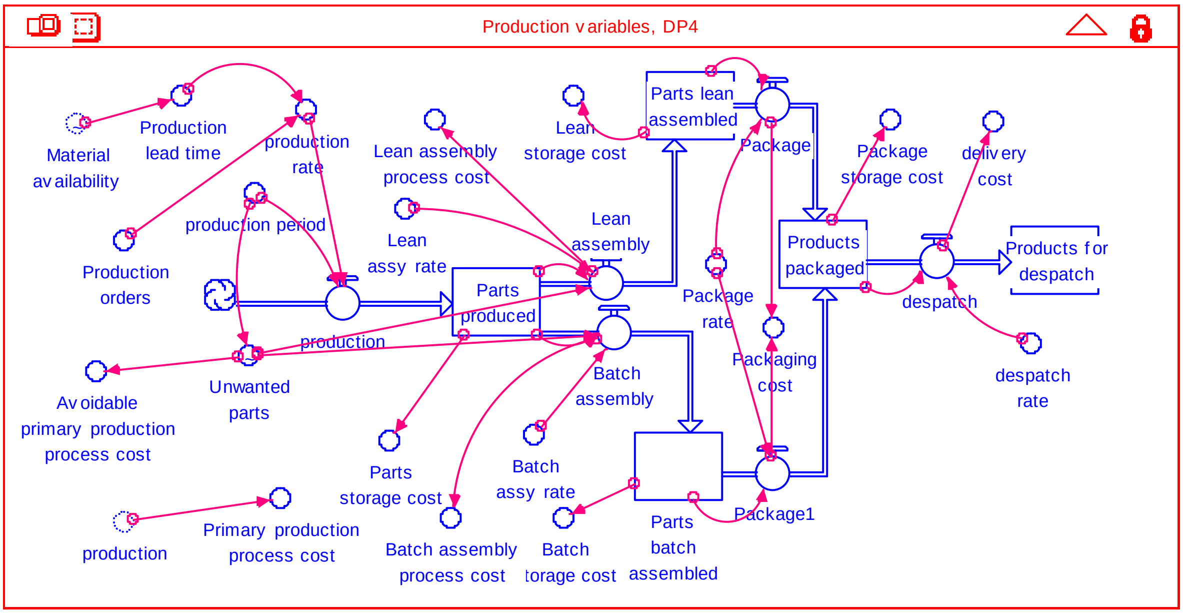


Figure 121: iThink model for 'production variables' (DP4)

Because the prime focus of the research is to determine how process variables impact on cost and value generation, it was considered necessary that after deriving the respective sector models, essential cost indicators and value variables would be brought together for analysis of the process based on cost and value generation. Data for this aspect of the model was derived from the main models described above. The dotted convertors indicate that the variables have mostly been ghosted (copied) from the bigger model. The algebraic and process relations are left unchanged when ghosted, thus any change observed in the models during simulation exercises are reflected in the cost and value estimation model shown in figure 122.

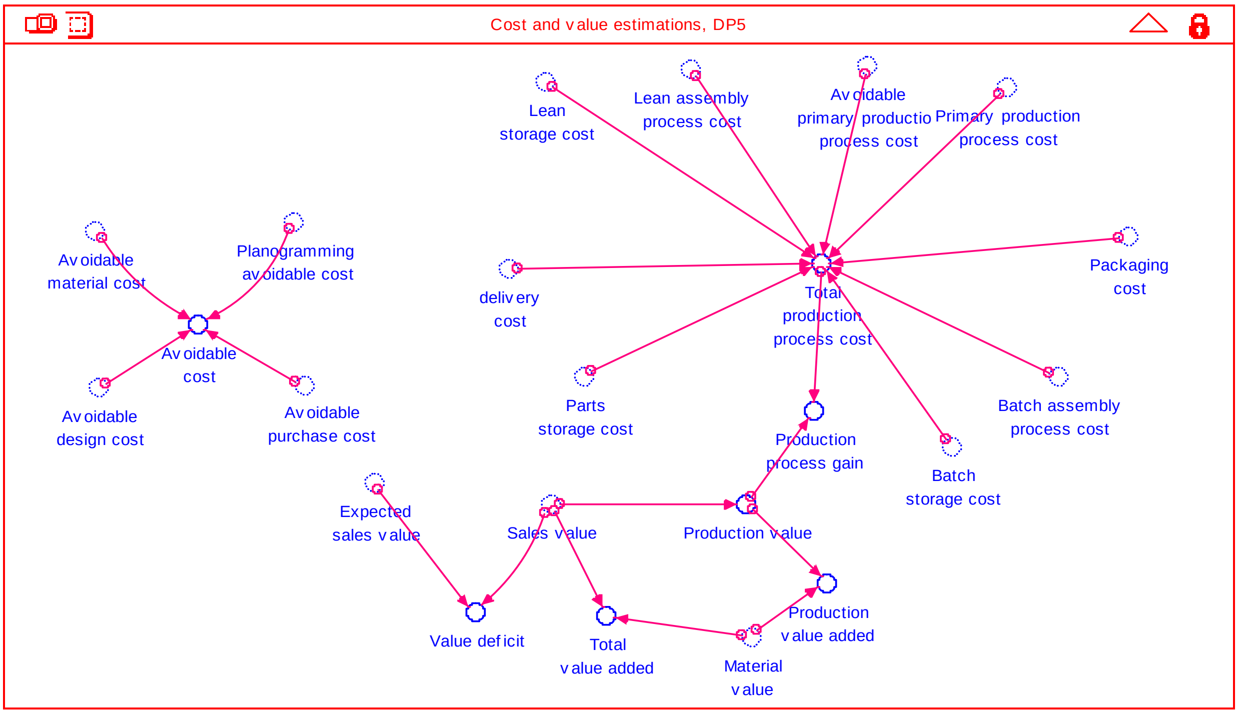


Figure 122: iThink simulation model for POP Ltd showing cost and value estimations

Initial values were inputted into the model and the results were compared with observed trends of performance in the company. Factors such as production lead times, sales values, profit margin, avoidable cost, material cost and volumes of parts waiting, were critical variables which were verified by the Production Managers to confirm that the model best describe their production system. The logic behind the connectors were also verified and identified to best represent the process states. Observing results provided through the simulation run over a ‘virtual simulation clock time’ of 6 months, very useful understandings were generated and used as basis to improve upon performances in POP Ltd. Typical results show the quantitative effect of planogram errors on the business. As shown in the casual loop model in figure 117 and logically described by the iThink model in figure 119, planogram errors are typically caused by wrong customer order specifications often experienced during the initial interaction of sales team members and customers. In some instances reported, sales team members stated wrong customer specifications whilst in some other instances, customers gave wrong specifications either from inexperience or wrong engineering specifications. Either of these factors contribute greatly to planogram errors. However another contributing factor is the competence of the Planogrammer. Therefore a competence factor is introduced in the model to reflect the percentage of accurate customer specifications which end up with errors caused by planogrammers. Records were available to quantitatively specify the amount of orders which had been processed for 6 months and quantity of planograms generated. As shown in the system dynamics models, variables of processes were interconnected such that the effect of change in planogramming conditions can be seen in other process parameters of interest. The graph shown in figure 123 explains the impact of planogram errors on design and material cost as well as purchase lead times. The graph shows that a linear relationship exist between the number of planogram errors incurred over a given time and the respective avoidable design and material cost.

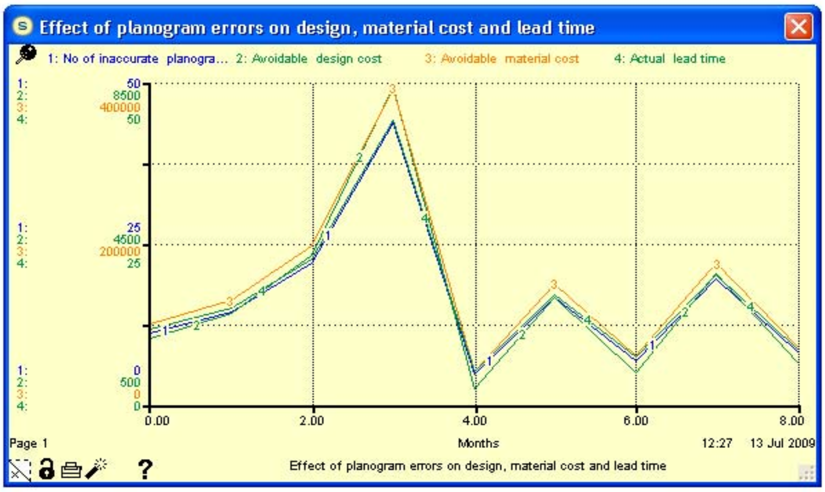


Figure 123: Effect of planogram errors on design, material and lead time

This means that although there could be other factors affecting these avoidable cost components, planogramming errors play a major role increasing these costs. The pattern of planogramming errors as depicted by the graph is indirectly derived from the sales order pattern over the period which the simulation is conducted. Carefully studying the graphs show that as planogram errors fall, design and material cost also fall. In addition to the cost variables, total purchase lead time is also reduced. The extent of reduction varies from one variable to the other but cumulatively, they all reduce fractionally with response to planogramming error reduction. It is therefore evident from a strategic business point of view that, to reduce potential avoidable cost, it is necessary to maximize efforts to reduce planogram errors. Later sections of this chapter has explained how planogramming errors can be reduced.

As depicted in the causal loop (figure 117) and iThink model (figure 121), there are a number of storage points in the production processes. This is basically due to over production of component parts, unavailability of needed parts for assembly, changes in customer order requirements, planograming errors, etc. Thus as a result, cost are incurred in keeping components in stores or keeping components in the production processes whilst waiting for other parts. The implication of the random production ordering patterns on the generation of storage cost was analysed. The iThink model shown in figure 121 describes how 'parts storage cost', 'lean and batch storage cost are accumulated. Running the model with six months data produced a graph shown in figure 124. Parts storage cost continuously increase whilst the lean and batch storage cost reduce till they become minimal.

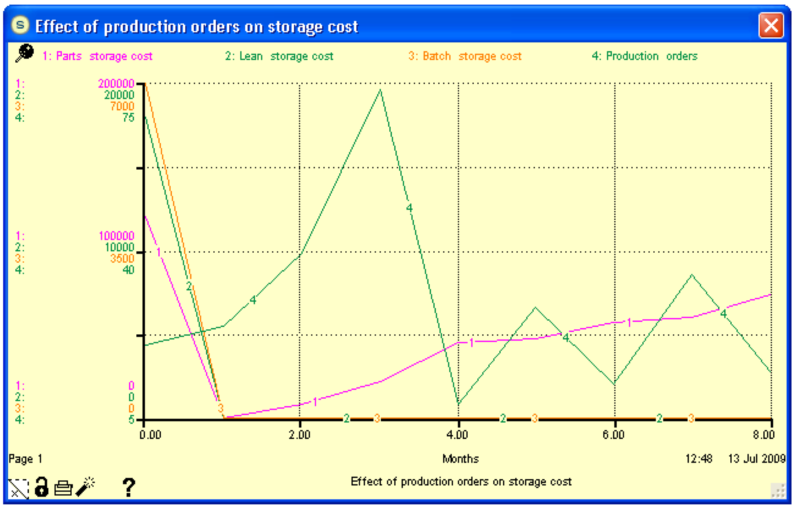


Figure 124: Effect of production orders on storage cost

To further understand this phenomenon, it was necessary to investigate quantitatively how inventory was accumulated during parts production, lean assembly and batch assembly. Figure 125 shows results for number of parts produced, assembled, packaged and despatched. These useful results explain further how inventory is accumulated and hence cost generated. From the graphs shown in figure 125, it can be seen that stock of parts produced increase over the simulation time.

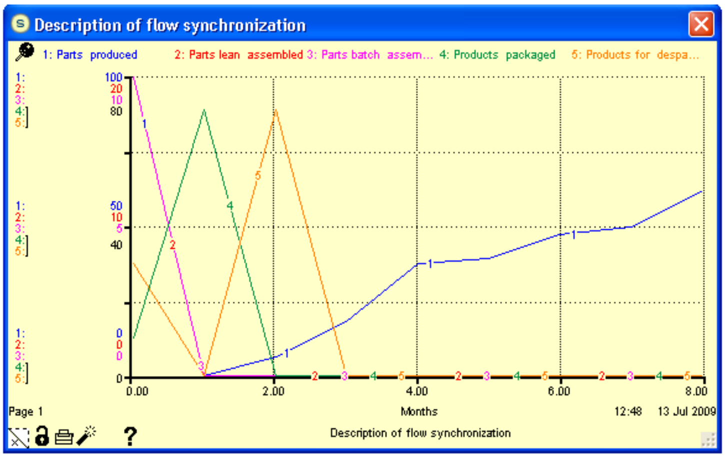


Figure 125: Problems with product flow synchronization

Parts which are lean and batch assembled fall over the simulation period. This can be explained with the causal loop model shown in figure 117. In effect because of wrong designs, wrong parts are produced and unnecessary parts are stocked. Other contributing factors are that purchase delays caused only a few products to be assembled since in most cases parts have to be waiting at the assembly shops for their counterparts. Also production flow is not synchronized and thus processes such as vacuum forming produces various parts for assembly but for a particular order some injection moulded parts would not be available. This requires detail planning of production and instituting of 'pull mechanisms' to help synchronize production.

Other strategic level analysis was conducted on the results provided by the cost and value simulation models (figures 119-122). Very interesting and formative results were obtained which became one of the major basis for recommending further improvements in production processes of POP Ltd. From figure 126, it can be observed that production value is a function of sales and material values. This is because when sales value remained constant, the 'production value added' fluctuated inversely with the material value. This means that for constant selling prices of products and a well defined production process with a set of established resources, the determinant of value is the input variable, in this case the material value. This is because in this Thesis, value addition is viewed in economic and monetary terms as the difference between the output and input values.

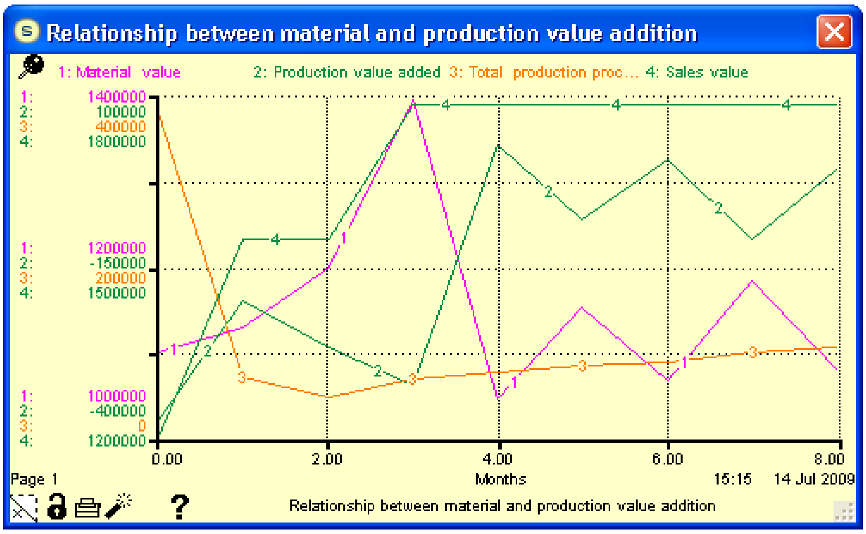


Figure 126: Relationship between value flows

8.3 Rendering strategic solutions to POP Ltd

The foregoing discussions have shown how causal loop and iThink modelling techniques can be instrumented to derive dynamic cost and value streams models suitable for dynamic analysis. In effect, the approach assisted in enhancing the authors understanding of the processes and the complexities of the problems faced by POP Ltd. After analysing the qualitative and quantitative results generated by the cost and value stream models, a list of strategic and specific recommendations were made to the Managers of POP Ltd. These recommendations were borne from the understanding rendered by the cost and value stream models so generated. More specific solutions were offered through the detailed modelling of business process with the discrete event simulation modelling tool. However, the system dynamics modelling tools provided strategic or top level solutions to the problems outlined by the Managers. This section provides some strategic solutions which were derived from the results presented in the preceding sections.

8.3.1 BOM and design errors

At the start of the research in POP Ltd, BOM and design errors were initially understood to be one of the major causes of production delays and hence generation of low sales value. Carefully studying the causal loop models presented in figures 113-116, it can be deduced that although BOM and design errors were contributing factors, there existed many other connecting reasons for their lack of performance. From figures 114, 115, and 117, it can been seen that, fundamentally, BOM and design errors are triggered by ‘planogram errors’ and incompetence of designers. Figure 123 further shows graphically, the impact of planogramming errors on the product design, material acquisition and lead times. Hence to prevent or reduce BOM and design errors, there is the need to concentrate on the reduction of planogram errors. To achieve this, further investigations were made on the causes of planogram errors. The causal loop and iThink models shown in figures 114-116 show that planogram errors are influenced by inaccurate ‘customer order specifications’ and ‘competence levels’ of planogrammers. Thus to reduce planogram errors, further work was required to investigate how customer specifications were captured into POP’s sales database. Reflecting on earlier data captured during an interview with the Sales Manager, it became evident that errors in customer specifications can be split into two. About 60% of these customer specification inaccuracies is caused by customers whilst 40% is caused by inaccurate documentation by Sales Officers. Further investigation revealed that there was no standard ordering template and customers chose methods of description of their specifications which best suited them. Most often, Sales Officers received customer specifications through the telephone. Quite critically, for customers with no technical background, describing and specifying requirements become subjective and hence the tendency of recording inaccurate information is high. The approach lacked uniformity in description and depending on the experience of Sales Officers, different interpretations can be assigned to customer specifications. It is therefore recommended that a ‘request template’ with standard descriptions should be designed by the Sales department and used as a front line tool for requesting and receiving customer specifications. When the forms are completed they could be sent through email, faxed or posted. In addition, Sales Officers may be required to visit local shops of clients, where possible, to take accurate dimensions to limit planogramming errors.

To reduce the frequency at which customer specifications are modified, the request template will have to be endorsed by both parties, POP Ltd and customers, such that it becomes binding on what POP Ltd will have to deliver. In extreme cases, minor penalties can be introduced for further changes in specifications by either of the parties. Further to this, customer ordering, planogramming, design and BOM processes will have to be modified to include sectional managers verifying and approving requests and designs as being accurate and true reflections of customer specifications.

8.3.2 High inventory levels

Observing the iThink and causal loop models shown in figures 114-121, it can be established that there are three major sources of inventory. These are raw material stock, in process inventory and finished goods inventory. Studying the cost components of these inventory sources, it was realized that about 80% of storage cost was due to raw material inventory. Relating this finding to the static value stream model, it can be noted that there are three main sources of raw material inventory. One of the stores is responsible for keeping raw materials for ‘make prints’ business processes (BP4.1.1). Raw materials required for ‘vacform parts’ (BP4.1.4) and ‘produce moulded parts’ (BP4.1.5) are kept in the second store whilst the third storage point is for ‘make wooden and plastic parts’ (BP4.1.2) and ‘heat bend parts’ (BP4.1.3). It can be deduced from studying the causal loop and iThink models in figures 114-121, raw material stocks are essentially influenced by the number of purchase orders produced by the purchase department. The ithink model attempted to quantify the number of purchase orders and their corresponding material type requests which influenced in essence the raw material supplied. Reflecting backward on the connecting processes, it can be observed that purchase orders are largely influenced by BOMs which are also largely dependent on number of planograms and hence sale orders and customer requests. Thus fundamentally, errors incurred in any of these connecting processes will induce errors in the type of raw materials supplied. There are obviously other associated errors which could be due to the supplier. But this aspect requires further investigation. Basically, wrong materials are supplied when POs for materials are not accurate. This leads to the accumulation of parts. Currently errors in supplies are not identified early enough until materials are needed for production or parts are needed for assembly. There are also no contractual agreements to return parts or materials which are not needed by POP Ltd. Hence the stock of unwanted materials and parts rise. Also when customers change their requirements when parts or materials have been purchased already, it leads to stocking of materials or parts which will not be used. In many instances, in anticipation of delays in supplies and future production demands, the purchasing department make bulk purchases which lead to overstocking of materials especially when production demand does not fall in line with predicted patterns. The quality of purchased items is also a matter of concern which adds to the inventory level of raw materials. With these understanding derived from the system dynamic models, it was fairly clear to indicate that to reduce raw material stock inventory, practical efforts must be made to reduce planogram errors. All the other associated forms of errors will be cater for, if the primary source of error is reduced or avoided. Methods capable of reducing planograms errors have been explained in section 8.3.1. To avoid the late realization of supply of wrong parts, the parts receiving process may need to be revised to include an Engineer inspecting and certifying parts which are received. When this is done, wrong parts can be identified early and returned or replaced in relatively short time. To simplify and reduce the tendency of ordering wrong parts, purchase orders should be checked and signed by an Engineer to confirm that the content of the PO meets the requirements of the order. There is also the need to form a dedicated supply network with flexible contract agreements which allows POP Ltd to return materials or parts when the need be. It should however be critically analysed and instrumented in a way that the return of materials and parts will not create additional cost. Detailed planning is required to determine when parts need to be supplied. When these are derived accurately, JIT principles and arrangements can be enforced between POP Ltd and its suppliers.

Similar explanations can be given to the increase in ‘work in progress’ or parts inventory. From the graph displayed in figure 124, parts inventory and hence in progress inventory rises significant after a period of accumulation. This is because parts production and assembly requirements are currently not effectively synchronized. Although the planning department makes project plans for production schedulers, these plans barely take into account work loads of production departments and hence parts are either produced before needed or long after scheduled time. This brings about imbalances in the production flow. In some other instances, parts are supplied earlier than needed or late after they are needed. When assembly is due and parts are not available, parts which are available will have to wait for the other parts to be purchased or produced. Matching the results provided by the iThink model (figure 125), it can be understood that moulding and vacforming equipments are batch build facilities commonly deployed in build to stock environments. The facilities therefore build in large quantities parts which are required. It is therefore required that the production flow be redesigned such that key lean metrics can be deployed. Typical lean techniques such as the appropriation of supermarkets, building to takt, instrumentation of pull techniques may be necessary. It is however necessary to analyse the impact of these techniques lean on the overall production system. This is necessary so that experiments and alternative reconfiguration of resources and production lines can be conducted and production system redesign tested before implemented. A higher level integrated dynamic planning scheme is required to monitor and update production plans regularly. This can be done manually with production supervisors reporting to the planning department on current work loads. Alternatively, a dynamic front end planning tool can be deployed which updates and edits production plans according to real data inputs on the production shop floors. More work is required to identify strategic stock levels for all the storage points and production process planned accordingly. Production processes are to be planned and realized with assembly due dates in mind. This later recommendation can best be informed through the utilization of discrete event process simulation tools.

Although finished goods inventory is not very high, measures may be taken to commit customers to their goods. In the initial stages of the contract agreement, it can be negotiated between POP Ltd and customers that customers bear responsibility of the cost of keeping finished goods in POP Ltd. Average cost of storage based on size of space occupied and resources needed to keep can be estimated and communicated to customers.

8.3.3 Long production lead times

Earlier models shown in figures 113-115 described the causes of increased production lead times. Critically, the major causes are the unavailability of needed parts when assembly is due. Other reasons are inaccurate parts produced by the primary production processes and generally specifying delivery due dates without thorough assessment of production workloads. Methods with potential to reduce unavailability of needed parts are explained in sections 8.3.1 and 8.3.2. This is basically based on the continuous reduction of planogramming errors and their associated impacts on errors in purchased parts. Other streamlining factors include developing dynamic planning schemes which takes into consideration dynamic instances of the production processes, resources and workloads. In the interim, inaccurate specification of due dates is a major contributing factor. The reason is that due dates are specified without necessarily taking into consideration current work loads. It is estimated with the view that production facilities are available at all times. To prevent this, the sales team may need to be constantly updated on production capacities, resource availabilities and due dates for in-progress orders. It will be necessary to support decision making thorough investigation into product types by adopting the product-process matrix defined in Section7.2. Once orders are received, sales officers will be able to classify orders along their process routes and make spans. With a background information of resources and availabilities of identified processes, sales officers will be able to fairly estimate possible due dates. The planning team would be instrumental in this approach by providing a dynamic end to the data the sales team uses. To simplify the approach the DES model created for POP Ltd can be used to define various possible due dates for different product types based on different process and resource configurations. Section 8.4 explains how the dynamic value stream model created can be utilized to support due date estimations based on dynamic properties in the production processes.

8.3.4 Improving production flow

Reasons for lack of production flow have been established through the causal loop and results derived from the iThink models as shown in figure 125. Major factors are the lack of synchronization of production processes. A key issue is that primary production processes are not aligned to assembly process requirements. Late arrival of purchased parts and materials also contribute to the ‘pulsating effect’ of the POP production system. Production flow is actually dependent on the flow of parts through the elemental business processes hence it can be best analysed and improved at the operation level with the DES model shown in figure 127.

8.3.5 Reducing production cost and improving production value addition

From the graph showing the relationship between material and production value addition (figure 126), it can be deduced that one of the major value limiting entities is material cost. This is because of the many parts or materials which go to waste. Thus when errors are reduced in purchases, wrong materials will be reduced which will reduce the cost of unwanted materials. Also figure 121 shows that some of the costs incurred are due to storage. This is so because of the lack of production flow, appropriate production plans and production of wrong parts which tend to increase inventory cost. Methods for reducing inventory cost have been explained in Sections 8.3.1 and 8.3.2. From figure 126, production value oscillates with the material value when sales value is constant. To however reduce production costs, efforts will have to maximized towards reducing production lead times, delays and inventory. The reduction of these factors will reduce production cost and hence higher profits will be obtained.

8.4 Creation of detailed dynamic cost and value stream model of POP production processes

From the results generated from the static and system dynamic cost and value stream models, strategic solutions were recommended to the Managers of POP Ltd. Although this was good, the Managers of POP Ltd was of the view that, it was necessary to be able to know which specific ‘threads’ to pull to derive the needed outputs. Notwithstanding the system dynamics tools enriched the static cost and value stream model by providing a means of analysing dynamic instances and impacts of changing variables on the POP business. The author was also of the view that models capable of analysing detailed operational processes or activities was required to provide a background for recommending specific solutions to needed processes. By so doing the proposed methodology will be complete and capable of rendering solutions at various levels of abstraction.

Therefore at the next level, the enriched cost and value stream model was transformed into a number of discrete event simulation models through the application of the Simul8 modelling tool. The main objective at this point was to observe how multiproduct flows could be captured and real production systems mimicked so that alternative improvement methods can be experimented and results examined before implementation. Although the iThink model assisted in providing top level strategic solutions, it was conceived that at the operational level, the discrete event simulation tool could offer greater help. This assertion is based on the results which the same tool provided in the first case study presented in Chapter 5. Instead of taking a simplified approach, because of experience gained in modelling the first case company processes, attempts were made to model holistically, the 'direct value adding' production processes. To limit modelling complexity, a hierarchical simulation modelling approach was adopted. This means that almost all the contributing enterprise activities (EAs) belonging to specific business processes (BPs) were captured dynamically and modelled at the background such that changes in these activities could be reflected in the top level BPs shown on the screen. Also based on experience gathered from the application of simulation techniques in the first case study, the material flow approach was applied in this case. Modelling by the material flow approach required detailed understanding of the product structure and BOMs. These are the two main entities which determine the material entry points and the processes required to assemble them. This implied that the model showed entry points of materials and how they were converted into components and sub assembled at various process stages before final assembly. By viewing the realization of the production processes in this form, production flow, lead times, material unavailability, production cost and value addition which were key issues to measure at the elementary level in the system dynamics models could be visualized, estimated and its impacts analysed. A snap shot of the detailed dynamic cost and value stream model created for the six different product types is shown in figure 127. In the dynamic simulation model shown in figure 127, 'front end' and 'manage business' domain processes (DP3 and 5) were not modelled to be consistent with the static cost and value stream model presented in Chapter 7. Another reason for not modelling DP3 and DP5 was that, it was understood that the execution of the direct value adding processes, mainly DP4, was directly influenced by the realization of DP3 and aspects of DP5. Therefore the process attributes of DPs 3, 5 were indirectly used in the estimation of inter-arrival times, availability of materials and resources for the DP4 processes. Another reason was that because the material flow modelling was adopted, the model would have been unreasonably complex since DPs 3 and 5 are more related to processing information and not physical materials. Separate dynamic models can be created for analysing DPs 3 and 5 depending on the modelling intent.

The dynamic discrete event simulation model shown in figure 127 combines all the static value stream models created for the different product types and applies the ‘job matrices and labels’ function provided by the Simul8 tool to define different process times and resource requirements. Material storage points are denoted as entry points and the rate at which materials are released to queues are described in the model as material inter-arrival time. This inter arrival time is statistically determined by the historic material supply pattern. Before every work centre, there exist a queue which describes the quantity of materials or parts which have to wait whiles others are being processed. Where outputs from a work centre are required for different sub assembly purposes, work items are routed through their respective processes. For most cases, outputs from work centres are separated and connected to their onward processing routes by labels.

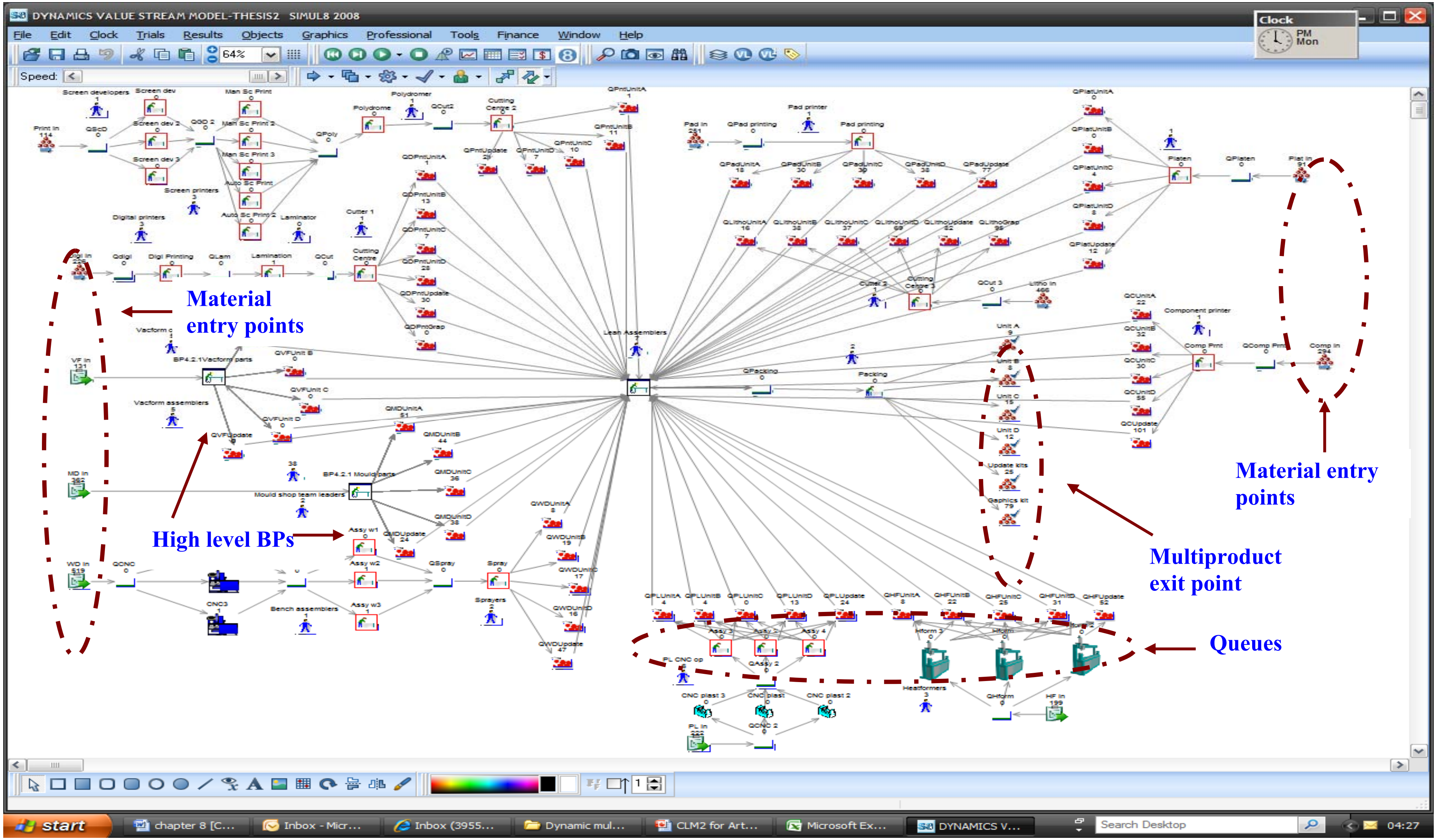


Figure 127: As-is top level multiproduct dynamic cost and value stream model for POP Ltd-screen shot from the Simul8 tool

For most of the processes, more elementary activities were required to fully represent the process sequence and flow of materials. It was assumed that at each work station, tools and fixtures were available for production purposes. Thus the model was built in granulation with links between parent and sub models to maintain robustness and model flexibility. Linking sub models with parent models was first proposed during the creation of the static cost and value stream model in Chapter 7 and further used in hierarchical modelling in system dynamics and discrete event simulations. For example, figure 128 shows the detailed activities required to fulfil ‘vac form parts’ business process. These activities are modelled at the background and only revealed when necessary. Similar elementary activity models exist for ‘produce moulded parts’ (BP4.1.5) and ‘assemble and pack parts’ (BP4.2).

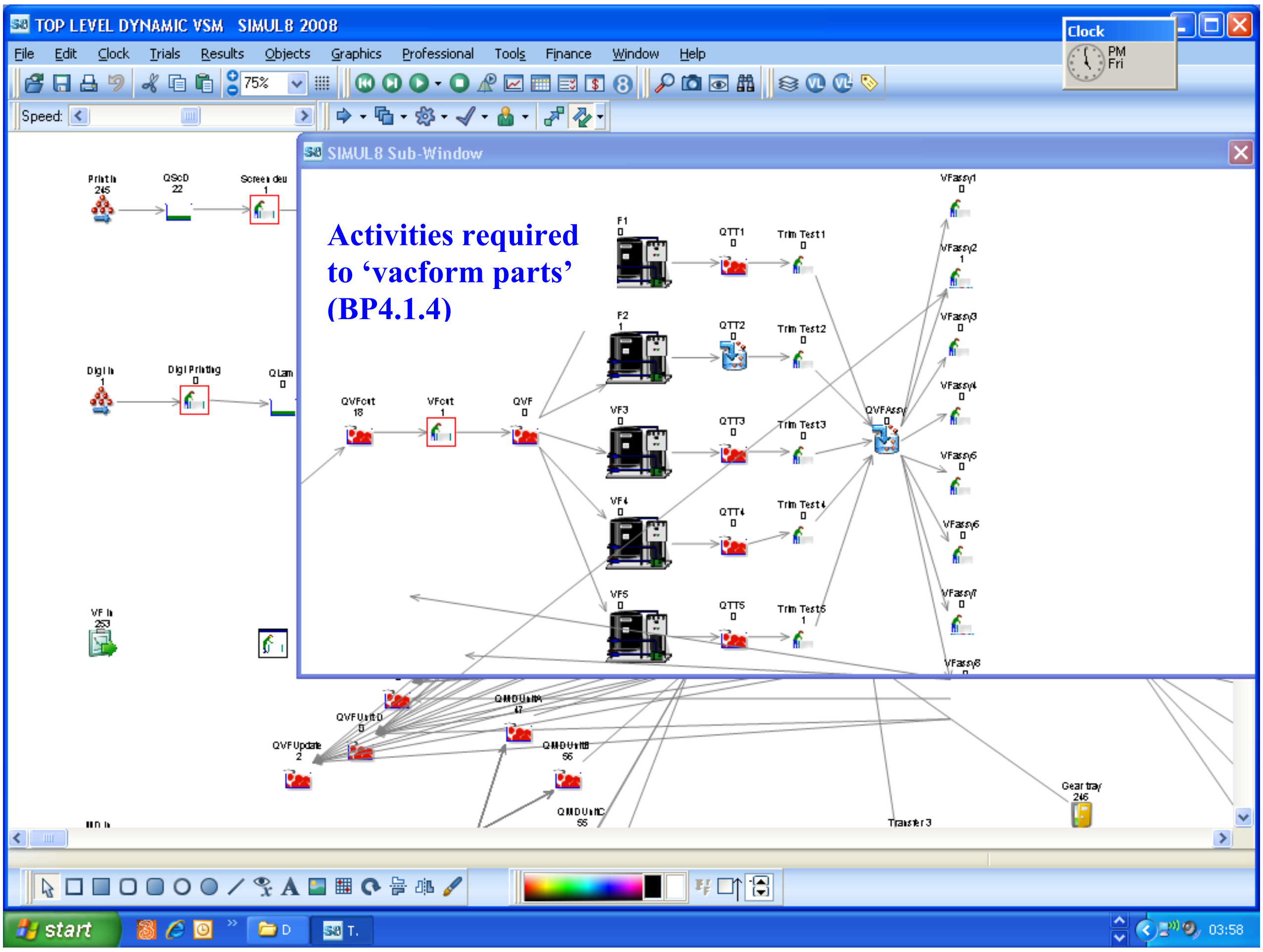

Activities required to ‘vacform parts’ (BP4.1.4)

Figure 128: An example illustration of hierarchical modelling technique deployed in Simul8

8.4.2 Testing and model validation

After creating the multiproduct dynamic discrete event simulation cost and value stream model of the six product families, the next stage in the modelling exercise was to verify if the model fairly represented the ‘as-is’ production system. Testing of the model was done at three different levels. These levels were: process structure, process logic and process results. In verifying the process structure it was first agreed between the author and the verifiers (selected process knowledge holders of POP Ltd) to use the static cost and value stream model as a bench mark. The reason was that the static cost and value stream model had been verified and proved to be suitable in representing the current state of the process of POP Ltd. Thus the product based process matrix which formed the basis for the product classification was used as the basis for checking if the process sequences described by the dynamic model was accurate. When the verifiers were satisfied about the process sequences for the different product families, the team checked together to ensure that the process connections described by the dynamic model was accurate. Special care was taken to ensure that no queues were connected to each other and also no work centres connected to each other. Because the model was built from the material flow approach, care was taken to establish that sub processes were properly routed and processes either converged or diverged properly to their assembly points. In addition the internal team used the BOMs to verify that the various product families had their material sources expressed as entry points to the model. Finally in relation to the model structure, outputs from work centres and work exit points were verified. After the recommended improvements were made, the team was satisfied that the model best described their direct value adding production processes.

The second stage of the test was about checking the process logic. This was difficult to verify from the perspective of the Managers of POP Ltd since that meant understanding the modelling language, flow and logic control. This was purely verified by the author by making sure that the material inputs are properly routed and labelled such that the right processed parts are assembled. Process parameters such as process times, resources times, and resource availabilities were compared with available data. Finally the outputs of the models were tested to see if results generated were similar to real production system outputs. Process parameters such as queue size, queue time, process lead times, inventory cost, values generated and through puts were verified by the Production Managers. During the creation of the static model, there was no available data for queue sizes and queue times hence storage or inventory cost could not be established. Although this data was still not available, it was possible to derive queue sizes and queue times from the simulation model. This is because queues exist between work centres whose processing times were available. Hence with the knowledge of the process times and total production lead times as were as material inter arrival times, the simulation model provides indicative results for queue sizes and queue times. These results are further used to estimate inventory cost for the production system. During the verification process, potential queue sizes and times were verified by the Production managers to see it was representative of the real state of their production system. This comparison of virtual and real results showed that the confidence level of the model was about 95% and hence was sufficiently suitable to be used for further simulation experiments. To help understand the dynamic process behaviours of POP production system, several test runs were made and the results was studied and used as basis to derive to-be models of better process results. Some sample results derived from the as-is model is shown and discussed in Section 8.4.3.

8.4.3 Results derived from 'as-is' cost and value stream model

After validating the dynamic model, results related to the problems expressed by the Managers at the start of the research were obtained from performing several test runs. The test runs took into consideration six months real production data of material arrivals, process types, process times, delays, cost and value generated. This was the same data used for the static cost and value stream models shown in Chapter 7 and the system dynamics models shown in Section 8.2. Generally in Simul8, it is possible to import or export data or results to MS Excel. Table 48 therefore shows results obtained from the 'work exit points' of the as-is simulation model. This shows results of five runs and the average throughputs realized for the six different product families. As can be seen from studying Table 48, POP Ltd produces more 'graphic only kits' and less standard units A

	Batches							Average number of products
Simulation Object	Run 1	2	3	4	5	Average batch	Batch sizes	
Unit A	9	10	8	9	9	9.33	15	140
Unit B	9	7	6	11	7	8.17	31	245
Unit C	16	15	16	11	15	15.00	20	300
Unit D	11	12	13	11	12	12.00	25	300
Update kits	27	23	25	24	25	24.86	37	920
Graphics only kits	86	83	72	70	80	79.17	23	1821

Table 48: As-is throughput results

Another set of useful results extracted from the Simul8 model was human resource utilization. The model automatically captures all resources required for the execution of processes. Their performances are measured as the model runs so that at the end of the simulation how these resources were utilized can effectively be analysed. The results of human resource utilization shown in Table 49, shows that in the current state model of POP Ltd, human resources in charge of component printing, digital printing, moulding, lamination, pad printing, platening and vacforming are grossly underutilized. This clearly shows that there is the great need of reorganizing how jobs are distributed among their resources.

Human resource utilization								
Simulation Object	**Performance Measure**	**Run 1**	**2**	**3**	**4**	**5**	**-95%**	**Average**	**95%**
Bench assemblers	Utilization %	143.41	133.32	150.92	147.07	148.86	136.10	144.72	100.00
CNC Operator	Utilization %	67.08	68.74	65.66	65.15	71.87	64.33	67.70	71.07
Component printer	Utilization %	0.84	0.88	0.76	0.82	0.85	0.77	0.83	0.89
Cutter 1	Utilization %	3.95	4.57	4.04	4.19	3.89	3.79	4.13	4.46
Cutter 2	Utilization %	8.70	8.39	8.28	8.07	7.90	7.89	8.27	8.65
Digital printers	Utilization %	1.56	1.80	1.63	1.70	1.54	1.51	1.65	1.78
Heatformers	Utilization %	15.69	15.70	12.26	14.86	14.98	12.94	14.70	16.46
Laminator	Utilization %	6.34	7.09	6.29	6.89	6.20	6.07	6.56	7.06
Lean Assemblers	Utilization %	26.30	26.17	26.20	26.27	26.18	26.15	26.22	26.30
Mould assemblers	Utilization %	14.42	15.28	13.74	16.34	13.40	13.15	14.64	16.12
Mould shop team leaders	Utilization %	0.51	0.49	0.49	0.48	0.48	0.47	0.49	0.50
Packers	Utilization %	47.42	44.58	45.88	48.68	46.01	44.56	46.51	48.47
Pad printer	Utilization %	0.79	0.82	0.76	0.80	0.86	0.76	0.81	0.85
PL CNC op	Utilization %	70.99	69.17	63.01	71.40	65.48	63.49	68.01	72.53
Platener	Utilization %	0.08	0.07	0.08	0.08	0.06	0.06	0.08	0.09
Polydromer	Utilization %	27.98	28.65	25.91	28.90	26.22	25.81	27.53	29.25
Screen developers	Utilization %	27.59	26.92	27.69	27.77	25.99	26.26	27.19	28.13
Screen printers	Utilization %	14.27	14.09	13.48	14.33	13.83	13.57	14.00	14.44
Sprayers	Utilization %	11.45	11.43	11.09	10.95	12.02	10.87	11.39	11.90
Vacform assemblers	Utilization %	60.40	57.71	62.05	62.01	57.48	57.16	59.93	62.70
Vacform operators	Utilization %	0.45	0.28	0.43	0.43	0.44	0.32	0.41	0.49

Table 49: As-is model results of human resource utilization

To further explore how individual resources were used during the simulation period, detailed analyses were conducted on each of the results to examine the pattern in which work was performed. Example snapshots of graphs showing the usage of vacform assemblers and operators are shown in figures 129 and 130 respectively.

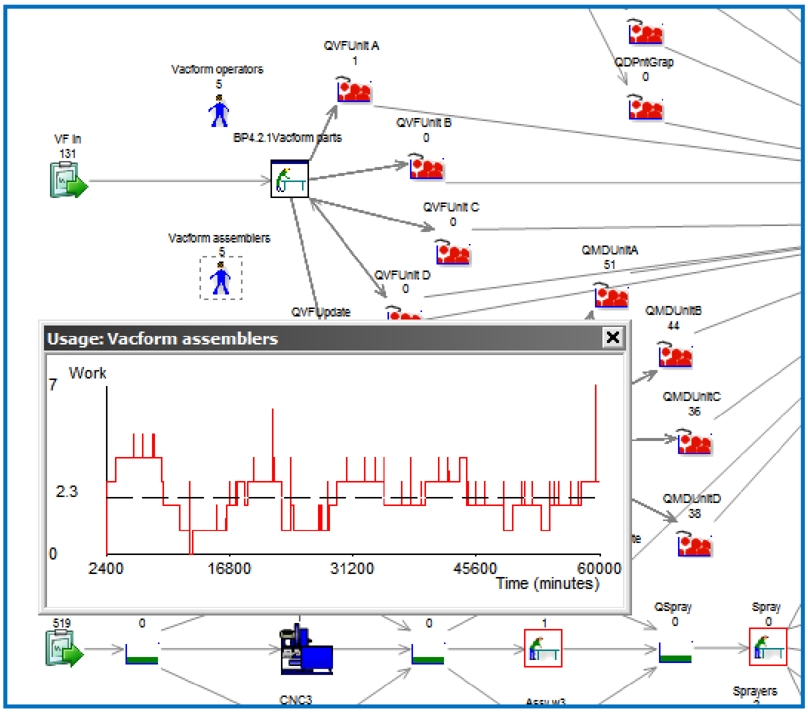


Figure 130: Performance of vac form assemblers

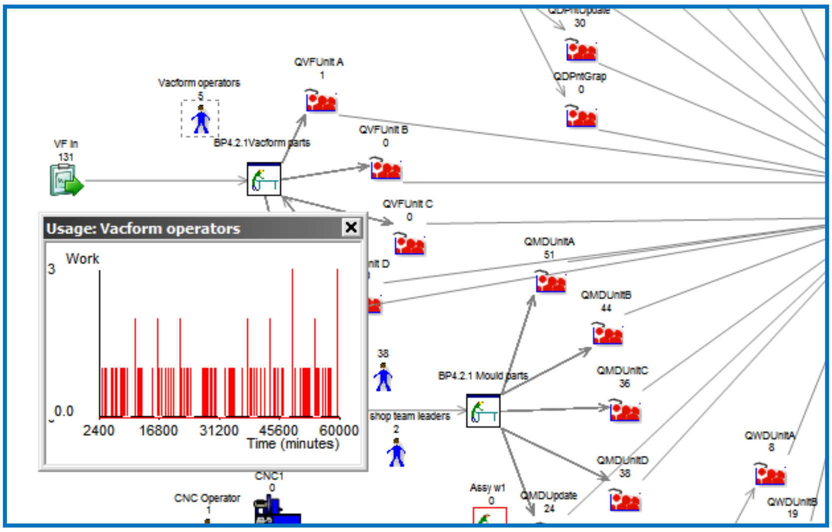


Figure 131: Performance of vac form operators

At the next stage of results collection, inventory sizes and queuing times were extracted from the 'as-is' model. The 'as-is' model consist of 56 queues which is too many to display in this Chapter hence results from two queues are shown in Table 50. The results from the queues show the minimum, average and maximum queue sizes during the run. In addition they show the minimum, average and maximum queuing time, current stock level and number of items which passed through the queue. Other statistical data such as number of non-zero queuing times and standard deviations are also available but not shown in Table 50.

Simulation Object	Performance Measure	Run 1	2	3	4	5	Average
QMDUnitA (Unit A inventory/parts from moulding process)	Minimum queue size	6	3	3	4	4	4
	Average queue size	6	3	3	4	4	4
	Maximum queue size	61	60	55	60	51	57
	Minimum Queuing Time	7868	8621	17050	9360	2575	9095
	Average Queuing Time	37979	20660	34360	29828	25096	29584
	Maximum Queuing Time	49919	32229	56659	55641	44498	47789
	Current Contents	61	60	54	60	51	57
	Items Entered	61	61	60	63	56	60
QMDUnitB (Unit B inventory/parts from moulding process)	Minimum queue size	1	0	0	0	0	0
	Average queue size	1	0	0	0	0	0
	Maximum queue size	56	53	57	47	45	52
	Minimum Queuing Time	14430	14052	7222	4800	17957	11692
	Average Queuing Time	29596	29168	19237	25894	37579	28295
	Maximum Queuing Time	51200	46291	40750	49625	51006	47774
	Current Contents	55	53	57	47	44	51
	Items Entered	64	57	63	58	52	59

Table 50: Selected example of as-is results of queues

Similar to other process entities, detailed process results which enhance understanding about the behaviour of queues can be derived by investigating further how parts are accumulated. An example results for queuing times for ‘make pad prints’ (BP4.1.1.7) is shown in figure 132.

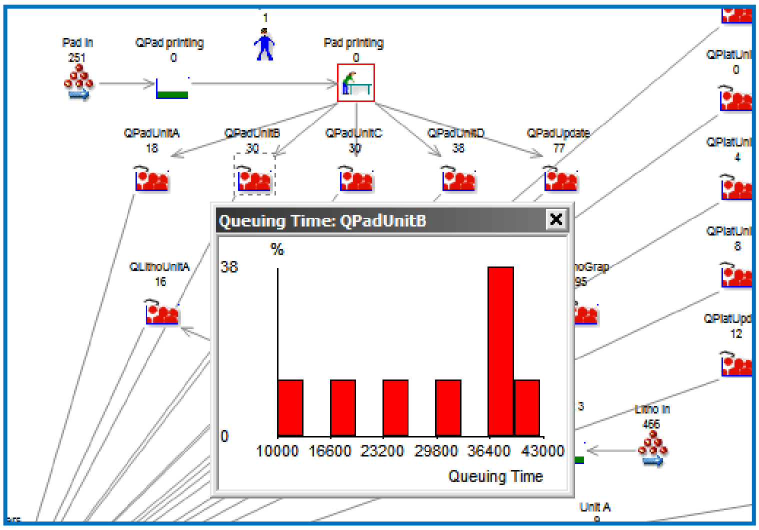


Figure 132: As-is results of queuing time for pad printing unit B

Another set of results which was collected was related to performance status of work centres. In the as-model, 25 work centres were identified and results for all these centres were extracted from the model. For the lack of space, results for only three work centres is shown in Table 51.

Results for three work centres		
Simulation object	**Performance Measure**	**Run Result**
CNC3	Waiting %	15
	Working %	36
	Blocked %	0
	Stopped %	0
	Number Completed Jobs	169
	Minimum use	0
	Average use	1
	Maximum use	1
	Current Contents	1
	Change Over %	0
	Off Shift %	50
	Resource Starved %	0
Comp Prnt	Waiting %	50
	Working %	0
	Blocked %	0
	Stopped %	0
	Number Completed Jobs	294
	Minimum use	0
	Average use	0
	Maximum use	1
	Current Contents	0

	Change Over %	0
	Off Shift %	50
	Resource Starved %	0
Cutting Centre	Waiting %	48
	Working %	2
	Blocked %	0
	Stopped %	0
	Number Completed Jobs	225
	Minimum use	0
	Average use	0
	Maximum use	1
	Current Contents	0
	Change Over %	0
	Off Shift %	50
	Resource Starved %	0

Table 51: Results of performance of three work centres

It was possible to visualize how work centres were actively engaged in processing jobs. The results shown in figure 133 describe for a selected number of work centres, the times or periods when they have been working, waiting or resources required been off shift. The green bars represent periods when work centres have been working, yellow bars represent periods of waiting whilst black bars show periods when human resources assigned to the work centres are off shift.

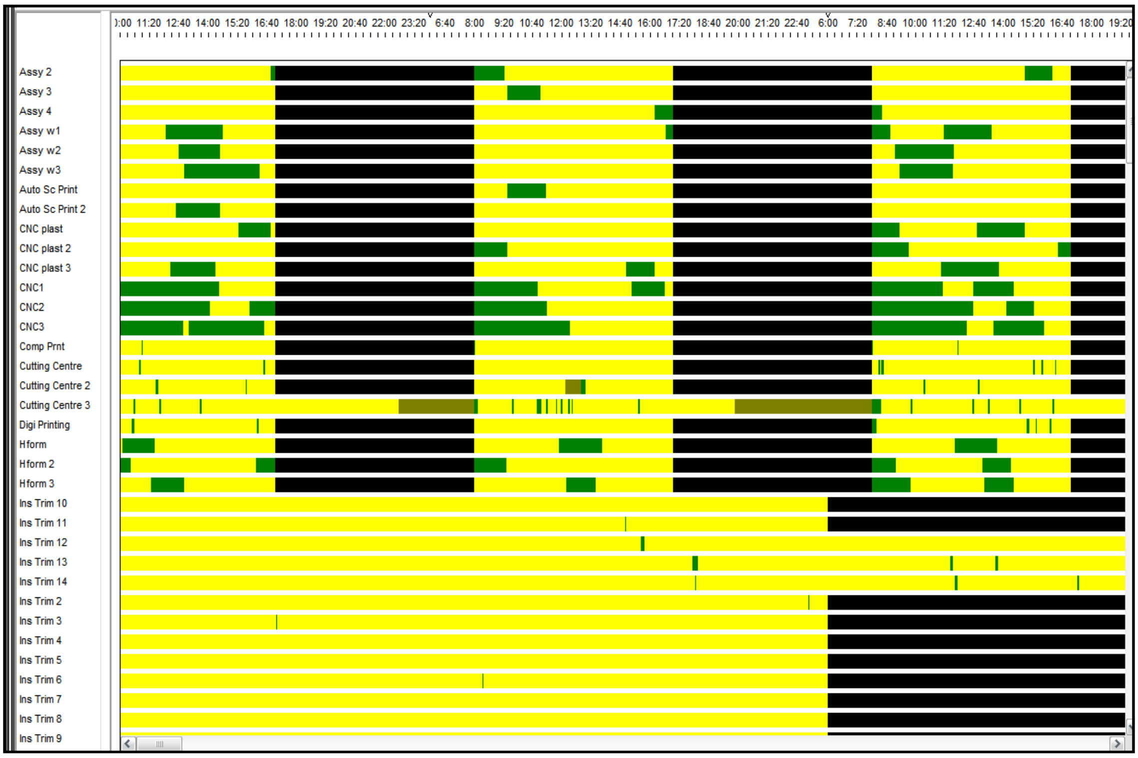


Figure 133: Operation times of selected work centres

Based on the current operations of POP Ltd, the results generated from the dynamic simulation cost and value stream model provided economic indicators of the as-is business. With the operating assumption that initial values of products are the material values, the overall cost and values realized by POP production system was provided by the Simul8 model 7 as shown in Table 52. These results in actual fact represent the cost and values generated by 'make components' (BP4.1) and 'assemble and pack products' (BP4.2). This is because the simulation displayed in figure 127 represent modelling entities belonging to these business processes. This implies that in the real case production system, additional cost and values are likely to be incurred considering the realization of other domain or business processes.

Category	Cost (£)	Value (£)	Average throughput	Unit value added (£)
Simulation Total Costs	***881,269.14***			
Unit A Total value in simulation		43,407.00	140	310.05
Unit B Total value in simulation		45,864.00	245	187.20
Unit C Total value in simulation		83,395.80	300	277.99
Unit D Total value in simulation		79,326.00	300	264.42
Update kits Total value in simulation		104,076.00	920	113.13
Graphics kit Total value in simulation		196,439.90	1821	107.87
Simulation Total value		***552,508.70***		
Profit	-328,760.44			

Table 52: Simulation results of cost and value generated by 'as-is' simulation model

Considering the vast difference between process cost and values generated, detailed results showing how cost were incurred in the realization of business processes was obtained. This was necessary to understand the cost components summarized in Table 52. The results obtained from the direct simulations of the Simul8 model for the work centres, human resources and queues is shown in Table 53.

Category	Operation cost (£)	Storage cost (£)	Category	Operation cost (£)	Storage cost (£)
Screen dev Total Cost	1,226.68		VFcut Total Cost	4.58	
Digi Printing Total Cost	155.05		VF2 Total Cost	5.98	
Man Sc Print Total Cost	43.57		VF3 Total Cost	5.74	
Auto Sc Print Total Cost	194.09		VF4 Total Cost	6.36	
Polydrome Total Cost	140.48		VF5 Total Cost	17.09	
Pad printing Total Cost	29.13		VF1 Total Cost	6.26	
QScD Total Cost		1,823.44	Trim Test 1 Total Cost	0.06	
QPoly Total Cost		26.24	Trim Test 2 Total Cost	0.07	
Platen Total Cost	2.14		Trim Test 3 Total Cost	0.06	
Lamination Total Cost	92.89		Trim Test 4 Total Cost	0.06	

Cutting Centre Total Cost	22.54		Trim Test 5 Total Cost	0.06	
QLam Total Cost		89.50	QVFAssy Total Cost		22.04
QCNC Total Cost		149.07	VFassy1 Total Cost	10.79	
CNC plast Total Cost	922.44		VFassy2 Total Cost	30.28	
QAssy Total Cost		0.16	VFassy3 Total Cost	7.23	
CNC2 Total Cost	2,285.63		VFassy4 Total Cost	13.01	
Assy w1 Total Cost	6.84		VFassy5 Total Cost	13.01	
Assy 2 Total Cost	362.92		VFassy7 Total Cost	21.28	
Hform Total Cost	64.25		VFassy8 Total Cost	23.33	
QHform Total Cost		231.95	VFassy6 Total Cost	11.36	
QSpray Total Cost		0.27	MD1 Total Cost	2.36	
Spray Total Cost	812.91		MD 2 Total Cost	2.51	
Assy Unit C Total Cost	40.96		MD 3 Total Cost	2.47	
Assy Unit B Total Cost	22.23		MD 4 Total Cost	2.74	
Packing Total Cost	5.32		MDB1 Total Cost	2.56	
VF in Total Cost			MDB 2 Total Cost	25.81	
QVFcut Total Cost		189.50	MDB 3 Total Cost	2.34	
MDB 4 Total Cost	2.63		MDC 2 Total Cost	2.53	
MDB 5 Total Cost	2.46		MDC 3 Total Cost	2.59	
MDC1 Total Cost	2.19		QPLUnitD Total Cost		430.14

Table 53: Cost indicators of some business processes

Category	Operation	Storage	Category	Operation	Storage

	cost (£)	cost (£)		cost (£)	cost (£)
QPntUnitA Total Cost		1,538.70	QPLUpdate Total Cost		64.69
Plat in Total Cost	182.00		HF in Total Cost		
QPlatUnitA Total Cost		9,638.50	Assy Unit D Total Cost	14.91	
QPlatUnitB Total Cost		16,648.50	Qdigi Total Cost		3,233.50
QPlatUnitC Total Cost		13,221.50	Screen printers Total Cost	1,403.31	
QPlatUnitD Total Cost		11,695.50	Polydromer Total Cost	759.94	
QPlatUpdate Total Cost		21,435.50	Digital printers Total Cost	133.66	
Pad in Total Cost			Laminator Total Cost	179.77	
Comp Prnt Total Cost	31.25		Pad printer Total Cost	24.96	
QCUnitA Total Cost		57,277.00	Platener Total Cost	2.03	
QCUnitB Total Cost		91,946.50	Component printer Total Cost	30.34	
QCUnitC Total Cost		79,801.50	Bench assemblers Total Cost	12,941.82	
QCUnitD Total Cost		160,679.00	Sprayers Total Cost	696.58	
QCUpdate Total Cost		313,015.00	Cutter 2 Total Cost	229.06	
QCut Total Cost		0.50	Cutter 1 Total Cost	112.70	
Cutting Centre 2 Total Cost	11.50		Screen developers Total Cost	1,757.75	
QCut2 Total Cost		10.38	Screen dev 2 Total Cost	533.55	
QCut 3 Total Cost		5,789.50	Man Sc Print 2 Total Cost	45.07	
Cutting Centre 3 Total Cost	371.08		Man Sc Print 3 Total Cost	45.35	
CNC1 Total Cost	2,367.93		Auto Sc Print 2 Total Cost	201.58	
CNC3 Total Cost	2,284.15		Vacform operators Total Cost	101.24	
WD in Total Cost			Vacform assemblers Total Cost	13,327.15	
PL in Total Cost			QPLUnitA Total Cost		13.06
CNC plast 2 Total Cost	872.77		QPLUnitB Total Cost		209.81
CNC plast 3 Total Cost	887.21		QPLUnitC Total Cost		16.20
QCNC 2 Total Cost		31.38	Assy w2 Total Cost	7.40	

Table 54: Continuation of cost of processes

Category	Operation cost (£)	Storage cost (£)
Assy w3 Total Cost	7.01	
PL CNC op Total Cost	11,385.54	
Assy 3 Total Cost	373.18	
Assy 4 Total Cost	355.51	
Heatformers Total Cost	1,302.74	
Hform 2 Total Cost	66.02	
Hform 3 Total Cost	66.75	
Assy Unit A Total Cost	24.75	
Assy update kits Total Cost	63.91	
Assy graphic parts Total Cost	208.59	
Mould shop team leaders Total Cost	87.43	
Mould assemblers Total Cost	25,729.34	
Lean Assemblers Total Cost	6,068.86	
QPad printing Total Cost		34.24
QPlaten Total Cost		11.56
QComp Prnt Total Cost		39.25
Simulation Total Costs	91,955.56	789,313.58
Total direct process cost	881,269.14	

Table 55: Continuation of cost of processes 2

8.5 Analysis of results derived through simulation models

The results provided by the dynamic cost and value stream simulation model confirmed the initial assertions generated through observing results provided by the static and system dynamic models. This was generally reflective in the number of products realized and values generated. The results on cost was greatly different form the results predicted by the static analysis in Chapter 7 because as explained previously, in the static model, queues sizes, queue times and movements were ignored but they were catered for in the simulation model. The difference between the static and dynamic simulation model in terms of results provision is that the discrete event simulation model provided detailed results of work centres, queues, work entries and work exits. Hence process performance can be visualized and experiments conducted so that overall process, resource and work flow efficiencies can be observed. In addition alternative workflows and work loading of processes can be examined and used as a front end decision tool.

Critically observing results about throughput provided in Table 48 and comparing it with the sales requirements, it can be said that POP Ltd are not meeting their demand. Reasons for not achieving their production targets have already been provided by the causal loop and iThink models in figures 114-121. It is therefore obvious that POP Ltd is under producing and hence not generating enough value to sustain its self. Directly, the value realized by POP Ltd is proportional to the number of products realized through the production system, since essentially that is the main revenue generating source for the company. Hence to remain competitive, there is the need to redesign the production system and its associated flows such that high numbers of products can be realized. Comparing Tables 48 and 52, it can be realized that although POP Ltd produces more of 'graphic based kits' the value it generates for the business is relatively low as compared to the potential values that could be generated from realizing Unit A and B. Since there is outstanding orders for Units A and B it implies that POP Ltd may have to strategize its production system to realize more of units whilst maintaining the large production volumes of graphic-based products. How this can be achieved have been demonstrated in the experiments and to-be model provided in section 8.6

Observing the utilization of human resources in the direct value adding processes of POP Ltd, it can be seen that human resources are grossly underutilized. The overall average human resource utilization is estimated at 35%. Also since wages are not paid based on number of products realized at a work station, it implies that POP Ltd spends a lot of money paying permanent and temporal staff who contribute only a little percentage of their effective time towards the actual value realizing processes. A number of human resource management solutions exist for such scenarios but in reality what is required is a re-organization of work. The Section 8.6 shows how work was re-organized and processes reengineered for better utilization of human resources in the to-be model. The cost benefits in deploying such approaches have also been shown.

From the system dynamics models shown in figures 114-121, it was deduced that one of the major sources of high production cost in POP Ltd is related to inventory. Causes, methods and possible solutions for reducing inventory in POP Ltd's business was provided in Sections 8.3.1 and 8.3.2. But these suggestions were given at a strategic level. In the results provided by the Simul8 model, key process areas where inventory is accumulated are related to the 'make prints' (BP4.1.1) business processes. This is reflected in the percentage of storage cost related to this area (see figure 134). Further analysis of results shown in Table 52 shows that inventory cost constitutes about 90% of the company's process cost. Hence money is locked up in inventory, making the processes inefficient.

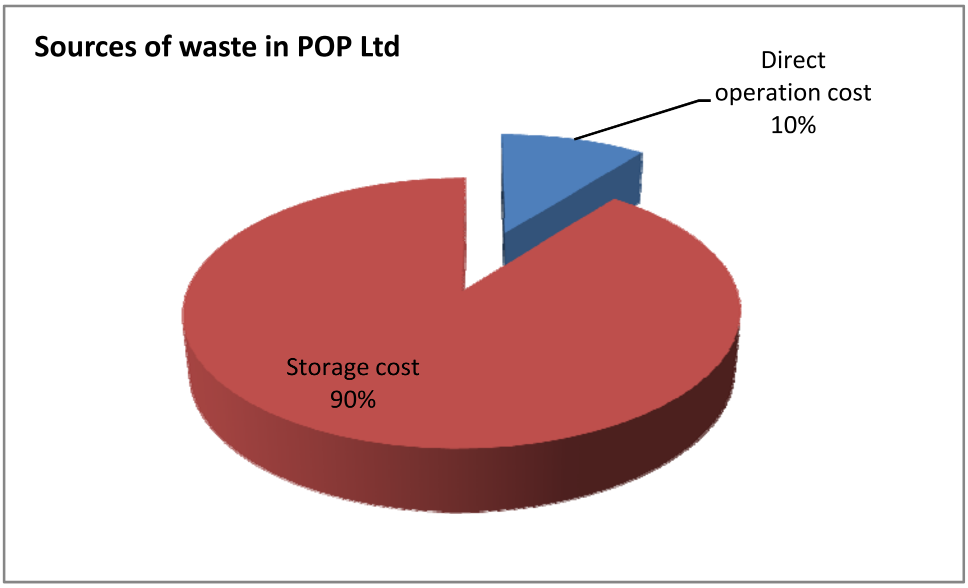


Figure 134: Inventory cost versus direct operational cost in POP Ltd

Further analysis of Tables 53-55 show that different queues contribute to the overall inventory cost. This is shown in figure 135.

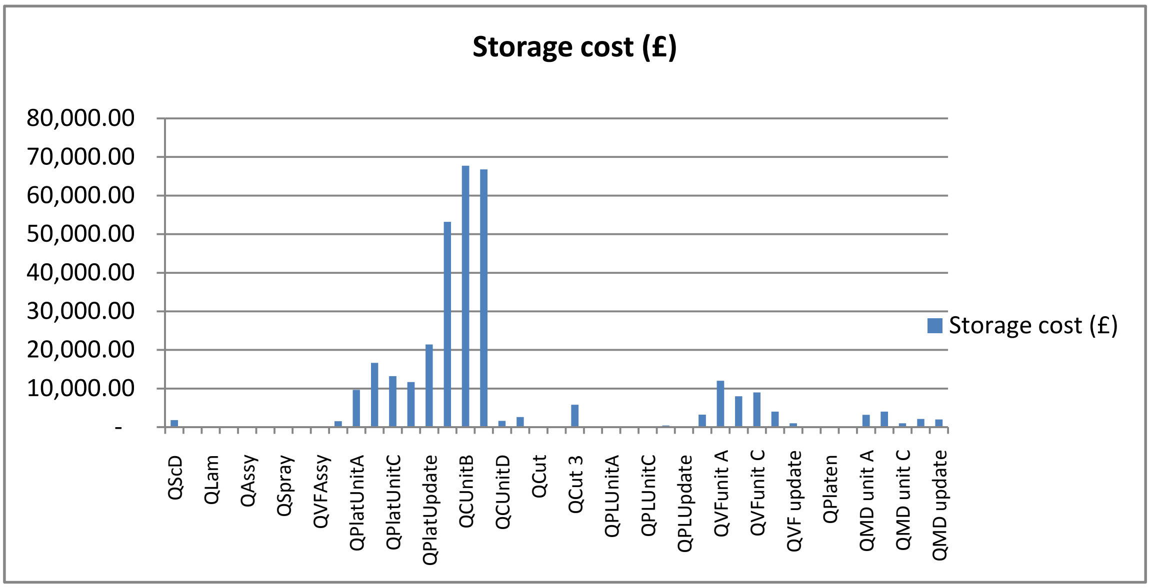


Figure 135: Comparing storage cost of queues

From figure 135, it can be seen that component prints, platens, vacformed parts and moulded parts contribute hugely to inventory cost. Therefore as part of the experiment, these processes were re-designed to ensure that these processes no longer produced large queues.

From the sampled results for work centre utilization, it can be seen that work centres are grossly underutilized. This is represented in the low 'working time' percentages scored by each of the work centres. From the results, most work centres waited for long times before processing next jobs. Also high percentages of 'off shifts' were recorded by the assembly, printing and wood workshops because work centres in these shops were utilized only during the day shift whilst vacforming and moulding shops operated a 12 hour day and night shift. This partially is also the cause of overstocking since the processing rate of the assembly shops and other associated processes do not match.

From the time view of work centres shown in figure 133, most of the work centres were idle with only small percentages of their availability utilized usefully. This is shown by the green codes in figure 133. From the graph, it is possible to determine which time of the days the work centres were idle or waiting.

8.6 POP Ltd production system design in support of high value realization and low cost

From the results derived from the 'as-is' model, it is evident that 'to-be' models of the POP production system capable of producing high volumes of units whilst maintaining the high volumes of kits was required. Whilst meeting these production requirements, low inventories are to be realized such that the overall process cost will be minimal. In addition to achieving these requirements, there is the need to design work and processes such that human resource utilization is increased and production synchronized. To achieve these objectives, it was decided that process variables responsible for:

1. process change
2. product change and
3. people and related mechanical resource change,

be utilized to effect changes in the design of POP production system for better cost and value indications.

Colleagues of the author at MSI Research Institute in Loughborough have already conceived that conceptually processes can be redesigned through alternative coupling of resource elements to processes or activities (Weston, Rahimifard et al. 2008). The idea was that different resource-process couples can achieve different outputs. Although this assertion required detailed examination of each of the processes, a simplified approach whereby selected processes which were deemed to be inefficient based on results presented in Section 8.4 were analysed.

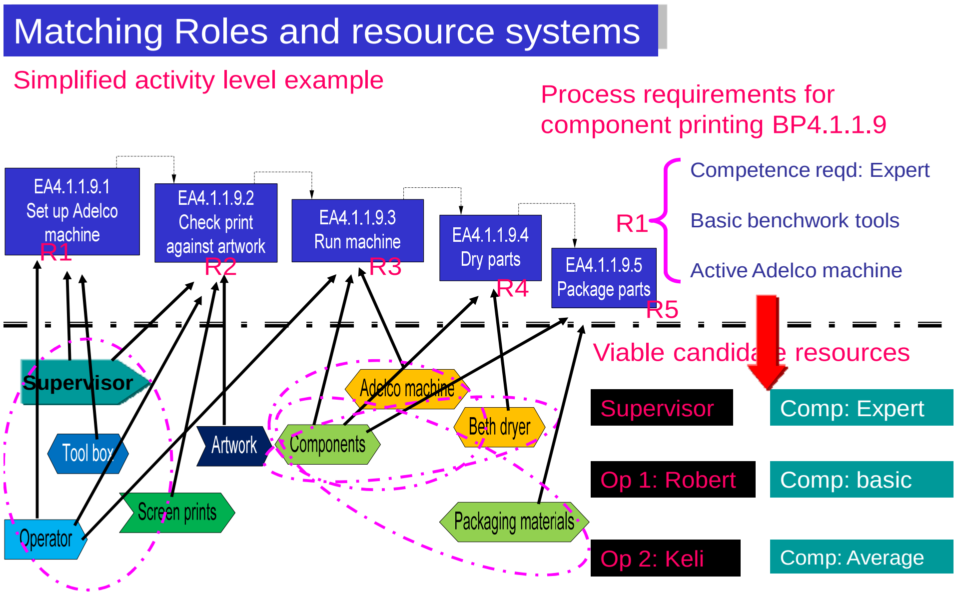


Figure 137: Conceptual process design

This approach is exemplified in the diagram shown in figure 137. For example, for component printing, based on the process requirements, alternative resource combinations was experimented. After best results had been obtained, selected resources are assigned to activities as described by figure 138. This approach formed the basis for conducting experiments on salient portions of the POP production system.

Figure 138: Context specific detailed process-resource design

Considering the ‘as-is’ operations of POP Ltd where high inventories and hence high cost and low values are generated, it was considered important to experiment with the possibility of introducing lean metrics such as pull mechanisms into salient portions of the production processes. Conceptually, the application of lean to all production processes in POP Ltd might not be helpful considering the demand pattern of POP products and the batch manufacturing equipments in their production system. Notwithstanding this concern, to improve their production performance and reduce inventory cost whilst maintaining high values through the realization of Units, there is the need to institute lean in some essential parts of the business. To achieve this it was necessary to:

1. Estimate takt time for the different product families
2. Identify the pacemaker process and ensure continuous flow for respective product families
3. Identify the ‘interval’ of production pacemaker and balance flow for the multiproducts
4. Estimate the ‘pitch’ of the pacemaker and reverse schedule the mix at the pacemaker
5. Use sequencing and first-in, first out lanes to institute pull from the pacemaker to upstream processes especially where shared resources exist.
6. Pull parts and materials from suppliers so that they are delivered only when needed

Based on current production records and customer demand, takt time, defined as the ratio of effective working time to demand during that time (Duggan 2003) was estimated for the different product families. The estimates made are tabulated in Table 56.

Product families	Demand/month	Demand/week	Effective working time (mins)	Takt time (mins)	Takt time (hours))
Unit A	40	10	2250	225	3.8
Unit B	60	15	2250	150	2.5
Unit C	67	17	2250	134	2.2
Unit D	63	16	2250	143	2.4
Update kits	160	40	2250	56	0.9
Graphic only kits	304	76	2250	30	0.5

Table 56: Takt time estimation

Unlike published approaches for implementing lean where estimations are manual and difficult to experiment, in the approach described in this Chapter, the dynamic model takes into consideration various lean options hence when takt time is specified for the pace maker, the other upstream processes are realigned to produce based on the takt time. Normally, experimentation in Simul8 proves that it is possible to design all systems to respond to lean but in practice this is not the case. Hence a leagile system approach where strategic critical stocks are kept is recommended. Whilst redesigning the processes to respond to takt, it was clear from the simulation results that key processes such as ‘make platens’ (BP4.1.1.6), ‘print components’ (BP4.1.1.9), ‘ make digital prints’ (BP4.1.1.4), ‘develop screens’ (BP4.1.1.1), ‘vacform parts’ (BP4.1.4) and ‘produce moulded parts’ (BP4.1.5) essentially produced at intervals exceeding the takt time, hence producing excess inventory. To balance production and reduce parts produced by these processes, the first set of experiments was related to the rate of introduction of materials to these processes. When the material introduction interval was reduced by 80%, massive savings on inventory cost was realized as shown in figure 139.

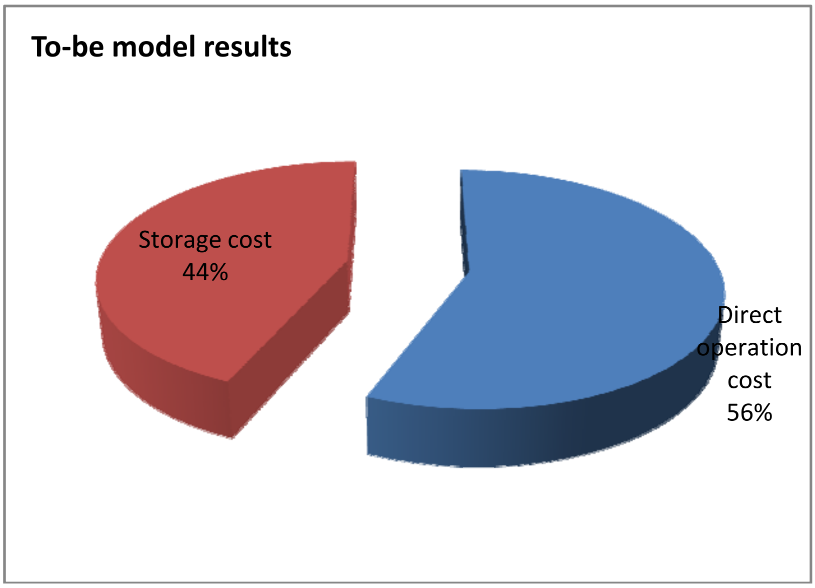


Figure 139: Savings on storage cost in ‘to-be’ model

As a result of the savings on inventory, overall process cost was reduced, giving a profit of £389,221.76 over the simulation period. The profit compared with the ‘as-is’ negative profit is encouraging. But critically, this relates to reduction in cost without improvement in values as shown in Table 57.

Category	Cost (£)	Value (£)	Average throughput	Unit value added (£)
Simulation Total Costs	***163,286.94***			
Unit A Total value in simulation		43,407.00	140	310.05
Unit B Total value in simulation		45,864.00	245	187.20
Unit C Total value in simulation		83,395.80	300	277.99
Unit D Total value in simulation		79,326.00	300	264.42
Update kits Total value in simulation		104,076.00	920	113.13
Graphics kit Total value in simulation		196,439.90	1821	107.87
Simulation Total value		***552,508.70***		
Profit	389,221.76			

Table 57: Cost and value results from experiment 1

In a related experiment, human resources performance was with the hope to increase their utilization as results from the as-is model showed that human resources were grossly underutilized.

It was however understood from the modelling results that the underutilization of human resources was due to the fact that in most cases materials or parts for production were not available. Hence when JIT techniques and dedicated supply systems are assumed in the model, resources are fully utilized and the net value generation is high. Particularly, whilst throughput of kits is maintained, there is an increase in the production of Units. Since units have high product values, this results in an increase in overall value realization by POP Ltd. The result derived from adopting this option is shown in Table 58. To maintain this positive impression it is required that lean supply schemes be employed and the purchase procedure revised as per recommendations specified in Section 8.3.1. When this is achieved high product values can be realized.

Category	Cost (£)	Value (£)	Average throughput	Unit value added (£)
Simulation Total Costs	***163,286.94***			
Unit A Total value in simulation		62,010.00	200	310.05
Unit B Total value in simulation		59,904.00	320	187.20
Unit C Total value in simulation		97,295.10	350	277.99
Unit D Total value in simulation		92,547.00	350	264.42
Update kits Total value in simulation		104,076.00	920	113.13
Graphics kit Total value in simulation		196,439.90	1821	107.87
Simulation Total value		***612,272.00***		
Profit	448,985.06			

Table 58: Results from improved utilization of human resources

A comparison of the results of values and cost generated in the as-is and to-be models are shown in figure 140. Based on these indications, value is increased by 11% whilst cost is reduced by 81%.

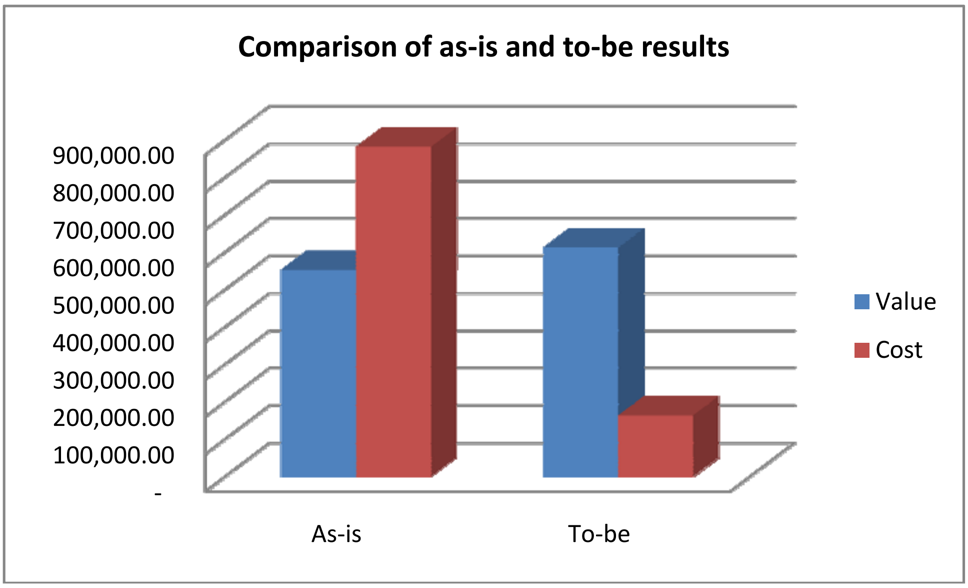


Figure 140: Total values and direct cost of as-is and to-be models

Results from the to-be model showed specific improvements in throughputs of Units A, B, C and D, whilst throughputs of updates and graphic only kits were maintained. This was useful since units increase the value of POP Ltd higher than kits

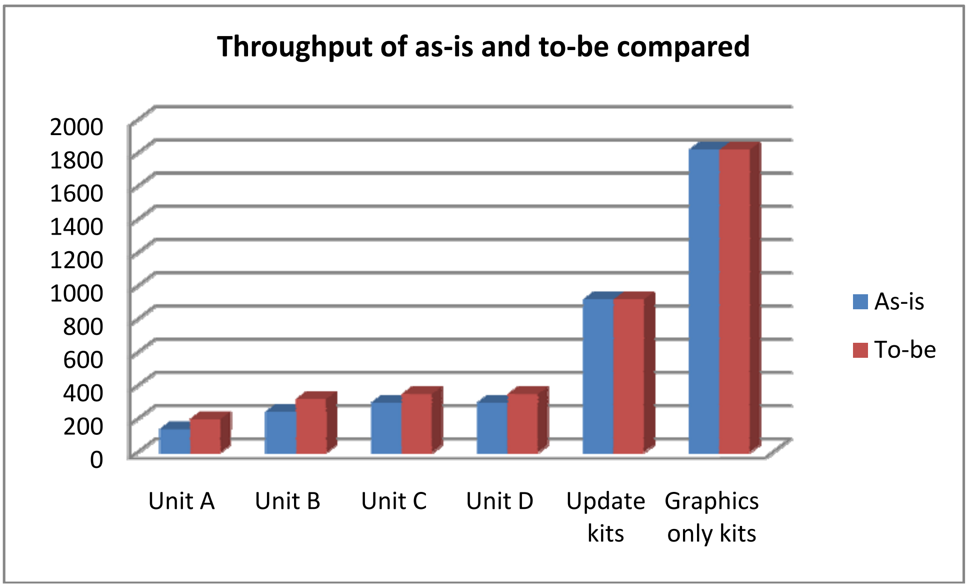


Figure 141: Throughputs of as-is and to-be models compared

A final analysis was made to observe the impact of the to-be model on inventory cost of the business processes in POP Ltd. From figure 142, it can be seen that when material purchases are properly synchronized with production and parts deliverd in time significant reduction in inventory cost can be attained

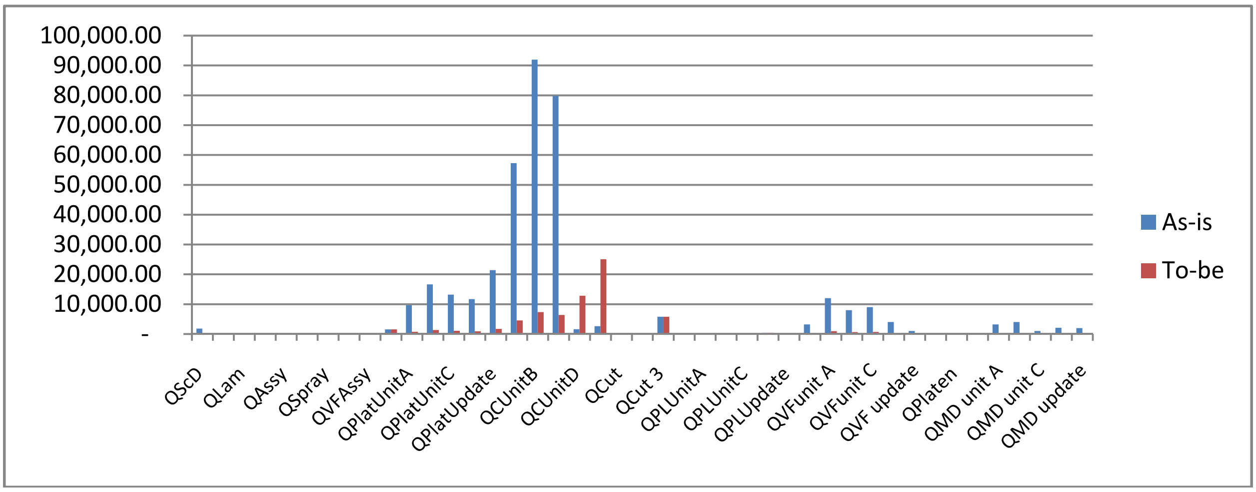


Figure 142: Inventory cost of as-is and to-be models

8.7 Observations about modelling technique and conclusions on Chapter 8

This Chapter has shown how system dynamic modelling techniques in the form of causal loops and iThink models can be integrated to capture aspects of process dynamics and change. Also to provide detailed process analysis of respective business processes and to support the design of alternative processes with the view to reducing process cost and improving values, the modelling technique was extended to the application of discrete event simulation modelling tool in the form of Simul8. Chapters 7 and 8 showed how all the modelling stages of the integrated multiproduct cost and value stream modelling technique was applied to help solve complex business problems in an engineer to order POP manufacturing company. However, based on the outcome of the model results, it is evident that CLMs and iThink models are suitable for capturing and analysing process dynamics whilst DES models are used for detailed process improvement exercises.

It was conceived that a transformation of the static cost and value stream model into dynamic simulation models had the capability to support business process analysis in POP Ltd such that methods can be developed to help increase production flow, reduce inventory, reduce production lead times, reduce process cost and increase values generated. With these objectives in mind, the causal loop modelling technique was used to enhance the structure of the static models derived in Chapter 7. After the enhancement, specific 'problem-descriptive' models were created to externalize understanding about the causes of inventory generation, lack of flow, high cost and low value generations. The set of CLMs provided deep insight into the causes and hence variables which can be manipulated to improve performances at POP Ltd were visible. Qualitative solutions were deduced from the application of CLMs but because the objective of the research extends beyond qualitative reasoning, CLMs were transformed into quantitative iThink continuous simulation models. These models further assisted in deepening understanding about process connections and their impacts on cost and value generation. Alternative business scenarios were investigated and used as the basis for developing solutions for improving POP Ltd processes. In general, because system dynamics tools are not necessarily process design tools, the solutions derived from the application of them was suitable for strategic business analysis. Through the application of the system dynamics tools, it was specified that to reduce inventories, improve production lead times and enhance value generation, care must be taken to reduce errors due to planograms. Methods to do so were specified in Section 8.3.1. It was clarified that planogram errors are mostly due to errors in customer order specifications and the incompetence of planogrammers. An alternative process for planogramming has been recommended. Other associated problems identified was purchase delays and lack of flow in production which basically were due to the utilization of production plans which did not take into account current workloads and capacities of the production system. Other reasons assigned were the production and supply of wrong parts. Most essentially, the inefficiencies in the production system resulted in high inventories which was a major problem for the Managers of POP Ltd.

In detail, the discrete event simulation model was further used to improve specific business processes. This led to the development of to-be models with potential to improve value by 11% and reduce total process cost by 80%. In the event of application of the to-be model, it was evident that current facilities of POP Ltd can support an improvement of throughput by 6.3% whilst reducing inventory cost by 46%. The to-be model was obtained through alternative experiments of flow of work and organization of resources. It is however noted that real life implementation of to-be models will need to be thoroughly assessed since in practice there might be some constraints in the implementation of the recommendations given in this Chapter. The Managers were encouraged to thoroughly study the content and apply as per their immediate needs.

The dynamic modelling technique enabled alternative business scenarios to be experimented and their impact on cost and value generation visualized. By adopting this technique, alternative means of increasing throughput, reducing process cost, reducing inventories and increasing value were observed.

9. Further application of the multiproduct cost and value stream modelling technique

9.1 Introduction

Previous chapters have described how the multiproduct cost and value stream modelling technique was applied to capture essential qualitative and quantitative process data which enabled key business process analysis on cost and values to be done. The technique was applied initially in two make-to-order manufacturing companies located in Loughborough and York. The third case study was conducted in an engineer-to-order manufacturing company also based in Loughborough. To further prove the applicability of the proposed modelling technique, the research was extended to an engineer-to-order air condition manufacturing company based in China, herein, referred to as AirCon China.

AirCon China became privately owned in 1988 and has since then expanded its manufacturing and supply scope to become one of the Chinese manufacturing companies specialised in the 'engineering to order' of customised industrialised air conditioners. Their unique expertise is demonstrated in their competence in meeting varying customer needs, although not with significant good production lead times. Despite these success indications, the Managers report potential room for improvement. It was on this premise that a team of researchers from the MSI Research Institute of Loughborough University was invited by the company to study its operations and recommend suitable improvement solutions to enable them remain competitive. Four researchers including the author, from Loughborough University, with unique skills and capabilities were involved in the AirCon China project. This chapter however reports on research work in AirCon China by the author. The case study was conducted to see how the already tested multiproduct dynamic cost and value streams modelling technique, can be applied in AirCon China to help solve problems related to cash flow and design of production systems for low process cost and high value generation.

9.2 Background of AirCon China

AirCon China is located in Shun De in the Guangdong province of South China. The company is led by a board of Directors headed by the President. The board of directors are responsible for the development of long term strategies and also see to the profitability and sustenance of the company. Apparently they are not involved in the day to day management of the company. Below the board of Directors is the General Manager and his associate managers who generally have oversight responsibilities over five main departments: Sales, Marketing, Finance, Technical/Production and Human Resource. On the average, AirCon China employs about 1000 people of which 60 are main stream Engineers. Most of their employees are young graduates from universities and colleges and hence the company exhibits high level of exuberance in terms of its personnel.

AirCon China specializes in the customized design and manufacture of air conditioners used at power stations, air ports, hospitals, trains and special environments. Their products range from chillers, air handling units, humidifiers, humid static equipments and 'standard' air conditioners. Approximately, 4000 unique products are manufactured by AirCon China with an average lead time of 45 days, although historically, due dates have varied from 10 to 90 days, depending on the product type, available production capacities, materials, et cetera et cetera.

The business is highly competitive with a number of other leading manufacturing companies scattered around the globe but AirCon China claims to have a competitive edge over its competitors because of the company's ability to deliver customized air conditioners and also provide after sales services to customers. The company is extremely supported by an internal highly skilled air conditioning research and development engineers whose prime focus is to develop key and leading technologies related to air cooling. At the time of the research, it was indicated that competition in the sale of air conditioners has increased because of the rapid change in prices of materials (especially metal sheets), influx of other competitors and changes in government policies concerning businesses in China. It is however the vision of AirCon China to become the leading air conditioning manufacturing and Supply Company in China.

9.3 Overview of AirCon China process flows

Business in AirCon China normally starts with the marketing team who identifies potential customers and explain the capabilities of AirCon China to them. These customers may be construction firms, Airport and transport authorities, Schools, Companies, etc. The interaction of the marketing team with these customers sometimes lead to order generation but in some cases they do not result in the awarding of contract. When potential customers are obtained by the marketing team, they are passed over to the sales team who follow up to obtain orders. Normally, all initial customer specifications (new orders and orders from existing customers) are received by the sales team. These initial documents are used to estimate the contract price and due dates. Several interactions occur between the sales team and customers in order to establish common prices, acceptable due dates and required designs. About 80% of contract prices and due dates are estimated by the sales team. The sales team utilizes an existing price lists, material cost data, and assumed production lead times together with prices quoted by competitors to estimate contract prices. In extreme cases where product difference is high, consultations are made across various departments for appropriate price indications. Eventually when the terms of the contract are mutually agreed by sales team and customers, contract document are signed by both parties. There are several sale depots in China who are involved in order initiation processes but final signing of contract documents are done by the in-house sales team.

A copy of the signed contract is transferred to the Design department for the creation of detailed product drawings and Bill of Materials (BOMs). Various groups of designers from main stream mechanical, electrical, electronics and thermal fluid systems engineering, concurrently develop working designs and drawings of the air conditioners (A/Cs). The outputs of these design activities are detailed product drawings, product design specifications and BOMs. The drawings and BOMs serve major purposes in the order fulfilment processes of AirCon China. The BOM document becomes the driving file for the creation of purchase lists and purchase orders. Suppliers supply based on purchase orders received from the purchasing department. These purchased materials and parts are received into the good-in stores and internal arrangements exist for the production department to take parts and materials from the stores.

The product drawings and BOMs further serve as the main working documents which guide all machining and assembly operations in the production department. On a similar ground, they are utilized by the Process Control department to generate process flow charts, design and manufacture tools to support production operations. The Production department notifies the sales team of their expected completion dates. These dates are relayed to the transport owners and they intend plan suitable times for delivery of the packaged A/Cs.

9.4 Creation of AirCon China multiproduct cost and value stream models

9.4.1 Initial description of problems at AirCon China and research approach

During a meeting with the Managers of AirCon China, it was reported that the company was in its critical stage of growth but there were key problems associated with overall planning of activities in the company. Further explanation on the planning issue revealed that, they perceived the cause of their problems to be the lack of an appropriate planning tool and the inability of the production system to adjust or maintain production plans. Hence their immediate solution was to acquire an Enterprise Resource Planning (ERP) tool with the hope that they might be able to generate fairly accurate due date estimates, maintain production plans and support the timely delivery of purchased parts and materials. Achieving this goal was however complex for the Managers of AirCon China because they realized that the issues and factors could not easily be analysed. This was because:

1. Every customer order (contract) is unique. This is because the products are highly customized

2. Orders arrive at random and therefore it is difficult to plan ahead.
3. Due dates are specified by sales personnel without adequate consultation with relevant departments because of the need to win contracts within relatively short intervals.
4. Purchase lead times are difficult to estimate and factor into production plans.

Due to experience gained through solving similar problems in the case studies reported, it was naturally assumed that the problems defined by the Managers had underlining causes and reasons which the Managers were not aware of because in most cases a scientific approach and methodology are required to unearth some of these factors. As gathered in previous case studies, it was conceived that a thorough understanding of processes in AirCon China and how material, information, and resources flow across processes will help unveil the actual causes of the problems mentioned. Also assumed was that the cost and value stream modelling technique possessed useful modelling stages which had the capability of revealing causes of problems and further provide through experimentation knowledge of key levers which can be manipulated to achieve needed results.

Because of the distance and cost involved in travelling to AirCon China, maximum effort were put into the periods of stay in China. In all, two project trips each spanning about 10 days were made during the research period. Detail work plans for the two visits are shown in Appendix C1. During the first trip, it was considered in the light of the overall research methodology described in section 3.6 that, it was necessary to specifically:

1. Gain understanding of the company and its associated challenges. This was estimated to take three days. It involved studying company documents, organizational charts, production flows, purchase records, sales records and finance details so that a big picture Enterprise Model (EM) could be generated. Based on the EM so generated, static cost and value stream models as well as causal loop models (CLM) can be developed. Whilst in AirCon China, company documents and knowledge of processes were gained through:
    a. interviewing key persons in the company and
    b. using their knowledge to form a visual ‘big picture’ of the company.

   The models created:
    a. described explicitly the team’s understanding about the operations of AirCon China
    b. helped the managers of AirCon China to discuss issues that cross their sectional and departmental responsibilities.

   c. helped to discuss with the managers of AirCon, possible potential areas of improvements.
2. Select areas of potential research improvements. This was designed to be held on the fourth day after the team had presented their initial understandings and findings to the Managers of AirCon China. After achieving this it was initially agreed to conduct lead-time, quality, cost & value analysis to inform 'planning in the company' and redesign of the assembly shops to ensure higher throughputs and less lead times. These areas were chosen because:
   a. AirCon China believed that significant business benefit might accrue from work in these areas;
   b. that the team and their colleagues have expertise to address them.
3. Detailed capture of data .This involved interview of 'third level' AirCon China Managers who were experts in the departmental units and sections concerned with the agreed areas of potential improvement. Shop floor visits were also made to capture data which can be used to create dynamic multiproduct flow cost and value stream models that can be used to render solutions to AirCon China.
4. Verify initial models and recommendations. On the last day of the visit the models were presented to the company for discussions. Also initial recommendations were made and a proposal for the establishment of an internal project team was made to help further collect data, verify and validate models sent to AirCon China. A set of proposed deliverables to achieved in nine months but reported quarterly was defined to be:
   a. develop and verify 'as-is' enterprise models
   b. develop and verify product based static cost and value stream models
   c. Develop and verify dynamic value stream models
   d. Use dynamic models to help solve problems on cash flow and derive alternative pricing, payment and purchase policies
   e. Create and validate production system model (digital mock up of production system) and use for production flow analysis, inventory reduction, paradigm selection, and cash flow analysis

Upon satisfactory completion of these targets, a second visit was made to present findings and further collect specific data and offer training to relevant personnel who will serve as change actors in AirCon China.

9.4.2 Creation of AirCon China enterprise model

To facilitate understanding and provide a basis for in-depth analysis of operations in AirCon China, interviews of relevant actors in the company was conducted. This involved interviewing Senior

Managers, Middle Managers and specific persons whose job was related to the research scope. The set of questionnaires used during this interview section is shown in Appendix C2. One idea behind understanding the different operations in the company was to help develop a means of classifying processes in the company. Initially, reference was made to a body of literature on process classifications (Salvendy 1992; Pandya, Karlsson et al. 1997; Weston 1999; Chatha 2004,) and a decision was made to classify the processes into ‘obtain order’, ‘fulfil order’ and ‘manage order’ (Salvendy 1992; Pandya, Karlsson et al. 1997) so that data and interviews can be conducted along these lines.

In relation to AirCon China operations, the ‘obtain order process’ comprises the independent processes (and activities) involved in receiving and confirming orders or contracts. This involves processes which are performed primarily by the Marketing and Sales departments. The objective of the ‘obtain order process’ is to win contracts and prepare all necessary documentations associated with contracts. ‘Order fulfilment process’ was used to describe the set of processes (and activities) required to transform contracts into finished A/Cs meeting customer specifications. In a way, it was viewed as the set of ‘value adding processes’ required to produce A/Cs. This included processes involved in the development of product designs and BOMs, metal sheet and heat exchanger fabrication and its associated assembly activities as well as tool making processes. The third class of processes called ‘manage order’ consists of the supervisory, control and managerial processes (and activities) required to fulfil customer orders. It includes processes and activities related to business management such as finance control, human resource management, management of inventory and purchases, quality control and process control.

These initial classifications were deduced from human resource organization charts received before the interviews. During the interview, it became evident that the company was more complex than was depicted on the organizational chart. A process view was then adopted to carefully capture all processes required to obtain, fulfil and deliver, manage and control processes. The CIMOSA modelling template was used to capture various decompositions of these processes. As developed in earlier chapters, spread sheet was used in structuring process objectives and hence their sub processes and activities. The spreadsheet information became the backbone for generating CIMOSA graphic enterprise model of AirCon China. Appendix C3 shows the spreadsheet which was used to structure the documentation of processes in AirCon China.

Based on knowledge of processes acquired through AirCon China enterprise data and interviews of relevant personnel, information was extracted from the spreadsheet and used to create a context diagram describing the various stakeholders in the engineer to order of air conditioners at Air Con

China. As shown in figure 143, nine domains were identified to be contributing to the engineering of air conditioners to customer orders. Decomposition and hence further modelling of processes belonging to these domains were focussed on ‘Sellers’, ‘Product Designers’, ‘A/C Producers,’ ‘Business Managers’ and ‘Production supporters’ (DMs 3, 5, 6, 7 and 9) enterprise domains, since the remaining domains had their scope outside the control of AirCon China.

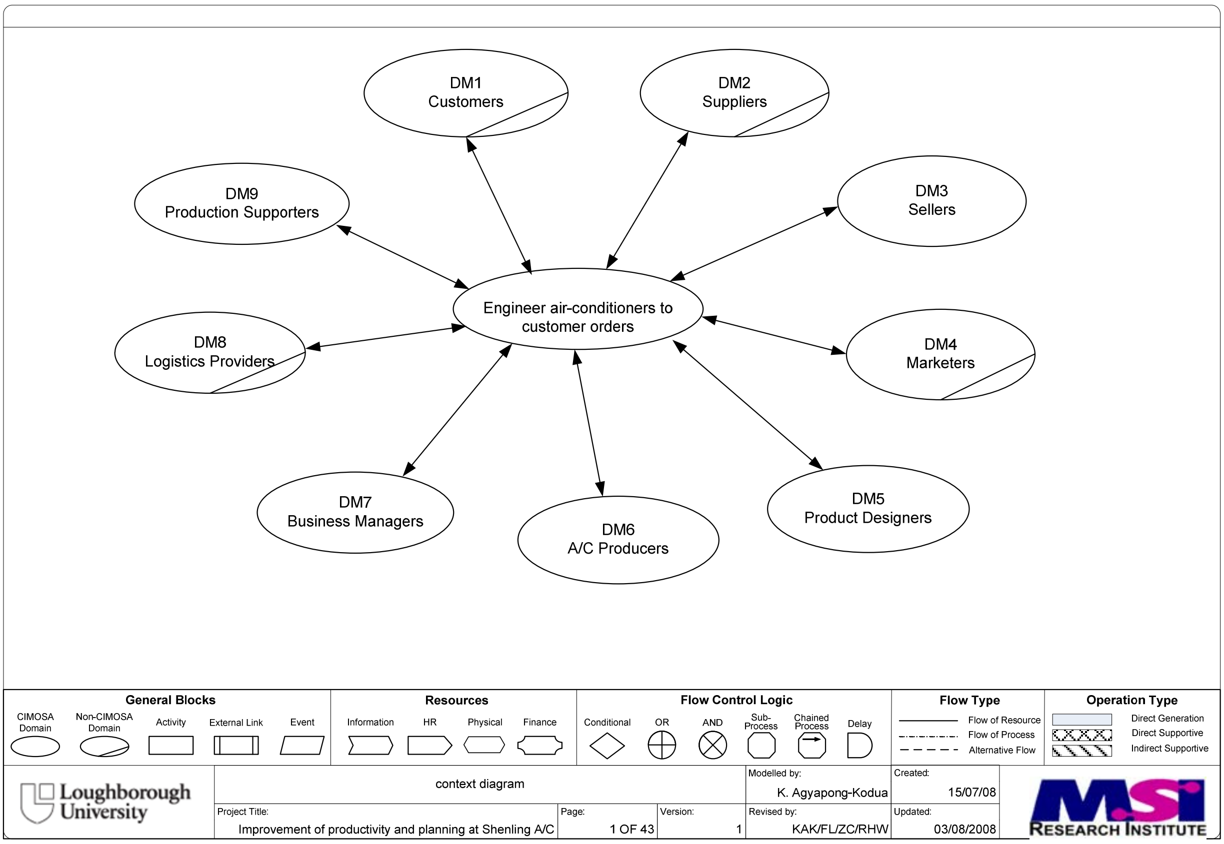


Figure 143: Context diagram of AirCon China

As explained in all the three previous case studies, in support of the modelling technique, an interaction diagram showing the top level decomposition of enterprise domains into domain processes, and also the flows which exist between domain processes, is created. Detailed description of how these diagrams are created and connected for useful process understanding have been provided in previous chapters.

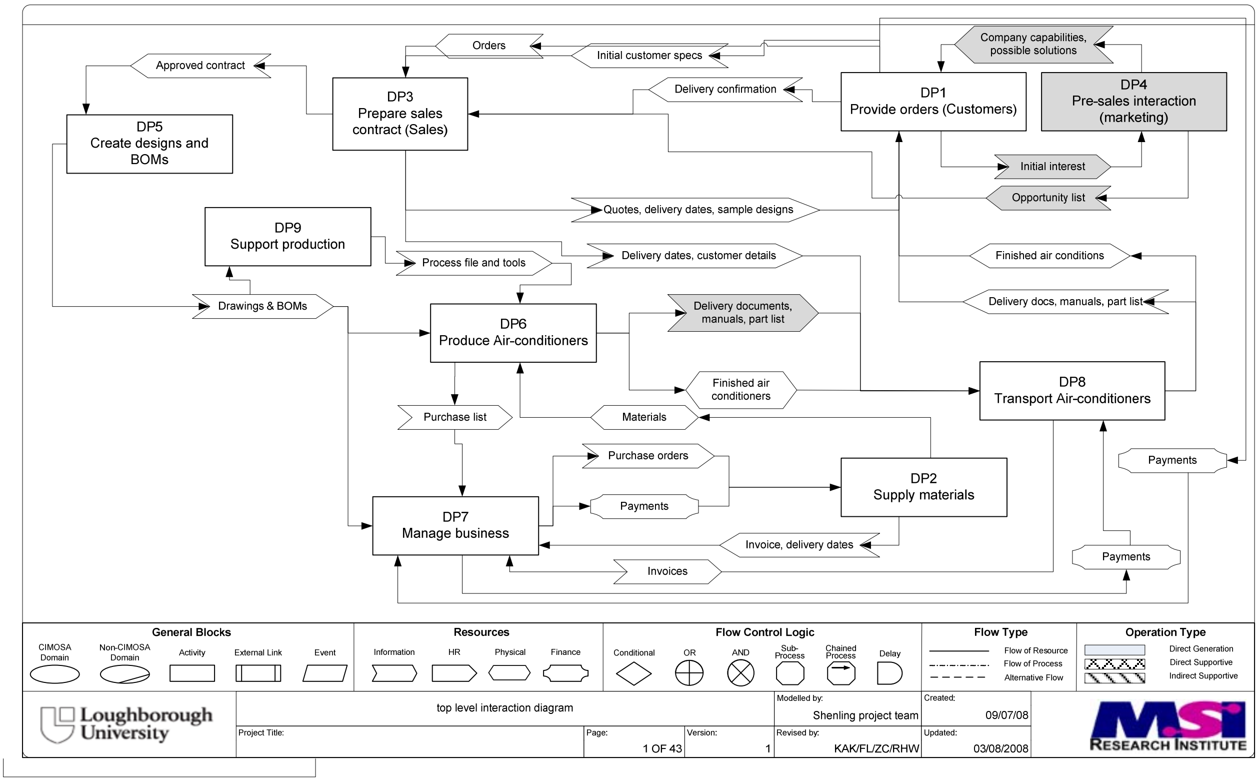


Figure 144:Top level interaction diagram of AirCon China

Because AirCon China business operation is mainly to engineer to order A/Cs, product designing plays a major role in the performance of the Company. The company's success is partially dependent on the ability to design accurately, especially, using standardized parts and most importantly designing to reuse parts that are already in stock. As a result, the company introduced a policy to offer bonuses to designers who are able to design using parts already in-stock. Although started this year, some designers had benefited from 100,000RMB through this scheme. Contrary, penalties are given to sales officers who give wrong customer specifications which lead to the purchase of wrong parts. This started in April 2007 and two cases have been reported where 100RMB were deducted from the salaries of the staff concerned.

There are two main aspects of the design process: development of product designs and the creation of BOMs. There is a PDM software which helps the designers to avoid the creation of drawings of parts which are common in many products. Completely new designs are created for only products whose specifications are extremely different from all other previously created designs. In this case, the design exercise will involve all the steps of: concept development, concept selection, scheme designing and detail designing. A structure diagram showing the decomposition of 'create designs and BOMs' (DP5) is shown in figure 145. Similar structure diagrams for the remaining three DPs:

‘prepare sales contract’, ‘produce air conditioners’ and ‘manage business’ are shown in Appendix C4.

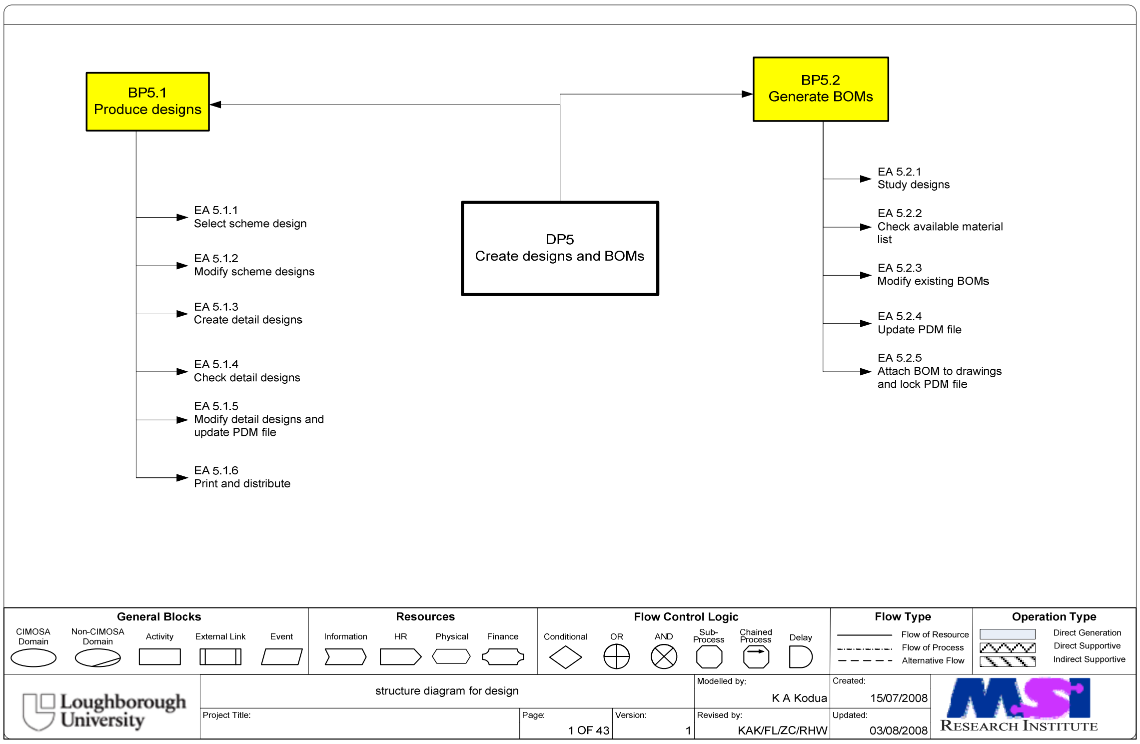


Figure 145: Structure diagram of DP5

A sub interaction diagram showing how the decomposed Business Processes (BPs) of DP5 interact with each other is shown in figure 146.

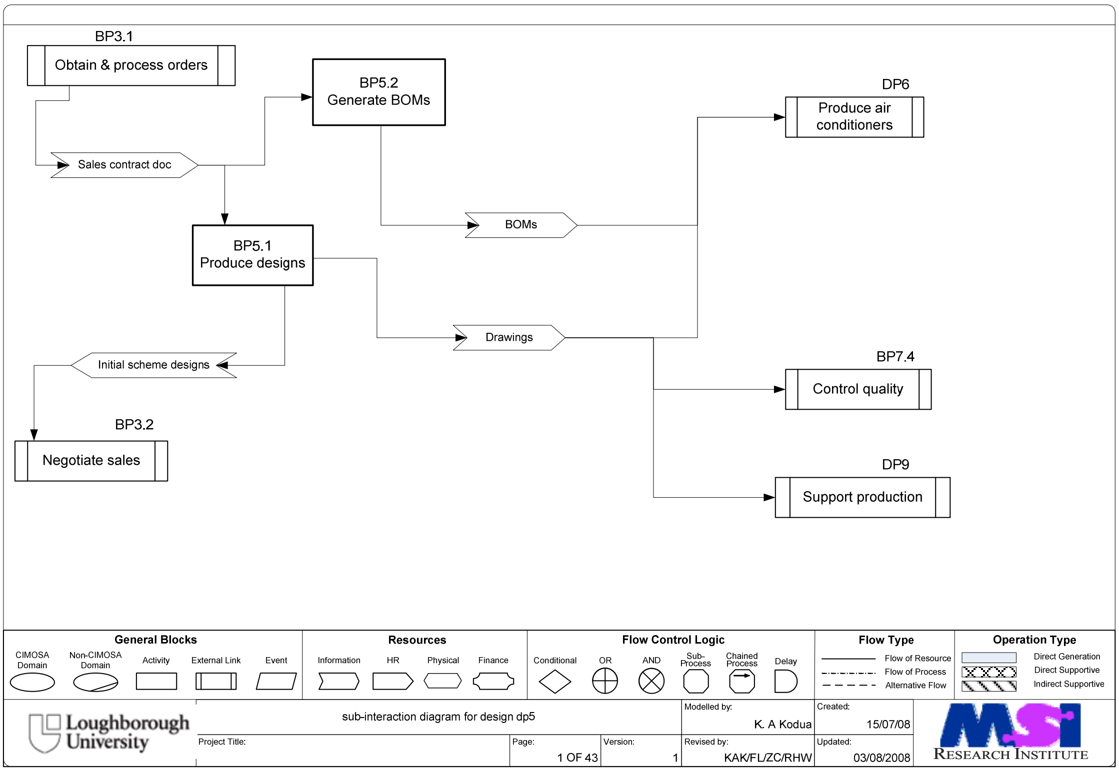


Figure 146: Sub interaction diagram of DP5

As explained in previous case study enterprise model creation processes, the next stage after the creation of the sub-interaction diagrams is to generate activity diagrams which indicate how BPs are further decomposed into Enterprise Activities (EAs). The activity diagrams for all BPs identified in the enterprise model of AirCon China is shown in Appendix C4. In the activity diagram for 'produce designs' (BP5.1) shown in figure 147, the Product Design Engineer obtains the contract document when fully signed by both the Sales Manager and the customer. This document indicates the agreed customer specifications. Based on these specifications, the designer translates the data into 'components and sub assemblies' required. Previously prepared designs are saved into respective folders of components, sub-sub assemblies, sub assemblies and final assemblies. Thus parts which match current design specifications are selected from the existing design database and assembled together to form the scheme design/drawing. This scheme design/drawing is at the 'top level' without detail component calculations and also parts are not careful checked to see how they match each other. Where there are similar designs which can be used for the current design, the designer modifies the selected scheme design to meet the requirements of the current contract. With the help of their CAD software and knowledge of engineering design calculations, detailed component calculations and drawings are generated. These drawings specify in 2-D form the dimensions, assembly configuration and basic manufacturing requirements for the air conditioners. The Design Manager then checks the drawings and from his experience and skill in product and engineering design, modifies the drawings to attain a status that the production department can produce with ease. Although this in principle is the case, it does not prevent production department from consulting with designers for clarity of some design features on the drawings. It was claimed that there were instances where the designs were not very accurate in terms of using standard parts. Also there are recorded instances of dimensional inaccuracies and assembly mismatches. This has generally been attributed to the experience level of designers and also the limitations of the software package being used. When the manager is satisfied about the quality of drawings generated, it is saved in the PDM file whilst hardcopies are also printed and distributed to the production, process control and quality control departments.

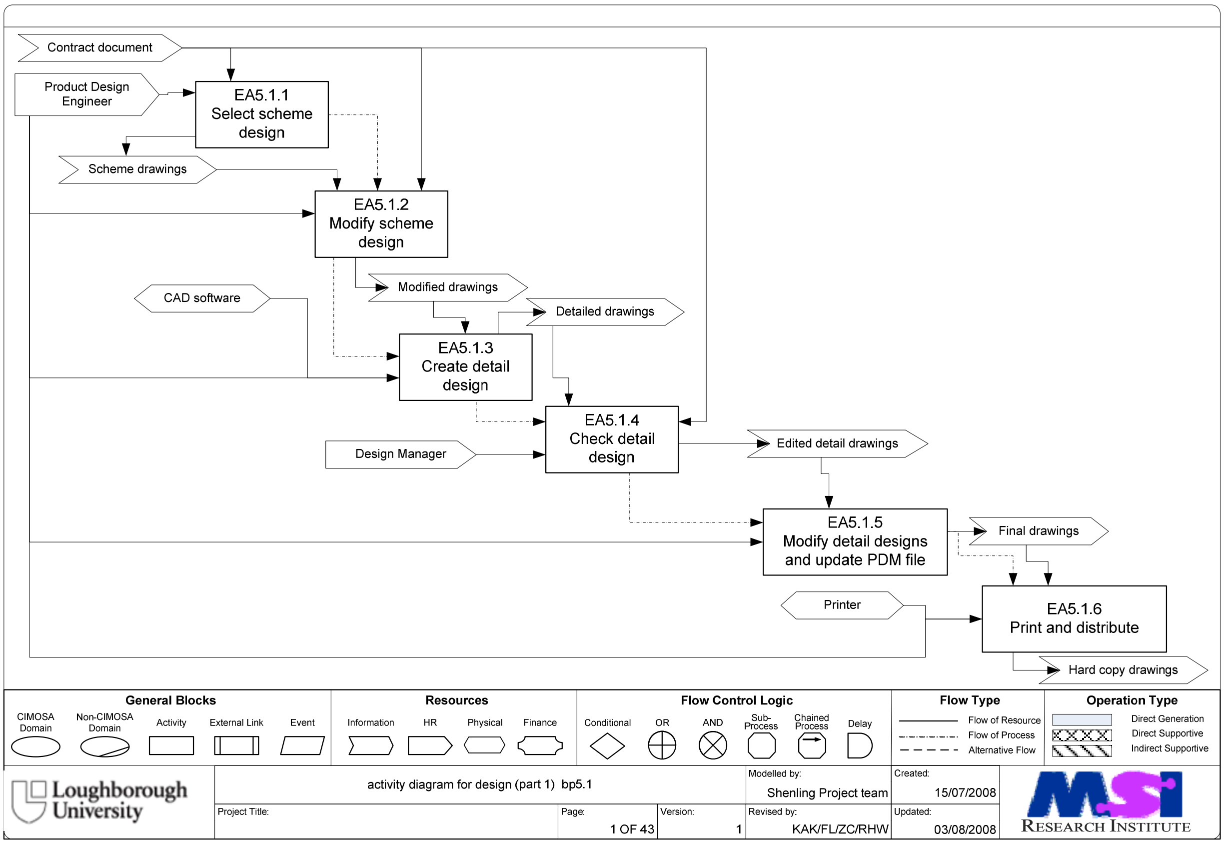


Figure 147: Activity diagram for 'produce designs' (BP5.1)

In addition to the creation of detailed design drawings, BOMs are also prepared. This is also produced by the designers by studying the design and BOMs data base to select similar product requirements. With the PDM file updated to reflect the current requirements, the BOM file is attached to the drawings and locked with a secret code in the PDM system as a specific product design file. This becomes the standard design document that the downstream processes feed on. One major decision the designers make on the BOMs is to determine which parts need to be internally made or purchased. This decision is based on experience and tacit knowledge of the company's capabilities and also the expected due dates. Activity diagrams describing the set of EAs required to realize 'generate BOMs' (BP5.2) is shown in figure 148.

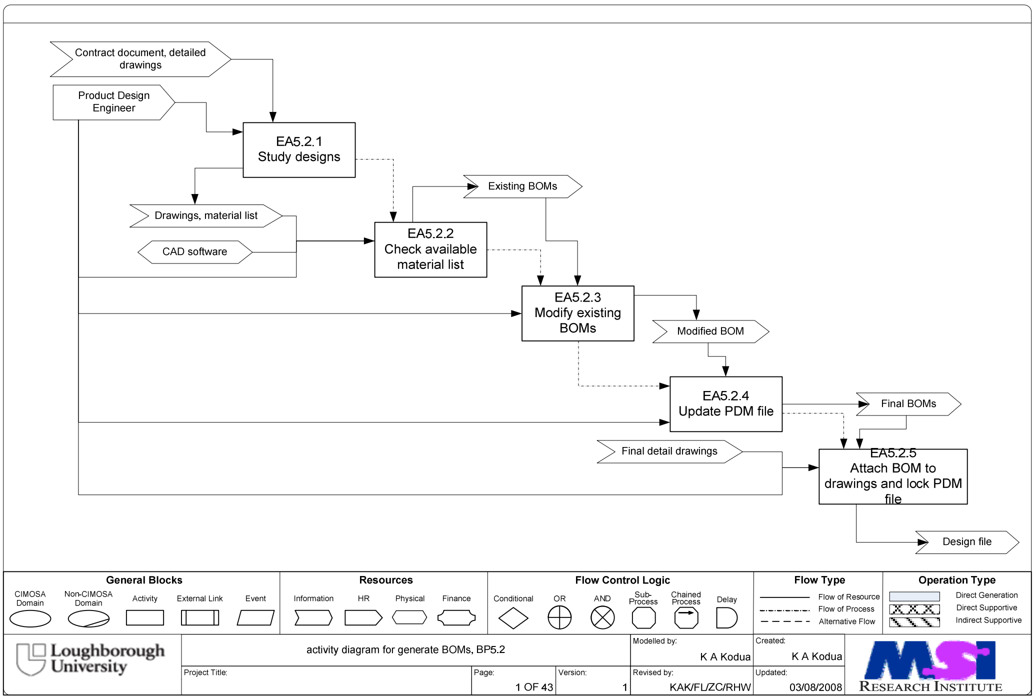


Figure 148: Activity diagram for ‘generate BOMs’ (BP5.2)

At the next level of modelling, efforts were concentrated on decomposing the ‘produce A/Cs’ domain process (DP6). The main objective at this point is to show all relevant BPs involved in this domain. This is necessary because in most cases of the application of multiproduct flow cost and value stream models, emphasis is made on ‘direct value adding’ processes which is normally concentrated in the production processes. Although all the diagrams representing the Enterprise model for AirCon China are shown in Appendix C4, it was deemed necessary to show here the structure, sub interaction and aspects of some of the activity diagrams belonging broadly to DP6. As shown in figure 149, DP6 is decomposed into eight BPs with each of them further decomposed into their respective sub BPs. Each of these BPs is responsible for the realization of a specific goal within the broad DP 6 objective.

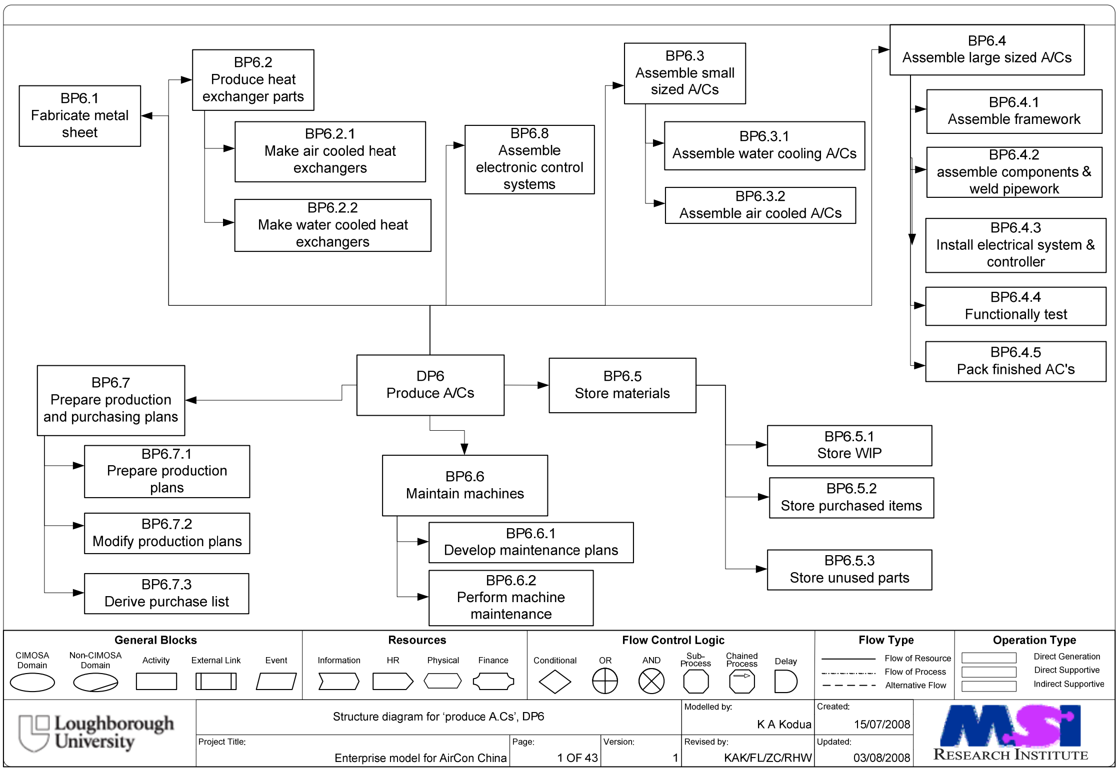


Figure 149: Structure diagram for 'produce A/Cs' , DP6

To provide understanding about how these BPs interact, a sub interaction diagram was developed and is shown in figure 150.

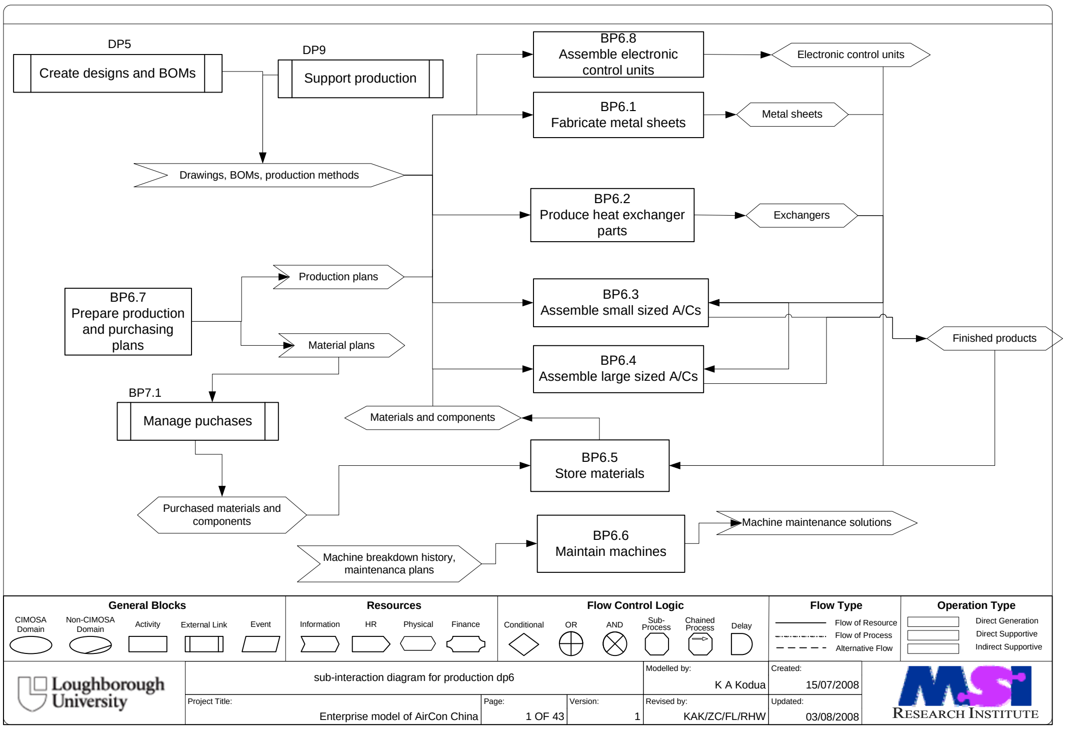


Figure 150: Sub Interaction diagram for DP6

From figure 150, when design documents are received by the production department, they are used to initially develop production plans and material purchase lists. These plans to some extent determine what needs to be done in the production shops. After the realization of the processes in the productions shops, mainly metals sheets and heat exchangers are transferred to the assembly shops and together with materials and components obtained from the purchase stores, assembly of large size and small sized A/Cs are realized. Activity diagrams for all these BPs are included in the enterprise model for AirCon China shown in Appendix C4. For clarification purposes and also to enhance understanding about the direct value adding activities involved in the production of A/Cs in AirCon China, activity diagrams showing how metal sheets are fabricated (BP6.1), and how heat exchangers are produced (BP6.2) are shown in figures 151-152.

Figure 151 shows that during the fabrication of metal sheets, coils are opened by manually operated machines to produce flat sheets that are cut to shapes of sheet required to produce panels and structural elements. This shaping is also done using manually operated machines. Holes are drilled into most of these sheets using 3 CNC machines and a number of manually operated machine tools. The number of holes that need to be drilled can vary very significantly dependent on the products being made and their differing panel and assembly requirements. Metal plates are also curled (mainly at right angles) to produce structural elements. These curled elements are welded together to produce various metal sub-assemblies. A shortage of people with appropriate welding skills is the main constraint in the realization of this process. Panels and structural elements are then sanded and washed in acid before spraying. Some panels are subject to frothing; where they are required for air conditioners that will operate in hazardous environments. Panels and structural elements are sprayed manually whilst moving on an overhead conveyor. Only one colour is used and the conveyor routes the spray panels and structural elements through an oven where they are dried. Afterwards, these processed panels are stored ready for transit to the other production shops. The information system in the metal sheet shop comprises mainly paper-based documents that are completed by production personnel.

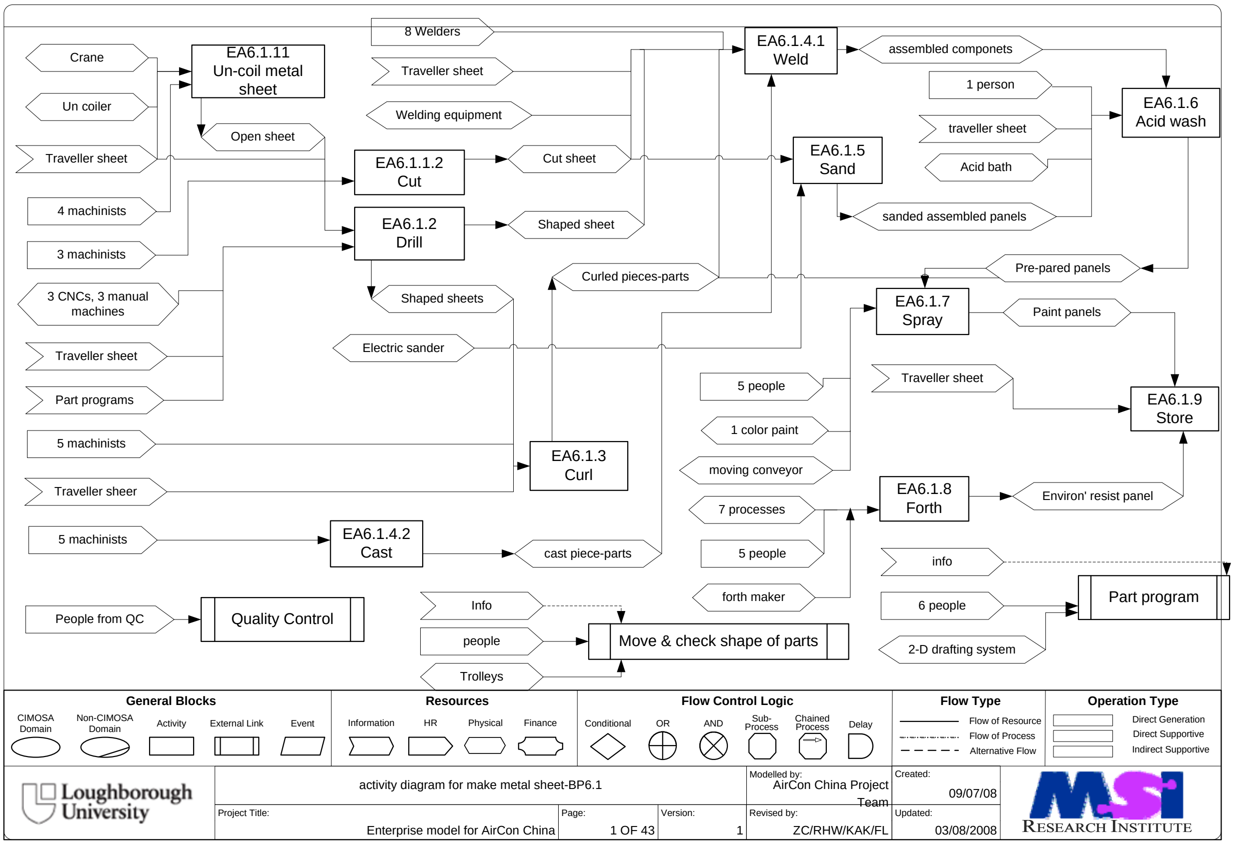


Figure 151: Activity diagram for 'fabricate metal sheets' (BP6.1)

One of the machine shops, dedicated to the making of heat exchanger, is mainly resourced with various manual machine tools including lathe machines, drilling machines, milling machines, borers, welding machines, etc. This machine shop is divided into two main sections. One of the sections concentrates on the making of air cooled heat exchanger parts whilst the other section is mainly focused on the fabrication of water cooled heat exchangers. In the production of air cooled heat exchangers, the major constraint is the timely arrival of metal sheets from the second machine shop which deals with the fabrication of metal sheets. It was also observed that the arrival of purchased parts was not a major constraint on this shop, since parts were purchased in large quantities.

Figures 152 shows that to produce an air-cooled heat exchanger the machinist loads sheets of metal at the entry point of the slitter. The machine then produces perforated and serrated strips of sheets which are later assembled together with curled pipes which basically pass through the perforations in the metal strips. At this point personnel from quality control are invited for product inspection and tagging of the sub assembly created. The quality control at this point is based on random selection and inspection of the sub assemblies. When the batch is passed by the QC officers, the assembly of the sheets and curled pipes are sent on a pallet truck to a heavy duty press which press fits the pipes on the layers of the sheets of metal. It does this by expanding the internal diameter of the pipes. This activity enables the pipes to expand to occupy the entire diameter of the perforations in the layers of the metal strips. After the completion of this process the products are transferred to a belt dryer which dries up lubricants and blows out debris or dirt in the product.

A separate curler exists for creating pieces of u-shaped ends to be welded to the open ends of the sub assembly described above. The next step after this is to conduct pressure test for leakages and sustainability. This is done by introducing nitrogen gas into the heat exchanger unit and then dipping the heat exchanger into a water bath. This is done by the production department without the involvement of quality control department. When successful, the product is transferred to the waiting area on the shop floor. However if the product fails the test, the joints observed to be leaking are welded again and re-tested. The test continues until the operators are satisfied that there are no leakages. When satisfied with the outcome of the pressure test, a secondary test for stress is conducted on the shop floor by again introducing nitrogen gas and allowing it to stay in the pipes for 4 hours or sometimes overnight. When this is completed the QC team thoroughly inspect the product to ensure conformity with product drawings and specifications. After this is done, a quality sticker is attached to the product to confirm that it has passed all QC test and hence ready for transfer to the assembly shop.

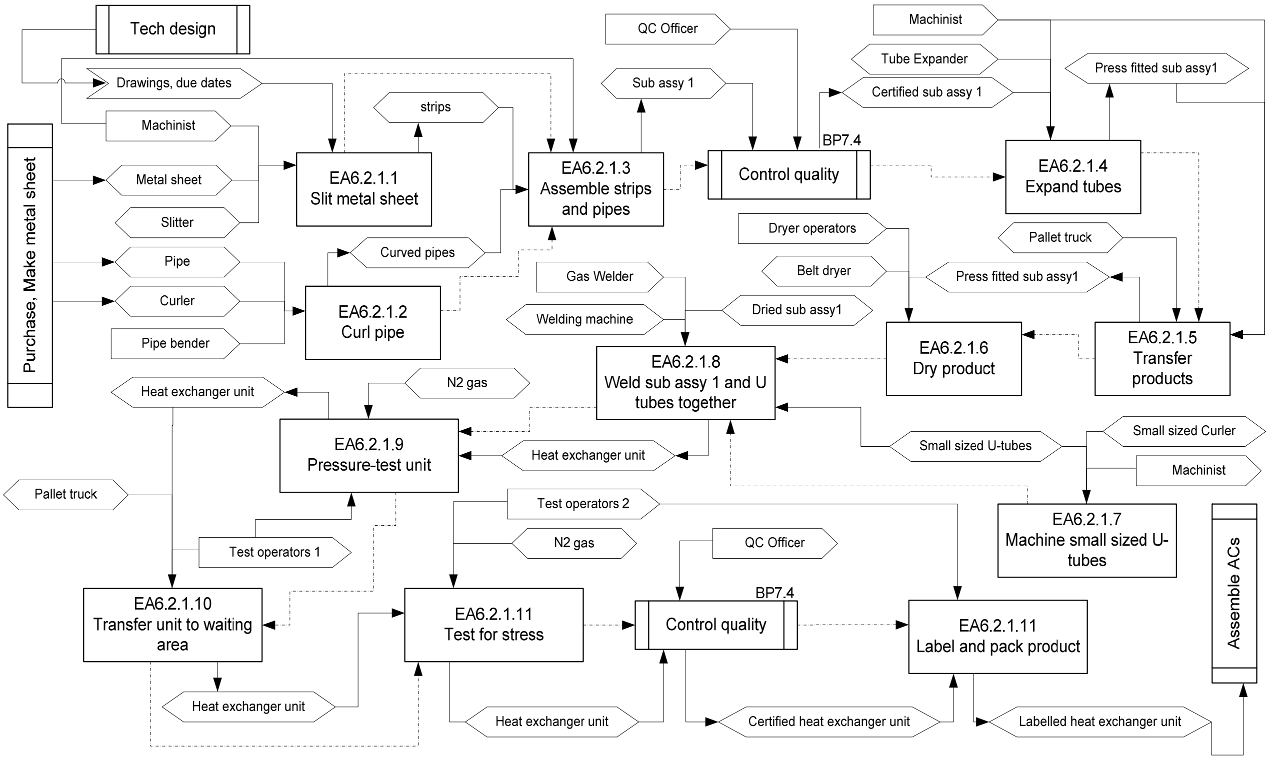


Figure 152: Activity diagram for ‘produce air cooled heat exchangers’, BP6.2.1

A separate set of activities exist for the production of water cooled heat exchangers and is shown among the diagrams in Appendix C4.

The production department has divided its products into small and large sized air conditioners and used this logic to determine where they are assembled. The size and weight is also dependent on the power rating of the A/C. The logic therefore for determining whether to assemble the products in shop 1 or 2 is based on the fact that all products with ratings less than 35kW are assembled in assembly 1 whiles those exceeding are assembled in assembly shop 2. The reason is that assembly shop 1 is located on the first and second floors (second and third floors-UK standard) and the lift is limited in capacity since the machine shops and raw material stores are located on the ground floor. This is therefore to limit excessive load movements around the factory. The assembly rate in assembly shop 1 is about 600 products in a month. These products differ in specifications and hence assembly requirements. Also assembly 1 is noted for assembling small sized ACs of low customization and complexity. These products are assumed to be relatively standardized. A batch size for assembly shop 1 is about 30 to 100 A/Cs. Assembly shop 2 is focussed on large sized and 'complicated' customized ACs. Historically a batch size for this shop contains about 10 to 20 products. A team size is 6 to 7 people and they operate with 2 to 3 groups of these teams. The major constraint in this shop is space because of the large size and geometry of the A/Cs assembled in the shop. Other issues are related to lost parts and the time spent for searching parts since there is little control on parts left on the shop floor.

The level of customization can sometimes be very high and may demand extra resources of the production team to complete. A typical example was related to a particular order containing 77 new products. The production department spent close to 3 months to complete production of these products. One other major problem is associated with the accuracy of the product drawings. Because the drawings are 2D they sometimes do not fit well when separately created components are to be assembled together.

The main economic drive of the company is in products assembled in the assembly shop 2. It was mentioned that products assembled in shop 1 is about two-thirds of the value of products assembled in shop 2. A separate assembly unit responsible for the assembly of electronic control units exists and integrated to the main assembly shops. The CIMOSA models in Appendix C4 describe in detail the various processes and their related activities for assembling various types of A/Cs.

9.4.3 Process-based product classification

Referring to the methodology for modelling multiproduct cost and value streams, after the creation of enterprise models, products are matched with BPs which are involved in their realization. Further sub classification is achieved by considering the work content in each BP. This form of classification helps in later redesigning processes to ensure continuous 'flow'. These means of classification was adopted in the first three case studies. However at AirCon China, because of the limited amount of time and resources, it was decided that, to achieve the same results, a different and easier approach may be required. Most essentially, it was practically difficult to align all their 4000 different products to observed BPs considering the fact that no previous data on process types had be captured. However during the interview with the knowledge holders of AirCon, China, it was realized that the company had already conducted a product classification based on product applications, cooling capacities and refrigerant type. This classification resulted in 8 different product families: unitary air conditioners, thermostatic and humid static air conditioners, dehumidifiers, purifiers, chillers, air handling units, packaged fan coil units, and roof air conditioners.

Although this means of classification was a useful starting point, it did not match well with the authors interest of using a process-based product classification. Therefore another meeting was held with the middle managers from all 'operational sections' of AirCon, China. The prime focus of meeting was to classify products in terms of their process differences in the various domains of responsibility of the middle managers concerned. The middle managers were left to discuss the classifications amongst themselves. The result of the classification is shown in figure 153.

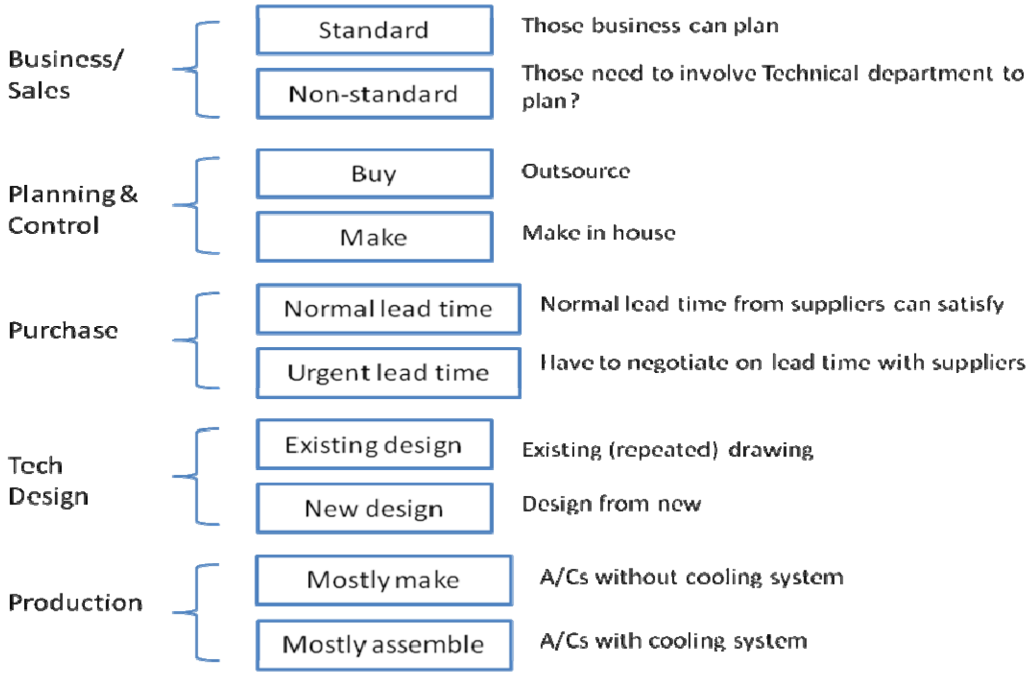


Figure 153: Proposed product classification from different departments in AirCon China

Figure 153 shows that within the sales department, products are classified as standard or non-standard depending on whether the sales team can predict contract due dates. This means of classification is different from how planners see product families in the company. From planning and control perspective, A/Cs can be categorized into 'make in house' and 'outsource'. Another form of classification proposed by the other managers based on their applications is shown in figure 154.

After the exercise, it was considered necessary to adopt the classification proposed by the production team. This gained some measure of universal agreement by all the departments since it was possible to route A/Cs along processes 'mostly make' and 'mostly assemble'. Figure 154 shows how different materials are routed through the production shops for 'mostly make' and 'mostly assemble' A/Cs

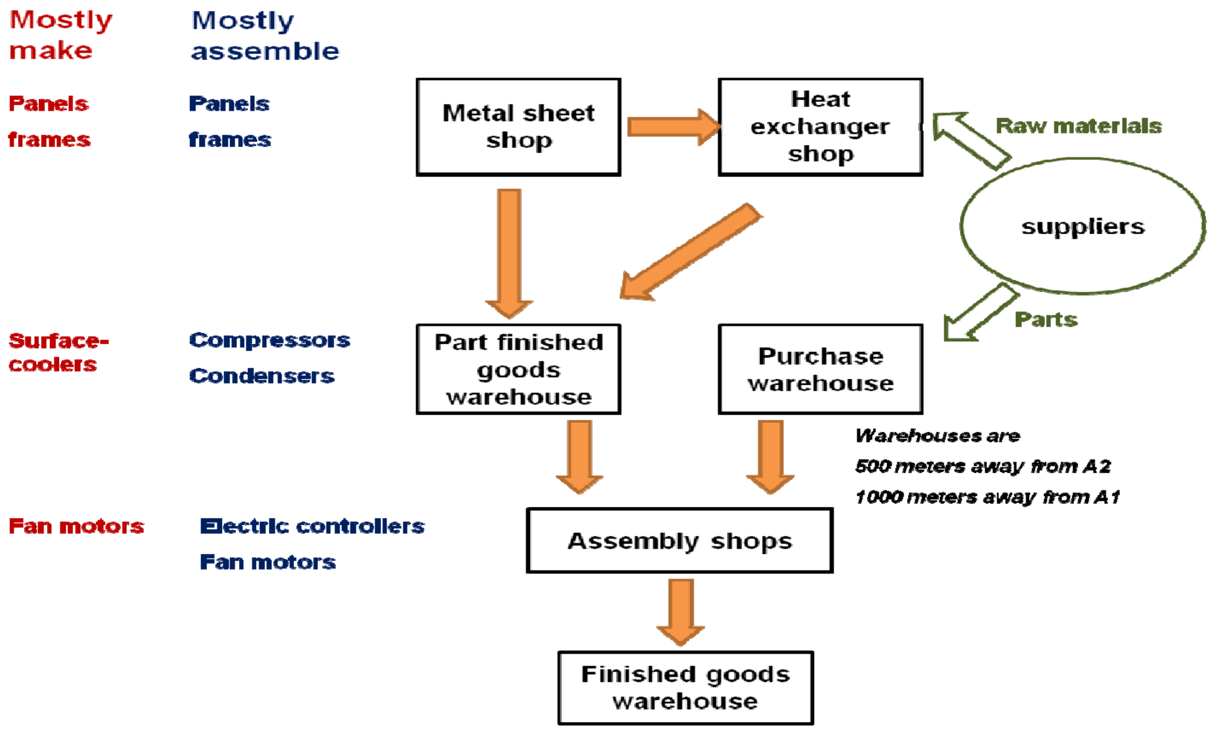


Figure 154 Top level production material flows of mostly make and mostly assemble A/Cs

Later in the research, this classification assisted in generating static and dynamic simulation models for the different product families in AirCon China.

Studying the process requirements of 'mostly make' and 'mostly assemble A/Cs' product families, it was observed that 'mostly assemble A/Cs' could further be classified into 'most assemble air cooled A/Cs' and 'mostly assemble water cooled A/Cs', because of the significant difference in the heat exchangers requirement which define their process routes. Similarly ‘mostly make A/Cs’ were divided into ‘mostly make small sized A/Cs’ and ‘mostly make large sized A/Cs’ based on their ‘work content’ difference. Also based on work content difference a set of ‘mostly assemble A/Cs’ assembled in the second assembly shop because of their size and assembly time was termed ‘mostly assemble large sized A/Cs’.

9.4.5 Static cost and value stream model of AirCon China

Based on the understanding derived from the process based product classification, it was possible to create static cost and value stream models for the different product families. Figure 155 shows the top level static cost and value stream model for the 5 product families described in section 9.4.4.

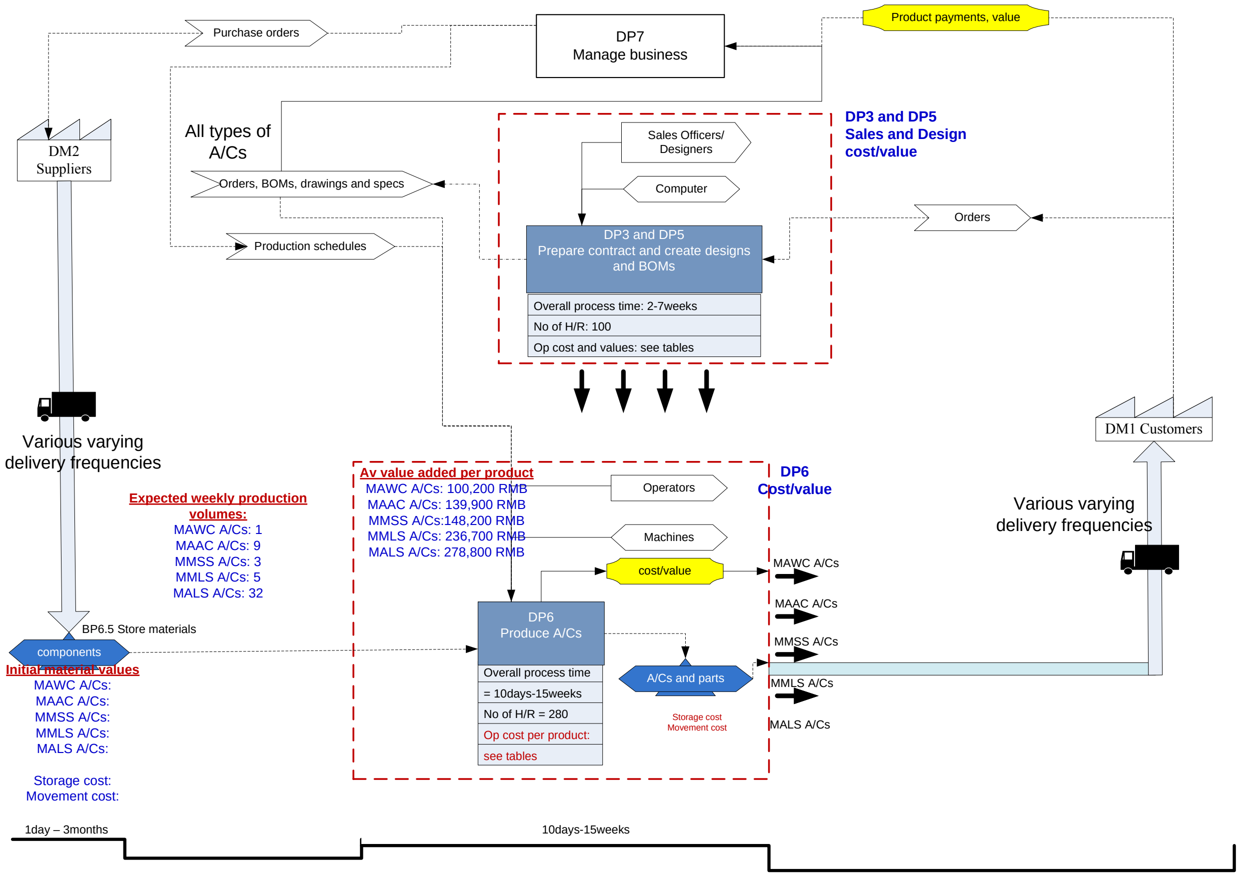


Figure 155: Top level cost and value stream model of AirCon China

9.5 Initial findings

The integrated multiproduct cost and value stream modelling methodology deployed enabled new understandings to be developed about operations of AirCon China. Particularly insight was gained into the causes of the problems the Managers mentioned during the start of the research. Since the traditional approach to solving problems in the company has been to observe and blame respective departments which were not meeting their deadlines, the interviews of different departmental staff and creation of enterprise model of the company showed the problems as largely being one of poor integration. Throughout the interviews and shop floor visits, key challenges and bottlenecks were documented and used as basis to derive a focus for improvement in the company. Whilst creating models, observing activities in the production shops and conducting interviews, the following were observed to be the major challenges in the company.

9.5.1 Estimation of delivery due dates

Due dates are often established by the sales team. This is often based on the customer requirements and also the experience of the sales team taking into consideration the due dates of similar contracts. There is no established data for analysing cycle times of any of the shops or order requirements. Sometimes, the Sales team have to give promises of earlier delivery in order to win the contract. In reality these are done without knowledge of current workload on the design and production shops. In approximation for the year 2007 about 40% of contracts did not meet their deadlines and the company had to pay penalties 5 times in the year. In extreme cases where contract documents flow across the departments for estimation of due dates, there remain some inaccuracies as good time estimates are not possible, due to the fact that there are no standard times data for any of the shops and because under high workload conditions there can be bottleneck ‘process-resource system’ elements. Estimations are purely based on experience and convenience. Key to these issues also is the underestimation or inaccurate estimation of arrival times of purchased items. In most of the due date estimates these arrival times were predicted inaccurately, partly because there are external influences which impart on the timely arrival of these parts. Most importantly, records do not indicate current operation or work loading conditions of the shops and since orders arrived randomly, it is extremely difficult to predict accurately due dates without the support of scientific tools which take into consideration current work loads, capacity and competencies of staff.

Since this front end decisions grossly impact on the entire business, it is important that measures are taken to make this decision fairly accurate. The challenge is that the wrong estimation of delivery due dates have causal impacts on several elements of the business. Examples of these factors observed was the cash flow of the company, production planning, purchasing requirements and high WIPs, high machine breakdowns and space availability.

9.5.2 Departmental Budgets

From the enterprise model shown in Appendix C4, the finance department prepares an annual budget which covers salaries, material purchases, capital expenditure, bills and other sundry expenses. In addition some departments such as Purchasing prepares monthly estimates of expenditure. The Finance department mainly uses a monthly estimate of revenue from sales forecast of payments. Apart from the sales and purchasing departments none of other departments give input to the monthly budget preparation. However the departments are free to make requests for things they need. The lack of adequate financial plans generate problems since the business is contract based. The fluctuating customer demands affect the company's ability to sustain cost or budget. The way the company operates allows the slightest delay in customer payments to affect their financial stability. This is because cash outflow are mainly based on the payment of previous contracts and this can be attributed to many factors including the lack of budgets for contracts

9.5.3 Unmet due dates

Whilst creating the sub-sub interaction diagrams, it was observed that besides the wrong estimation of due dates, there were many other internal factors which were observed to contributed to the unlikely meeting of due dates, even if due dates were estimated accurately. These issues are broadly classified under poor planning and material delays; frequent change in customer information and due dates; wrong product designs and lost customer information.

There are key design issues which affect the production department's ability to meet deadlines. Most often designed parts which do not match during assembly may require re-machining which ends up increasing cost and delays in the assembly process. This mismatch of parts causes severe problems in the assembly process since in some instances it takes a long time to rectify and may demand a redesign of the product.

There are also instances where customers request for change in specifications even when production has commenced. As it is common with mechanical products a change in the specification of a part affect the entire design and manufacturing of the product. This affect assembly requirements and hence production lead times. Sometimes information provided by the sales team on behalf of the customer is also not exact or accurate. Since this dictates the design of the products, there is the likelihood of producing parts to meet wrong specifications. When these are detected at a latter stage of the production process, they grossly affect the lead time of production.

9.5.4 Purchased part delays

One of the major problems attributed to the long delays in production is the unavailability of purchased items for both machining and assembly purposes. From interviewing the Managers, many held the view that it was the major bottleneck for the business. However a careful study of the company's business policies revealed that delays were caused by other factors also. This includes poor planning, insufficient funds, lack of integrated suppliers and late production request for purchases. Lack of adequate funds contributed to about 22% of the delays in purchases. Other causes include the long lead time of suppliers and limited number of suppliers for some components

Normally the purchase procedure requires that a purchase list is received from the material controller of the production department. Initial contacts are made to obtain proforma invoices and quotes before a decision is made to buy from a certain supplier. The earlier the purchase list is received the earlier the underground purchasing activities can be performed. When this is waited till it is late, delays in material arrivals cannot be avoided. One important factor to be noted is that different suppliers have different supply lead times hence different components arrive at different times. It was observed that production planning did not factor this into their plans and there was not adequate communication between the planning team and the purchasing department to identify and note appropriate supply lead times.

From observing interaction diagrams and activity diagrams of BPs7.1 and 7.2 (see Appendix C4), accounting policy for purchasing restricts the purchasing department to a large extent. The finance department releases a certain amount of money to the purchasing department weekly and they are expected to operate within this budget. The budget however does not take into account the current demands placed on purchasing by the production requirements. As a matter of fact the finance department are also limited in the amount of money they can provide to the purchasing department for their transactions as a result of their unhealthy cash balances. When suppliers are delayed in their payments, material arrival is affected and this affects the production lead time irrespective of the accuracy of the production plans. Some suppliers who have experienced similar delays in payment insist on upfront payments which sometimes exceed the budget allocation of the purchasing department.

In some cases, however, because of wrong customer specifications, wrong parts get purchased and the right ones are not obtained in time for the machining and assembly of operations, although this is a minor aspect of the main causes of purchase delays.

9.5.5 Production planning

Two main stages are involved in planning for production in AirCon China. There is the first staged planning which is based on the due dates specified on the signed contract. This plan assumes an infinite capacity of the shops and avoids consideration of potential complications in purchases. The main document used at this stage is the contract document. This plan is generated for 3 to 4 contracts at a time. These plans are not adequate since they over look the loading of the shops and the availability of resources for the contract. A modified production plan which recognizes the current stage shop conditions is generated and used to guide production. The modification is based on changes in customer requirements and work load on the shops. This is achieved by holding meetings with the managers of the shops every 10-15 days to modify the plans based on new customer requirements, purchasing lead times and other pending works to be done. The information on the shops is given by the shop supervisors and it is an approximation. Even if the modified production plan proves to be accurate by the time it is created the contract has deviated several time from the originally specified production due dates. Because these modified production plans are generated at relative shorter intervals it becomes practically difficult to organize the shops around it should the need be. Historically about 80% modified plans are followed by the shops. This is because the shop floor data is a guess and there is no data on operation times. In addition to the plans the Material Controller based on the BOMs, sales contract and current stock levels develops purchase lists for the purchasing department. The current production planning technique is described by figure 156. It shows that there are sub plans which are generated in each of the departments but they are done 'over the wall'.

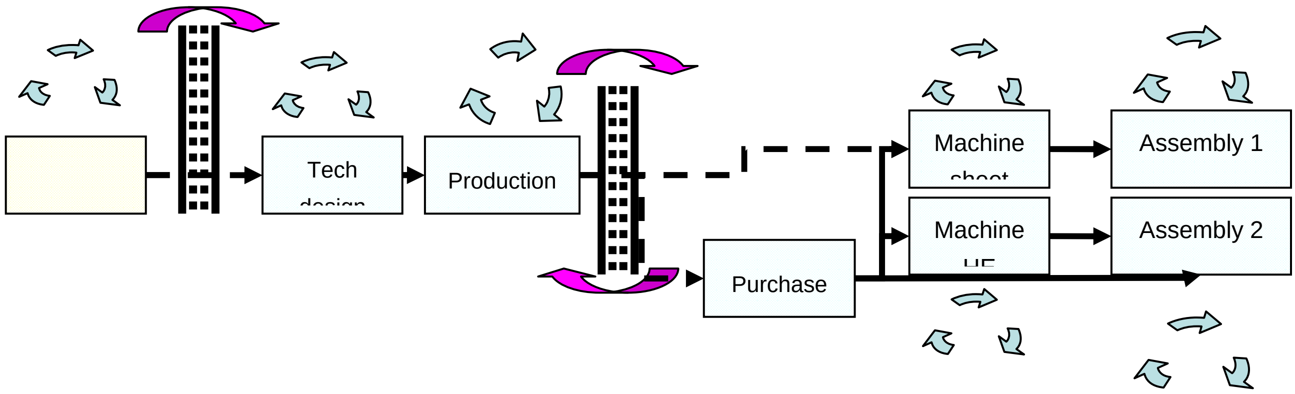


Figure 156: Current AirCon China planning method-observation reported to company by the MSI team

Some problems observed to be as a result of this approach were:

- Poor plans with bad cost and lead time behaviours
- Planning outside competency and responsibility range
- Unsatisfied customers
- Strained supplier relations
- Limits on growth and inappropriate inventory

In view of these challenges the Managers of the company have recommended the introduction of an ERP system. The fundamental impression at this point is that when the processes and plans are not understood and modelled accurately, the introduction of an ERP system will introduce further complications and inflexibilities.

9.5.6 High inventory level and waste

Because of the inappropriate planning approaches, wrong customer specifications, the lack of pull assembly systems, AirCon China continues to record high levels of WIP and raw material inventory levels unless developmental actions are taken. The current approach the company is using to solve this is to institute penalties for staff that out of the negligence of duty cause the purchasing of parts which are not required. Although these may be a temporal solution, it was important to identify the root causes of the specification of wrong parts for purchases. This may include the development and verification of customer specifications, improving design tools, among others. There are lots of WIPs because the arrival of parts is not synchronized with the shop floor manufacturing lead times. There is the need to investigate the possible introduction of lean and agile techniques such as supermarkets, postponement, producing according takt times, into the production process.

9.5.7 Inaccurate price estimation

The activity diagram for ‘ make payments’ (BP7.2.2) show that basically because price data are not current and not much consultation is made with relevant personnel for more accurate price estimates, taking into consideration the short time sale teams have to specify prices to customers, there is always the tendency of not making much profit and running at a loss. It is presumed that with standard and accurate material cost and overhead cost data, a more formal and accurate price estimation may be possible.

9.5.8 Cash flow issues

One of the outstanding problems with AirCon China is related to cash flow. In practice customers are required to pay 20-30% of the total price estimate before the commencement of the project. Apart from the fact that the price estimates may not be correct, there is the possibility of the paid amount not being sufficient to cover the cost of raw materials and energy required to fulfil the contract. Technically, it means AirCon will have to borrow money to meet these expenses which should have been borne by the customer. In the extended case of customers not paying the balances in time, AirCon China continues to pay the interest on the monies borrowed. This imbalance leads the company into serious financial difficulties which affect the monies available for payment of suppliers. This in effect affects the purchase of parts for production.

Also because different payment terms are used at the customer and supply ends, the slightest change in customer payment terms affect the ability of the company to pay their suppliers. Figures shown by the Finance manager described how difficult the company had managed to remain active till date. It has purely depended on bank loans of high interest rates and operated with negative end balances. The worse of it is when customers refuse to pay the total price of the products. As explained, the full payment spans over a year but the repayment of the company's commitments have shorter time intervals.

9.6 Dynamic analysis of AirCon China business

Section 9.5 describes some observed challenges in AirCon China. These challenges were discussed with the Middle Mangers of the company and it received great acceptance. Most interestingly, they observed the integrated nature of their challenges and therefore was prepared to team up to provide solutions. Therefore at the next stage of the modelling technique system dynamic modelling techniques in the form of dynamic causal loop models (CLMs) and iThink continuous simulations were used to further enhance understanding about problems at AirCon China and to provide intial strategic solutions to ensure cost effective processes and high value chains. The approach adopted avoided the tendency of considering the challenges in isolation as many traditional methods seem to achieve. Experience gained from previous case studies has proven that in most industrial-based problems, it important to understand the causal relations between processes.

Chapters 6 and 8 have shown how system dynamic models are created and used to provide strategic solutions for manufacturing enterprises. A simplified top level 'problem descriptive' causal loop model created to explain to the relevant managers in the company, the cause and effect of actions in the company is shown in figure 157.

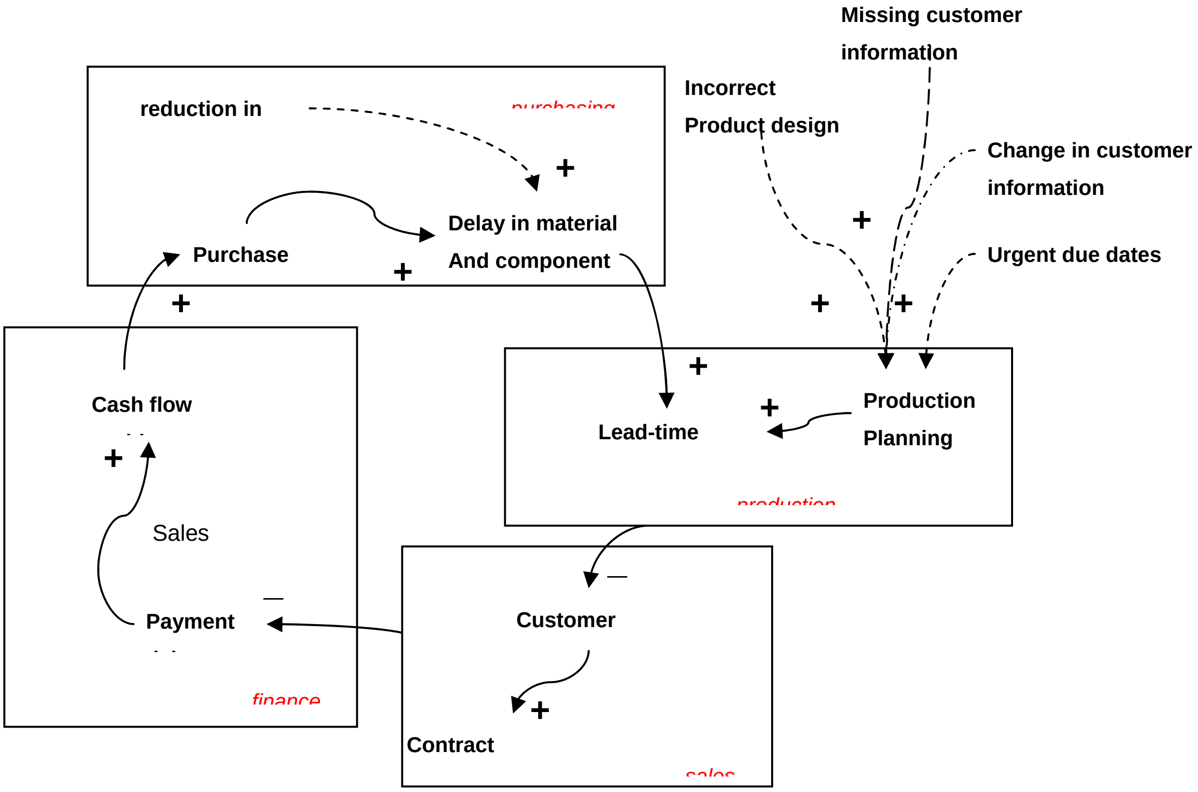


Figure 157: Dynamics of problems in AirCon China

The CLM illustratively explains that mainly production problems were created by factors such as inaccurate specification of due dates, changes in customer information, inaccurate product designs, etc. These production planning deficiencies impacted on the lead times of production . Other factors such as work load, production capacity, resource competence and resource availability also influence the lead time of production. When production exceeds its expected lead time it means that delivery cannot be made in time and hence customers have a high tendency to be dissatisfied. There is an associated problem of retrogressive contract winning possibilities and hence cash flow problems. But in actual fact a delay in delivery of finished products impact on payment. When payments are delayed cash flow is affected and purchased items cannot be paid therefore leading to delays in the supply of materials to production for timely manufacture of parts and assembly.

Although this model has a number of simplified assumptions embedded in it, it was sufficient to illustrate to the business owners how activities were interconnected and hence prove that their problems were not caused by one department. To further illustrate graphically and quantitatively how these variables affected each other and the parameters to manipulate to achieve recommended enterprise behaviours, a system dynamics iThink simulation model was created and presented to the managers and the staff interviewed. The objective was to clearly depict how production lead times and cash flow were influenced by other factors in the company. Figures 158,159 and 160 show the iThink model and graphs describing how factors influence each other. Chapter 6 dedicatedly show how stock and flows are deduced and hence CLMs enhanced to achieve iThink simulation models. Further application of this translation mechanism was shown in Chapter 8.

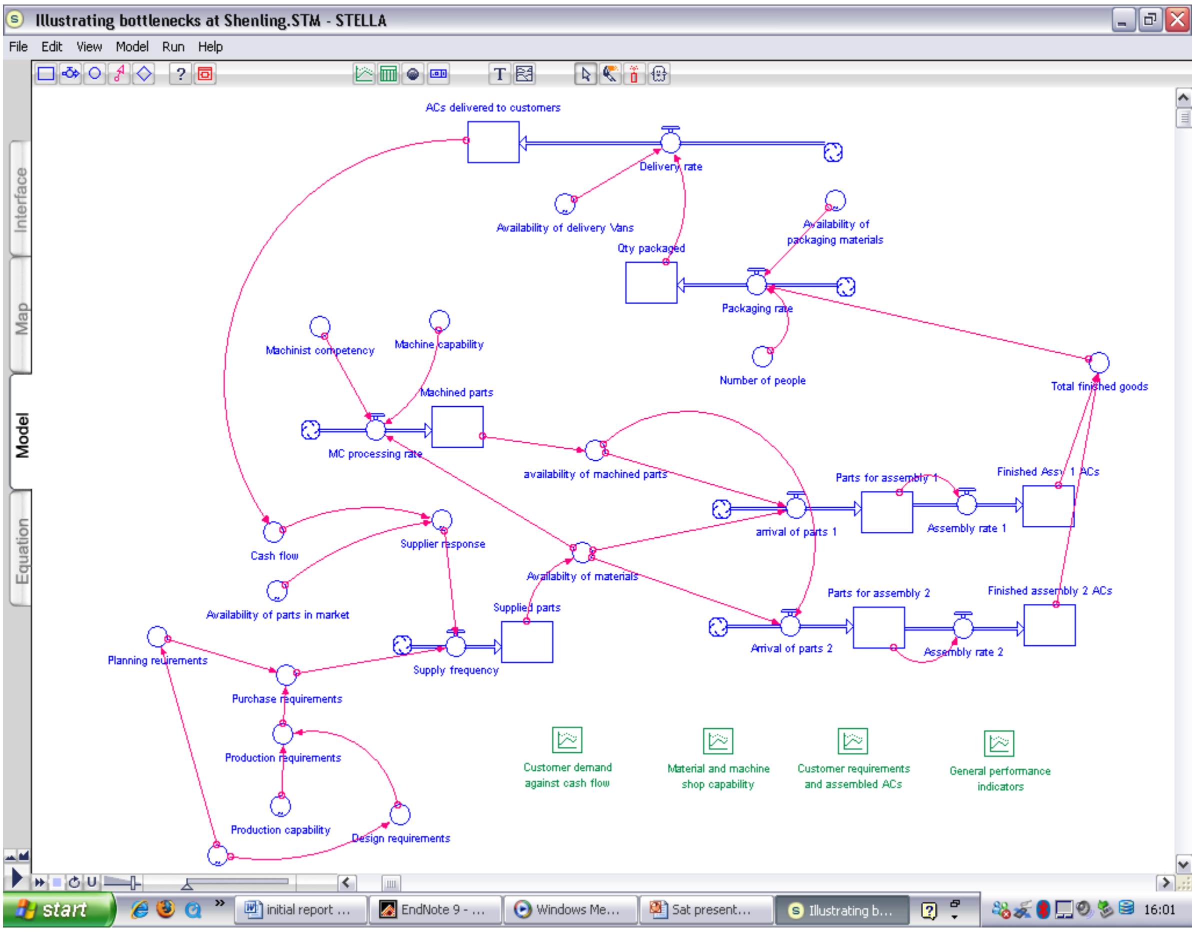


Figure 158: Dynamic iThink continuous simulation model

Figure 159 shows that for a fluctuating customer demand of varying contract requirements, the total number of finished A/Cs rises in the course of time. This is based on the assumption that the ordering pattern falls significantly at some point in time hence the company is able to catch up with the production demand. As illustrated if the customer orders do not fall and continues to rise then there is the tendency of having a reverse curve showing that the total quantity of finished A/Cs will decrease dramatically.

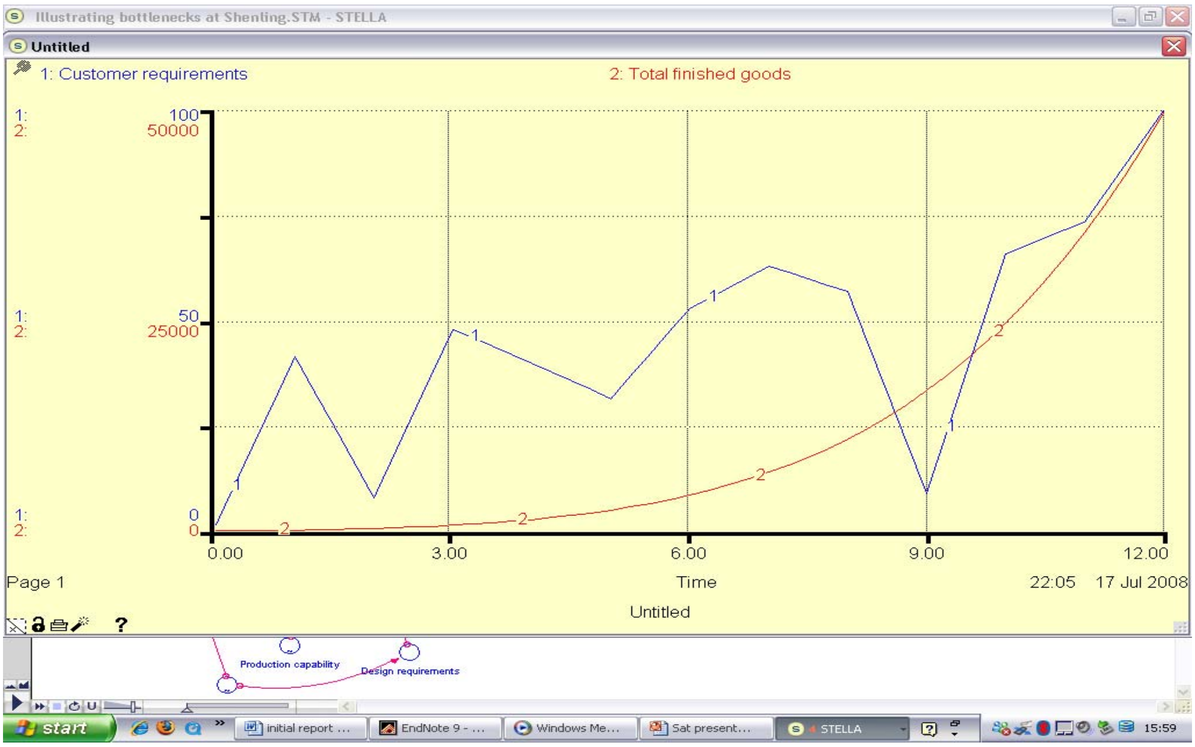


Figure 159: Effects of customer requirements on finished A/Cs

A number of factors influencing cash flow is shown in figure 160. This includes material availability and customer requirements and number of finished A/Cs. It shows that material availability and the total finished goods delivered to the customers positively impact on the cash flow in the company. Hence for the financial state of the company to improve, measures have to be taken to improve purchasing lead times and also organize the internal production systems to be responsive to changes in customer and purchasing requirements.

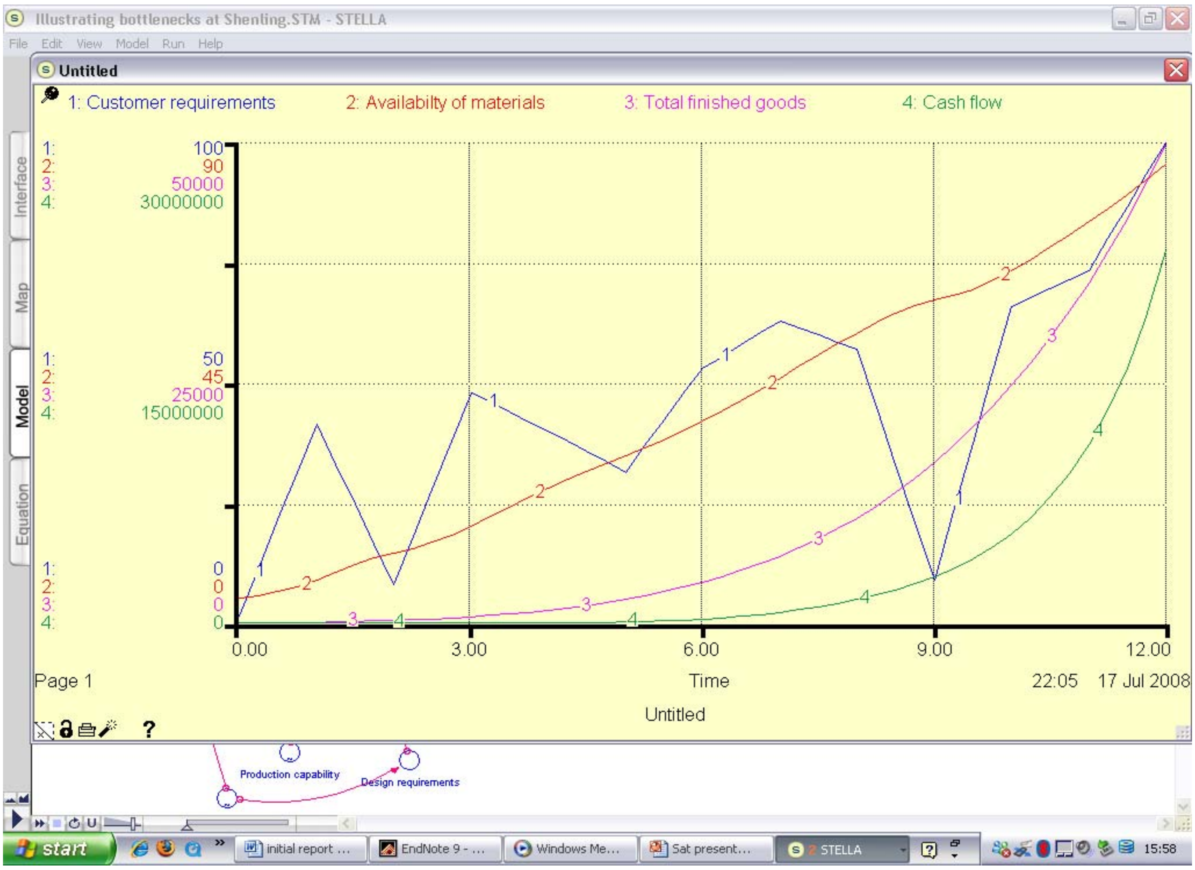


Figure 160: Effect of other factors on cash flow

9.7 Application of modelling technique to solve cash flow problems

To fulfil the cooperate objective of AirCon China and PhD study requirements of the author, it was decided to instrument the modelling technique to solve key cash flow problems in the company. This was because from the causal loop model, it was evident that because of the peculiarity of the business dynamics in AirCon China, the management of cash flow was not easy. This was confirmed in the earlier description of problems outlined by the Managers of AirCon China.

To achieve a better understanding of the cash flow situation in AirCon China and hence provide strategic solutions to improve the competitiveness of the company, the iThink model was extended to capture the various flow elements (sources of inflows and outflows) and how they influence net cash balances of AirCon China.

The cash flow model described in figure 161 shows that sales revenue is a combination of the revenue obtained from the sale of air conditioners in China and abroad. However sales figures show that no sales were made abroad. The total revenue as shown in the model therefore becomes the sum of all the income sources including revenue received from their sister company, Eco-packing. In this case, income obtained from Eco-packaging is maintained as zero since the objective is to analyse absolutely cash flows at AirCon China. The other part of the model shows the expenditure sources at AirCon China. As can be seen from the model, capital expenditure is a combination of a number of fixed asset purchases including vehicles, land and housing, local and overseas machine acquisitions and other minor office equipments. Other cost components like salaries and material purchase cost have also been shown. The daily cost component was made to comprise a range of cost elements denoted by running cost, production overhead cost, finance and management overhead cost, security, bank payback loans, tax and other daily expenditures. Again the cost component related to eco-packaging was maintained at zero.

This model was linked to a spread sheet which maintained data on the monthly cash components for each of the variables identified. This was necessary to give a true reflection of the cash balances on monthly basis.

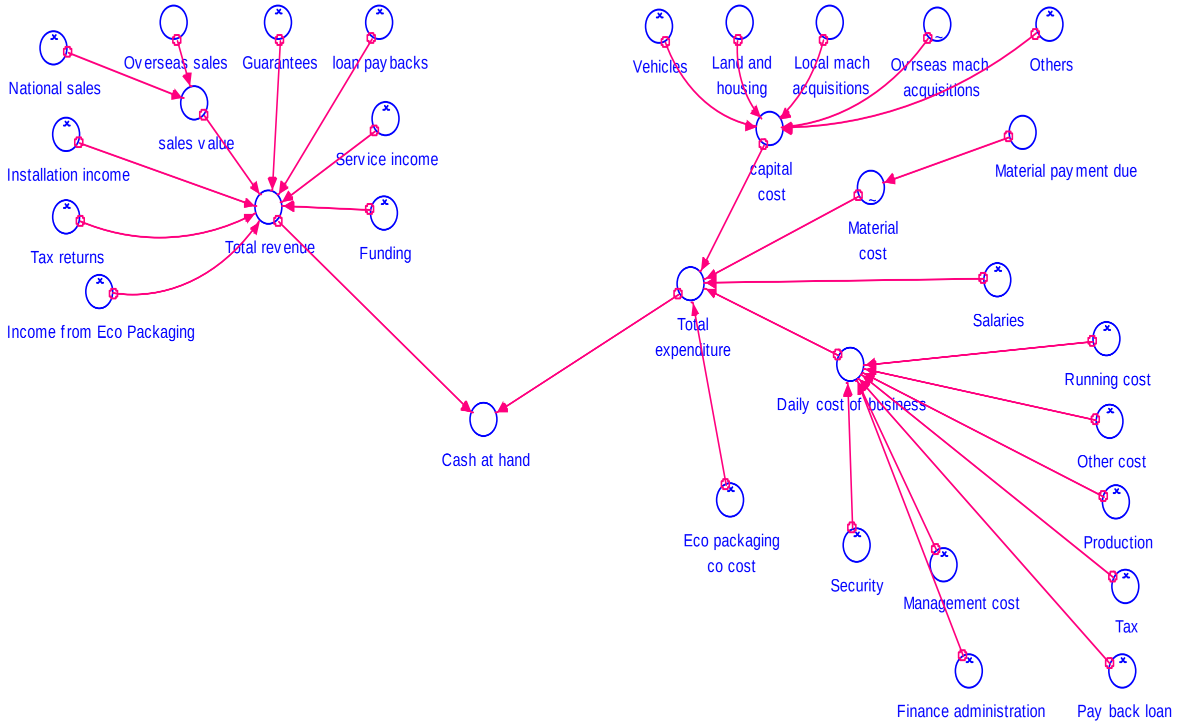


Figure 161: System dynamics model of cash flows at AirCon China

The Accounts department was consulted to confirm if all the cash inflows and outflows have been captured and that data used best represent the real company. It was confirmed that cash inflow was predominantly derived through:

- Sales revenue: both local and overseas sales
- Revenue generated from services
- Revenue generated from installation of equipment
- Tax returns

- Other funding
- Loan paybacks and
- Income derived from guarantees

On the other hand, cash outflows are due to:

- Fixed asset acquisitions
- Material purchases
- Salaries/wages
- Overheads
- Bank loan repayments
- Taxes
- Security
- Sundry expenses.

9.7.1 Model results and analysis

Results derived from the model were exported to MS Excel for easy presentation to the Managers of AirCon Ltd. One of the main results analysed was the percentage contribution of each of the sources of inflow. The graph shown in figure 162 was obtained from running the model.

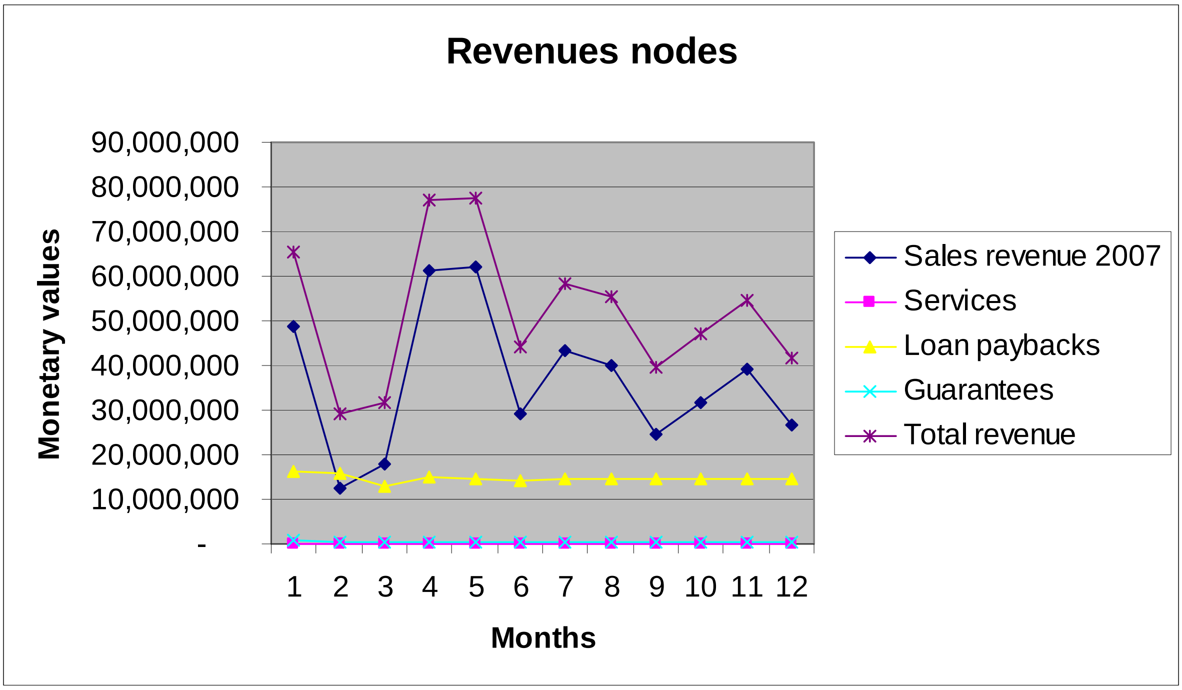


Figure 162 AirCon China's revenue sources

The results show that the major revenue source for AirCon China is the income received through the sale of A/Cs followed by loan paybacks. Thus there was the need to further investigate how revenue derived from the sale of A/Cs was generated.

9.7.1.1 Analysis of Sales record

Results analysed in Table 58 show that in 2005 the company exceeded its sales target by 5% but in 2006 and 2007 there was a shortfall of 21% and 9% respectively. It is important to clarify also here that the sales value presented do not represent the total sales made for the respective months. Instead they represent customer payments received in those months. Later portions of this Chapter has shown how percentages are allocated to the customer payments.

Month	**Sale(RMB) 2005**	**Sales (RMB) 2006**	**Sales (RMB) 2007**	**Sales (RMB) 2008**
1	13,293,947.01	18,131,553.79	48,575,511.94	27,422,948.81
2	19,485,478.88	16,037,728.30	12,613,619.98	14,205,964.52
3	15,360,461.56	21,522,457.66	18,058,160.49	32,353,589.56
4	23,711,771.69	18,260,494.37	61,355,952.15	63,143,584.84
5	27,517,586.65	26,669,164.75	62,253,886.81	32,618,441.26
6	37,923,695.94	40,685,897.01	29,241,737.62	53,677,831.19
7	39,992,025.11	33,176,704.97	43,229,557.04	33,137,579.55
8	31,509,659.23	50,329,683.00	40,062,632.25	51,093,028.66
9	31,628,620.35	50,444,595.66	24,578,560.07	
10	36,632,239.18	18,247,163.61	31,676,044.60	
11	37,318,476.58	18,663,741.10	39,355,679.12	
12	22,476,988.43	29,034,505.41	26,616,101.15	
Total	336,850,950.61	341,203,689.63	437,617,443.22	307,652,968.39
Sales target	319,896,439.33	429,998,348.62	480,001,583.00	
Balance	16,954,511.28	- 88,794,658.99	-42,384,139.78	
% exceed	**5%**	**-21%**	**-9%**	

Table 58: Sales value for Jan 2005 to August 2008

To benefit fully from this sales data, average sales figures were calculated and compared with the sales figures for each of the months. The results obtained from this calculation are shown in Table 59.

Average monthly sales (3 to 4 yrs records)	**Diff in target achievement-2005**	**% achieved**	**Diff in target achievement-2006**	**% achieved**	**Diff in target achievement-2007**	**% achieved**	**Diff in target achievement-2008**	**% achieved**
26,855,990.39	-13,562,043.38	-50%	-8,724,436.60	-32%	21,719,521.55	81%	566,958.42	2%
15,585,697.92	3,899,780.96	25%	452,030.38	3%	-2,972,077.94	-19%	-1,379,733.40	-9%
21,823,667.32	-6,463,205.76	-30%	-301,209.66	-1%	-3,765,506.83	-17%	10,529,922.24	48%
41,617,950.76	-17,906,179.07	-43%	-23,357,456.39	-56%	19,738,001.39	47%	21,525,634.08	52%
37,264,769.87	-9,747,183.22	-26%	-10,595,605.12	-28%	24,989,116.94	67%	-4,646,328.61	-12%
40,382,290.44	-2,458,594.50	-6%	303,606.57	1%	-11,140,552.82	-28%	13,295,540.75	33%
37,383,966.67	2,608,058.44	7%	-4,207,261.70	-11%	5,845,590.37	16%	-4,246,387.12	-11%
43,248,750.79	-11,739,091.56	-27%	7,080,932.22	16%	-3,186,118.54	-7%	7,844,277.88	18%
35,550,592.03	-3,921,971.68	-11%	14,894,003.63	42%	-10,972,031.96	-31%		
28,851,815.80	7,780,423.38	27%	-10,604,652.19	-37%	2,824,228.80	10%		
31,779,298.93	5,539,177.65	17%	-13,115,557.83	-41%	7,576,380.19	24%		
26,042,531.66	-3,565,543.23	-14%	2,991,973.75	11%	573,569.49	2%		
386,387,322.5	-49,536,3	-13%	-45,183,632	-12%	51,230,12	13%		

7	71.96		.94		0.65			

Table 59: Comparison of monthly sales with average sales

From Table 59, it was realized that the total sales value for the years 2005 and 2006 in comparison with the average sales for the four years were low by 13% and 12% respectively. Year 2007 saw a great increase of 13% (ignoring the sales in year 2008 since data only existed for 8 months). The pattern of growth is illustrated in figure 163.

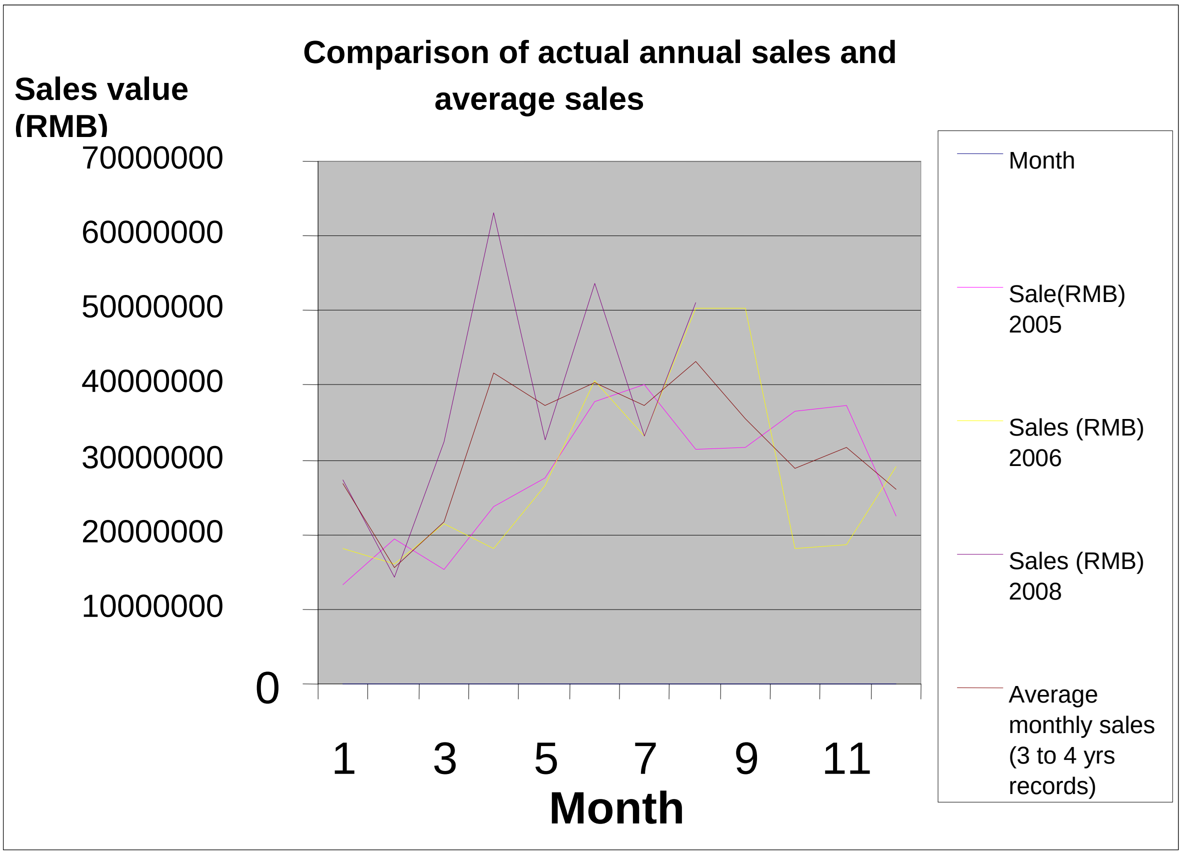


Figure 163: Comparison of actual sales with average sales

From the graph shown in figure 163, sales values for 2007 and 2008 largely exceed the average sales values. A better cash flow picture can be generated when the sales value is compared with the total cost of production for the respective orders received.

The percentage growth in sales when total annual sales values are compared with each other is shown in Table 60.

Years	Sales value	% increase
2005	336,850,950.61	reference sales value

2006	341,203,689.63	1.29%
2007	437,617,443.22	28.26%
2008	307,652,968.39	47.35%

Table 60: Increase in sales from year 2005 (*2008 data up to the 8th month)

9.7.1.2 Analysis of sales pattern

It was necessary to also understand the pattern of generation of sales value. This was deemed relevant because an idea of the pattern could help predict period of increase in revenue and hence support business strategic decisions. The sales pattern for the period January 2005 to August 2008 has been shown in figure 164.

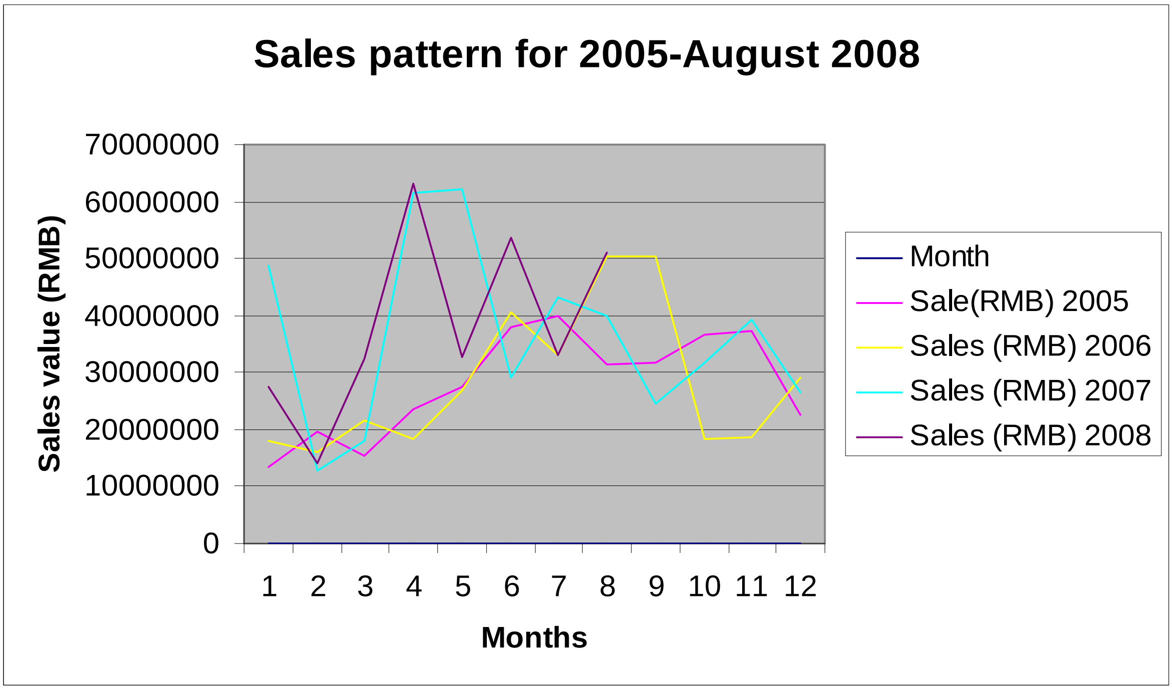


Figure 164: Sales pattern from January 2005 to August 2008

From the graphs shown in figure 164, sales revenue obtained for years 2005 and 2006 showed a gradual increase along the months of the year. But in 2005, there was a sharp fall after the month of November. In 2006, a similar fall was recognized in the months of October and November but a rise was observed in December which is contrary to the case of 2005. Thus in general terms there were significant increases in 2005 and 2006 but these increases do not necessarily follow any regular pattern.

Also sales revenue for years 2007 and 2008 did not follow any observable pattern, but it is clear to indicate that there were very high sale values in some months and extremely low sales figures in other months. From the graphs, in years 2007 and 2008 very high records of sales were realized in the months of April. Whilst 2007 figures showed a continued increase to the month of May, figures for 2008 showed a rather sharp fall in the month of May. For both years, the least sale value record was achieved in February.

It is therefore concluded that the generation of actual sales revenue for the company is random. In other words customer payments do not follow any regular pattern. This means orders arrive randomly and payments for these orders follow a similar random pattern. There was a constant rise and fall in the sales records for all the months of the years analysed.

9.7.1.3 Customer payment terms

As explained in Section 9.7.1, sales revenue is composed of various payments at varying percentages. Table 61 gives this indication.

Pattern of payments received from customers			
Year 2007 (Jan-Dec)			
Contracts	**Payment plans**	**Amount (RMB)**	**Percentage achieved**
Contract A	10% pre payment made before delivery	7,627,735.97	1.74%
	80% payment made before or after delivery and 10% during warranty	97,061,855.70	22.18%
Contract B	20% pre payment made before delivery	14,127,481.90	3.23%
	70% payment made before or after deliver and 10% during warranty	53,996,097.90	12.34%
Contract C	30% pre payment made before delivery	32,345,246.62	7.39%
	60 - 65% payment made before delivery and 5 - 10% made during warranty period	114,364,003.70	26.13%
Exceptions	Contracts with full amount paid before delivery	19,278,357.11	4.41%
	Other payments	98,816,664.00	22.58%

Total sales for 2007		437,617,442.90	100.00%
Year 2008 (Jan-Aug)			
Contracts	**Payment plans**	**Amount (RMB)**	**Percentage achieved**
Contract type A	10% pre payment made before delivery	7,552,438.00	2.45%
	80%payment made before or after delivery and 10% during warranty	81,580,575.50	26.52%
Contract type B	20% pre payment made before delivery	9,714,846.00	3.16%
	70% payment made before or after delivery ，10% during warranty	23,328,958.00	7.58%
Contract type C	30% pre payment made before delivery	25,641,418.00	8.33%
	60 - 65% payment made before delivery and 5-10% made during warranty	67,980,978.57	22.10%
Exceptions	Contracts with full amount paid before delivery	5,919,801.35	1.92%
	Other payments	85,933,952.58	27.93%
Total sales for 2008		¥ 307,652,968	100.00%

Table 61: Patterns of payment for 2007 and 2008

From Table 61, it can be deduced that in 2007 the gross sales revenue consisted of :

1. **Prepayments**

10% payments equivalent to 1.74% of the Total sales value

20% payment equivalent to 3.23% of the Total sales value

30% payments equivalent 7.39% of Total sales value

2. **Payments after delivery**

60% payments equivalent to 26.13% of the total sales value

70% payments equivalent to 12.34% of total sales value

80% payments equivalent to 22.18% of total sales value

3. Outright payments

4.41% of total sales

It shows that the bulk percentage of payments is received after delivery of the contract. This means delays in contract delivery have serious consequences on the finances of the company. Also a study of contract lead times shows that in 2007, about 40% contracts exceeded their expected lead times for delivery, meaning that payments were seriously hampered. Compounded with the lack of commitment of customers to pay as per arranged payment plans, the company can be in serious financial crisis.

In reality, for orders received in January, if payments were negotiated by the Sales team such that prepayment was 10%, then the next likely payments will be somewhere in late February or March depending on the contract completion time. Thus sales value in January will only comprise the 10% prepayment portions. It is not clear from the Tables which orders yielded the payments shown. Data available only showed payments received without associated orders. However a knowledge of the company's business pattern proves that sale orders are random and hence when payments are strictly based on percentages and delivery times, the company will become insolvent. This explains the financial situation of the company. At a point in time the company will be dealing with only 10%, 20% or at best 30% of the customer's payments whilst bearing 90% or 80% or 70% of the total cost. This approach will definitely squeeze the company down financially if it continues over a long period of time.

9.7.1.4 Analysis of cash outflows

A look at the expenditure sources also showed material purchases playing a leading role in capital intensiveness, followed by bank loan repayments and overheads. Salaries, tax and security, and asset acquisition had limited cost intensities.

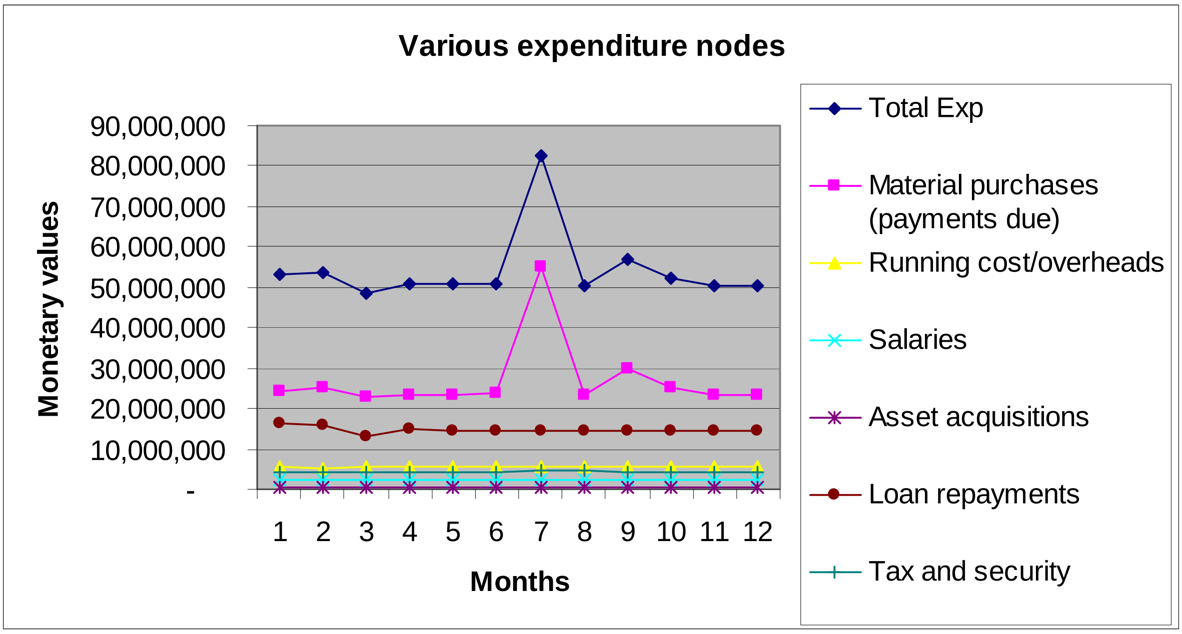


Figure 165: Sources of expenditure

After identifying these expenditure sources, it was important to critically analyse the individual variables to observe their monetary values and patterns. A study of the major sources of expenditure in the company showed that out of the six major classified expenditure sources, the cost associated with material purchases was close to 50% of the total expenditure. This is demonstrated by the bar chart shown in figure 166. It is important, however to clarify that these purchases are not related to single orders but they refer to bulk purchases which are made over a one month span. As explained before, purchases are made as and when necessary and these figures represent the cumulative payments of materials that were made over the given months.

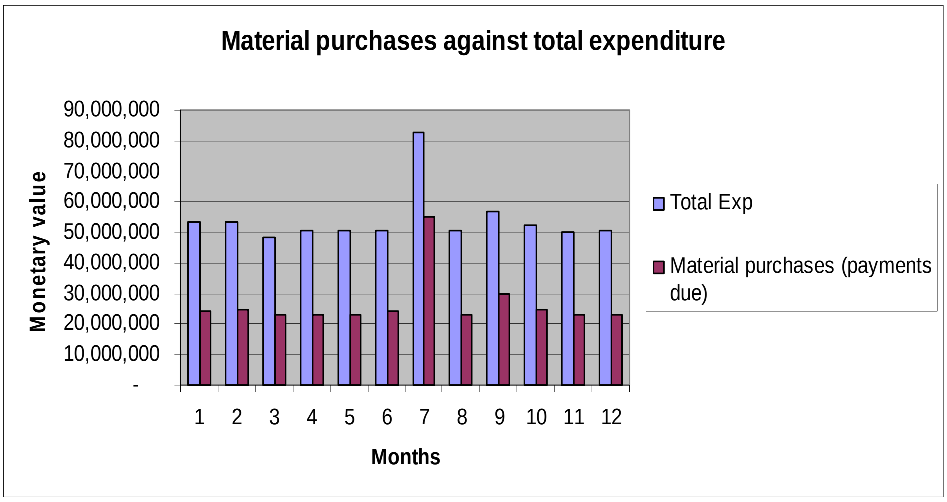
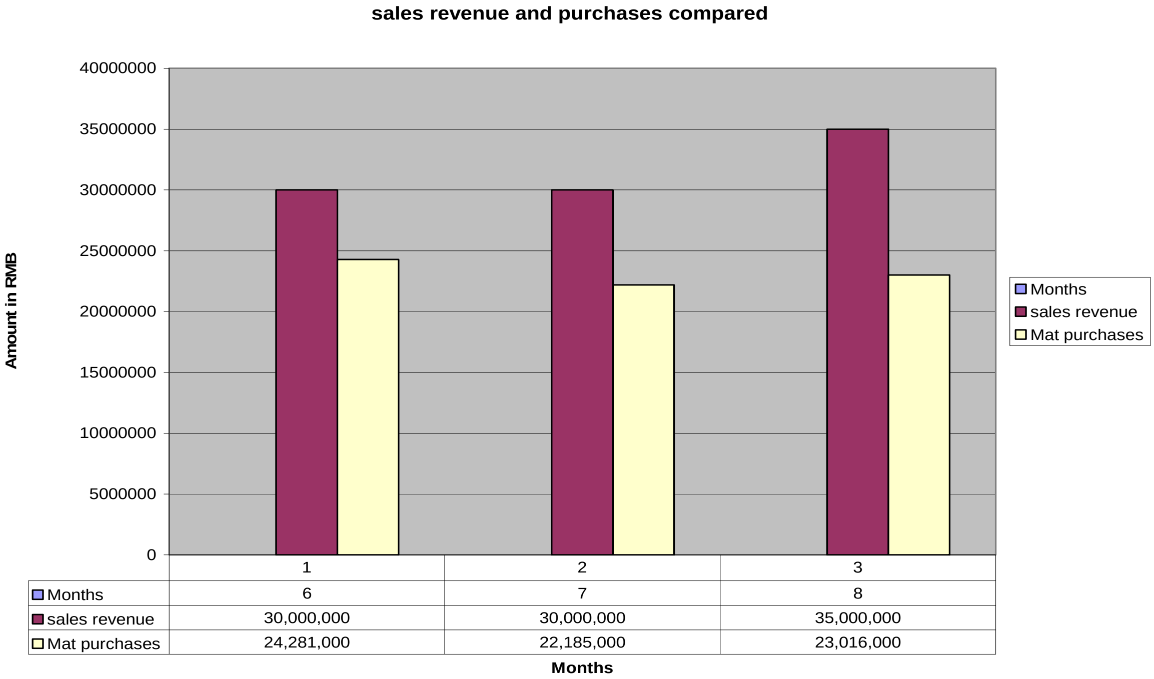


Figure 166: Material purchases against total expenditure

It can also be deduced that the amount of money paid between June and August 2008 in response to purchase requirements duly exceeds 75% of the total monthly sales value generated (see figure 167).



	1	2	3
Months	6	7	8
sales revenue	30,000,000	30,000,000	35,000,000
Mat purchases	24,281,000	22,185,000	23,016,000

Figure 167: Sales revenue and purchase payments due (June to August 2008)

This indicates that the company is completely spending a larger percentage of its sales revenue in the payment of purchased materials. The most challenging aspect is that these monies are not recovered in time.

9.7.1.5 Cash balances

The graph shown in figure 168 describes the difference that exists between the total revenue generated and total expenditure for each of the months in 2007. As shown in figure 168, with the exception of January, April and May 2007, the expenditure exceeded the income in the other months, except for the minute difference in August and November.

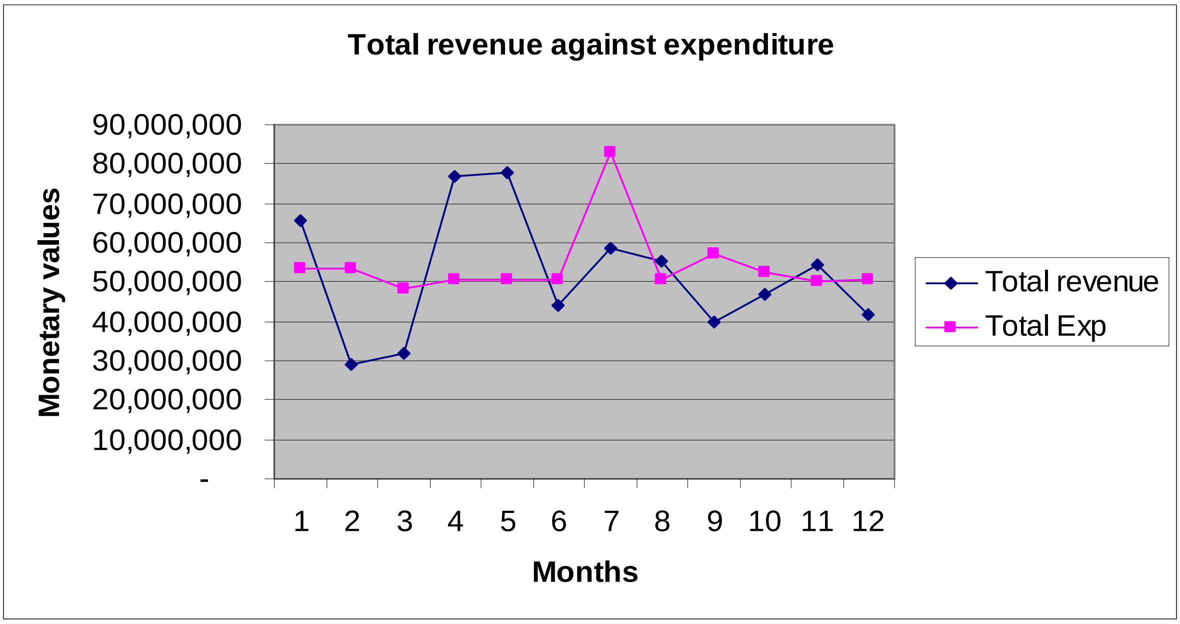
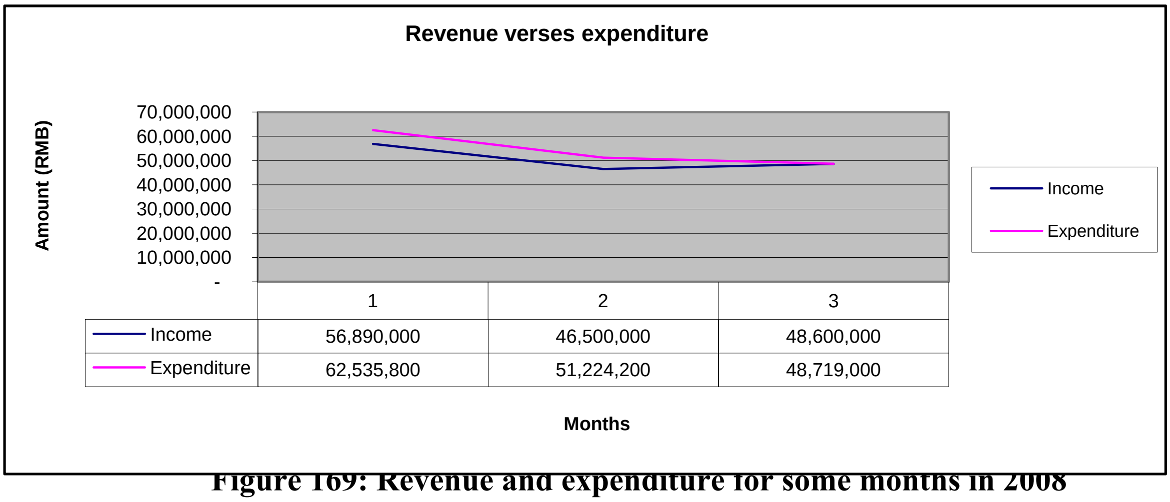


Figure 168: Total expenditure and revenue compared for 2007

In 2008, data existed for only the months of June, July and August and their performance is shown in figure 169.



	1	2	3
Income	56,890,000	46,500,000	48,600,000
Expenditure	62,535,800	51,224,200	48,719,000

Figure 169: Revenue and expenditure for some months in 2008

A study of the results shows that expenditure for this period always exceeded the income received. This explains why the company had need of continuous borrowing from the banks.

The monthly cash flow situation enabled the estimation of the net income or balance of the company. The net cash for a given month is the sum of the income balance of the previous month and the difference between revenue generated and expenses made in the given month. For the period under consideration the net cash is shown in Table 62.

2007	Net cash
Jan	12,299,712
Feb	-12,255,868
Mar	-28,946,708
Apr	-2,714,755
May	24,277,931
Jun	17,680,336
Jul	-6,523,441
Aug	-1,861,608
Sep	-19,216,382
Oct	-24,653,670
Nov	-20,282,569
Dec	-28,933,268
2008	
June	-5,645,800
July	-10,370,000
Aug	-10,489,000

Table 62: Net cash balances of AirCon China

The results shown in Table 62 indicates that there is the urgent need to address the cash flow situation else although business is growing in sales there is the high tendency of the company going bankrupt if the trend worsens. A number of suggestions have been given in Section 9.8 and it is expected that experimenting these suggestions will enable a better cash flow situation to be realized.

9.7.2 Rendering strategic solutions of cash flow at AirCon China

Currently the Business Managers of AirCon China risk by investing in contracts that takes a long time for them to recoup their capital. How successful this risk has been is reflected in their financial reports which was analysed in Section 9.7.1. In any business around the globe, there are some degrees of risk which need to be taken. In the case of AirCon China, the challenge is ‘tightening up’ in terms of payment policies or alternative pricing mechanisms, against potentially loosing in competition. Which way will yield better results will depend on a thorough investigation of their market domain. A number of suggestions have been given in the proceeding sections but it is important to recognize the risk element associated with the suggestions for cash flow improvement at AirCon China.

9.7.2.1 Freezing of payments

A practical approach to solving cash flow problems in an uncompetitive environment is to freeze payments (in this case payment of purchases) for a period of time to build adequate capital for the business. This may sound difficult but research proves that this has been practiced by many companies around the world and proven worthwhile. The approach is to win the confidence of their suppliers through thorough discussions and long term business plans. Thorough discussion about delayed payments may yield good results. When the impression is made to the suppliers about trading with them for a longer term, there is the tendency of suppliers relaxing on their payments. Relaxing in payments will enable AirCon China to create a cash buffer to stabilize the business. It is not advisable for the business to trade directly from their sales revenue. This will increase panic and financial instability. Creating a buffer is therefore necessary to reduce the impact of direct usage of their sales revenue. Negotiations with the banks for lower interest rates and trading options would also be ideal. In the worse case attempts should be made in checking interest rates and business potentials of other banks.

9.7.2.2 Revision of customer payment plans

A major issue which was born out of the data analysis was that customers are made to make low prepayments with the larger percentages paid only after delivery. Also from the data it was observed that material purchases covered more than 75% of their sales revenue every month. This implies that when a customer makes a 10% prepayment, the company must spend about 65% of their sales revenue for the cost of materials. This is alarming if the orders are many. An alternative approach will be for customers to bear the full responsibility of material cost for each contract. Because approximate cost estimates are made by the sales team, instead of quoting fixed prepayment percentages, it will be ideal to estimate the cost of materials as a percentage over the total cost of the contract and demand that amount as the prepayment percentage. Again, this may seem impracticable at the start. Especially if the culture and business domain of the company and China do not promote this form of transaction. But a study of the causal loop model (figure 157) showed that poor cash flow situation caused delays in contract completion which led to the dissatisfaction of customers. Thus it is necessary that measures are put in place to enhance cash flow which will lead to timely delivery of products then although customers will complain initially, they will be satisfied by the delivery time. Hence AirCon China will have a competitive advantage in terms of timely delivery. As a matter of fact, customers need not be told that they are bearing the cost of their materials. The sales teams can estimate material-cost based prepayment percentages and transact with those figures. The general impression from hindsight will be that customers will shift to their competitors but in reality this might not be the case. There should be room for flexibility for genuine customers who can not afford this recommended payment plans. In most cases, the value of the contract should be weighed carefully. For high capital intensive contracts, this approach is recommended whilst a lower percentage may be necessary for low valued contracts.

In reality when thorough investigation is launched in the estimation of material cost and also designers begin to design such that parts already in stock are used, there is the possibility of identifying that actual cost of material for some orders may be marginal, making it a plausible option.

9.7.2.3 Alternative payment of material purchases

Another immediate suggestion will be to revise their purchase payment schemes. As can be observed from the data, material purchases cover about half their total expenditure. This needs to be reduced. The approach will be to encourage designers to think of using materials already available in-house for most of their designs. As an associated support for managing payment of purchases, it will be ideal if a critical look is taken on what needs buying from a design and manufacturing point of view. Where possible, major attempts should be made to use the already existing stock of materials to cut down cost of materials and get rid of their inventory. This will reduce the tendency of the purchasing team having to buy new things all the time where as parts could be reused.

The purchasing team should also be encouraged to form a network of dedicated suppliers who will be willing to be paid about 30days after delivery. Dedicated suppliers scheme need to be employed in these initial stages until the company’s finances get stable. This means having an integrated network of suppliers for the various materials purchased. Payment terms should be discussed with these suppliers to arrive at reasonable instalment percentages. In the world of business, suppliers normally will agree if there are some mutual benefits to be gained. Full or part payments should be made 30-40 days after delivery to ensure healthy cash balances at AirCon China. The key issue here is the establishment of good business relationships with suppliers. This can further be enhanced through the giving of gifts and other souvenirs. Purchases should be divided into two. Those to be catered by petty cash and those to be paid after 30 -40 days of delivery.

9.7.2. 4 Better budgeting scheme

Every department is to be encouraged to present a budget at the beginning of the year for approval by Management. This budget should be distributed along the months for ease of monitoring. The accounts department needs to divide the company into cost centres with respective role holders managing these cost centres. Budgets submitted should therefore be distributed over the established cost centres for monitoring. Every form of expenditure should then be targeted to the right cost centre so that outflows can be managed not to exceed the budgeted figures. These budgets may be reviewed monthly. Allowing departments to create their own budgets will encourage in depth planning, forecasting and commitment. Once budgets are approved purchases outside the budget should be avoided. In this case the accounts department will have to manage the various budget figures for adherence.

AirCon China needs to understand that their business domain will require a completely different approach as far as management of finances is concerned. This is because AirCon China's business is contract-based and will require a budget for every contract. This will level the financial instabilities in the company. Contract budgeting requires a Project Engineer to oversee contracts which are won and manage the budget related to the contract. This is the simplest way of achieving profit over every contract which the company wins. Hence, in addition to the departmental budget forecast, the day to day business in financial terms should be run on contract budgets. Because the business is contract based, a front end project management team may be required for the different classes of products to support budgeting and implementation. This may not necessarily require additional staff but already existing staff in the Accounts, Production and Purchasing departments can be used together with the sales team to form smaller teams for contract budgeting and project management.

9.7.3 Implementation and feedback on recommended strategic solutions

A report summarizing the above recommendations and basis for arriving at these recommendations were made and presented to the Managers of AirCon China. All the suggestions were accepted without hindrances because they saw potential benefits which could accrued from these solutions. However a major concern was expressed on the recommendation for the revision of the customer payment terms. It was explained that due to the competition of A/C manufacturing and supply and also the general cultural position on payments in China, revising payments to allow customers to bear full cost of materials will have a negative effect on the company. The Managers were however keen to implement recommendations 9.7.2.1, 9.7.2.3 and 9.7.2.4. it was therefore decided to generate a 'to-be' enterprise model, essentially, showing how processes related to these recommendations can be enhanced.

An enterprise-based flow chart describing the stepwise approach to prepare contract budgets at AirCon China is shown in figure 170.

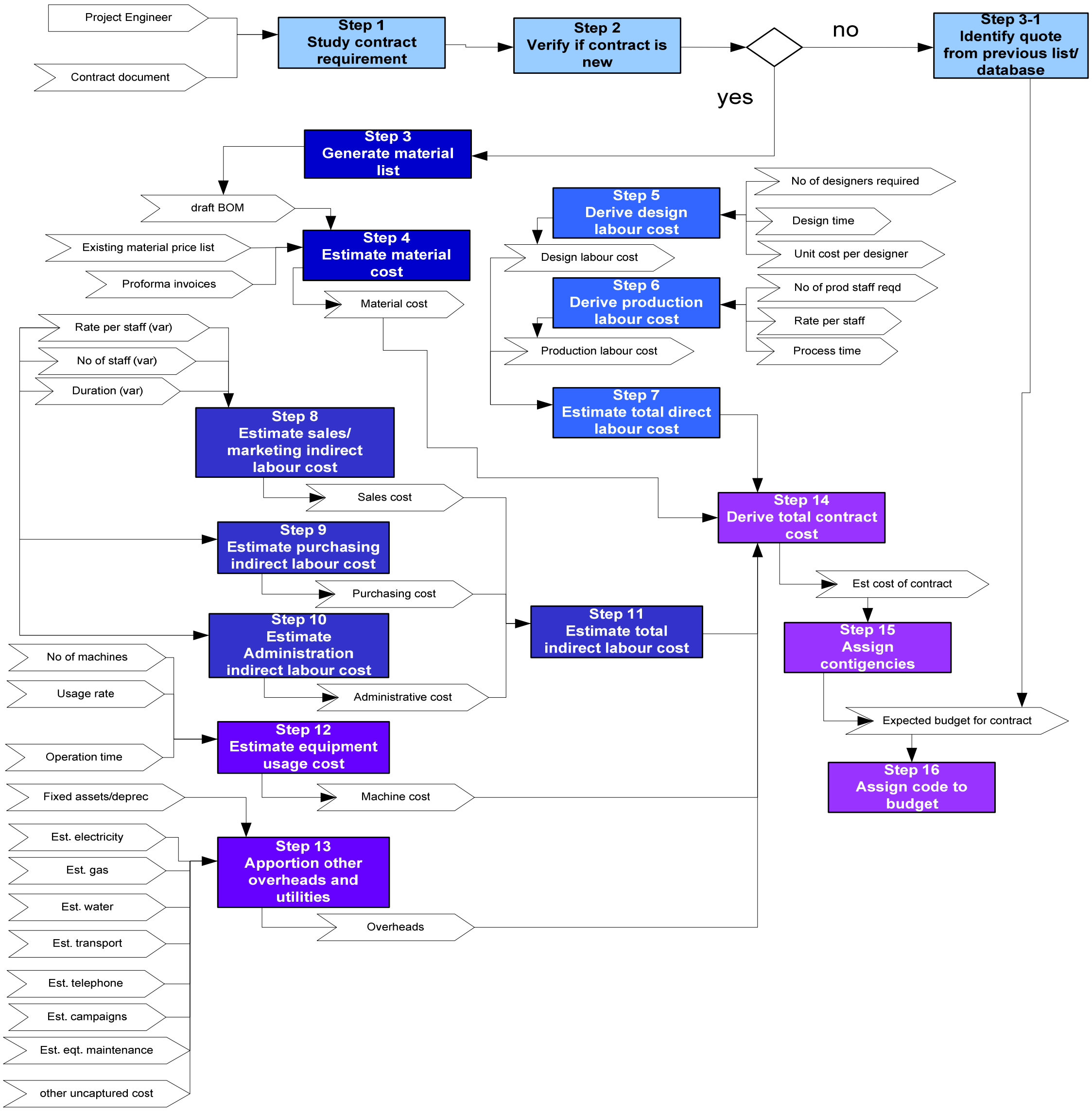


Figure 170: Enterprise based flow chart showing contract budgeting process

Basically, it is required that a Project Engineer or Contract Manager estimates the various cost attributes for each contract. This cost attributes will normally be related to material, labour, machine and overheads. An estimate of these attributes will give an idea of how much the contract will cost. Depending on how AirCon China will like to operate, the Project Engineer could work closely with the Sales Officer who does the initial contract estimate for their customers. The difference in their roles has to do with the level of detail associated with the contract budgeting task. Also in addition, the Project Engineer will have to ensure the adherence to the budgeted figures and work out alternative ways of receiving cash for the completion of the project. It will reduce the burden of the Purchasing department having to ‘chase up money’ for their purchases’. In addition, profits realized for each project can be conveniently identified and where there are losses necessary measures can be put in place to rectify them.

To illustrate how cost centre budgeting approach can be achieved at AirCon China, data related to their expenditure was used to derive a sample spreadsheet (template) cost centre to serve as a guide (see Table 63).

Sample cost centres for AirCon China		
Cost Code	**Cost Centre**	**Responsible account holders**
1100	**Personnel**	**Deputy General Manager (Personnel)**
1101	Staff recruitment	
1102	Staff training	
1103	Salaries (+ wages)-office staff	
1104	Canteen	
1105	Accommodation	
1106	Toiletries	
1107	Legal fees	
1108	Hospitality	
1109	Personal loans	
1110	Welfare	
1200	**Administration**	**Deputy General Manager (Administration)**
1201	Stationeries	
1202	Other office materials	
1203	Travels- inland	
1204	Travels - overseas	
1205	Bonuses	
1206	Entertainment	
1207	Donations	
1208	Consultancy charges	
1209	Postal fees	
1210	Insurance	
1300	**Assets**	**Deputy General Manager (Technical and Production)**
1301	Computers	
1302	Photocopiers	
1303	Printers	
1304	Telephones	
1305	Furniture	
1306	Land	
1307	Building	
1308	Production equipment	
1309	Tools	
1310	Vehicle	
1311	Fire alarm and extinguishers	

1400	**Production**	**Deputy General Manager (Technical and Production)**
1401	Materials	
1402	Consumables	
1403	Packaging materials	
1404	Salaries - permanent staff	
1405	Salaries - temporal staff	
1406	Transportation	
1500	**Maintenance**	**Deputy General Manager (Technical and Production)**
1501	Production equipment	
1502	Vehicle repair	
1503	Office equipment	
1504	Compound	
1505	Building	
1506	Fire alarm systems	
1600	**Utilities**	**Deputy General Manager (Finance)**
1601	Electricity bill	
1602	Gas bill	
1603	Water bill	
1604	Telephone bill	
1700	**Health and safety**	**Deputy General Manager (Personnel)**
1701	Medical bills	

Table 63: Sample cost centre description chart

To derive budgets for these cost centres, the account holders will have to study previous expenditures and based on the current trend of the business extrapolate potential cost likely to be incurred in the year or month. Revised 'to-be' models were created but simplified to enable better communication between Managers and the author. An activity diagram showing how AirCon China can generate cost centre budgets is shown in figure 171.

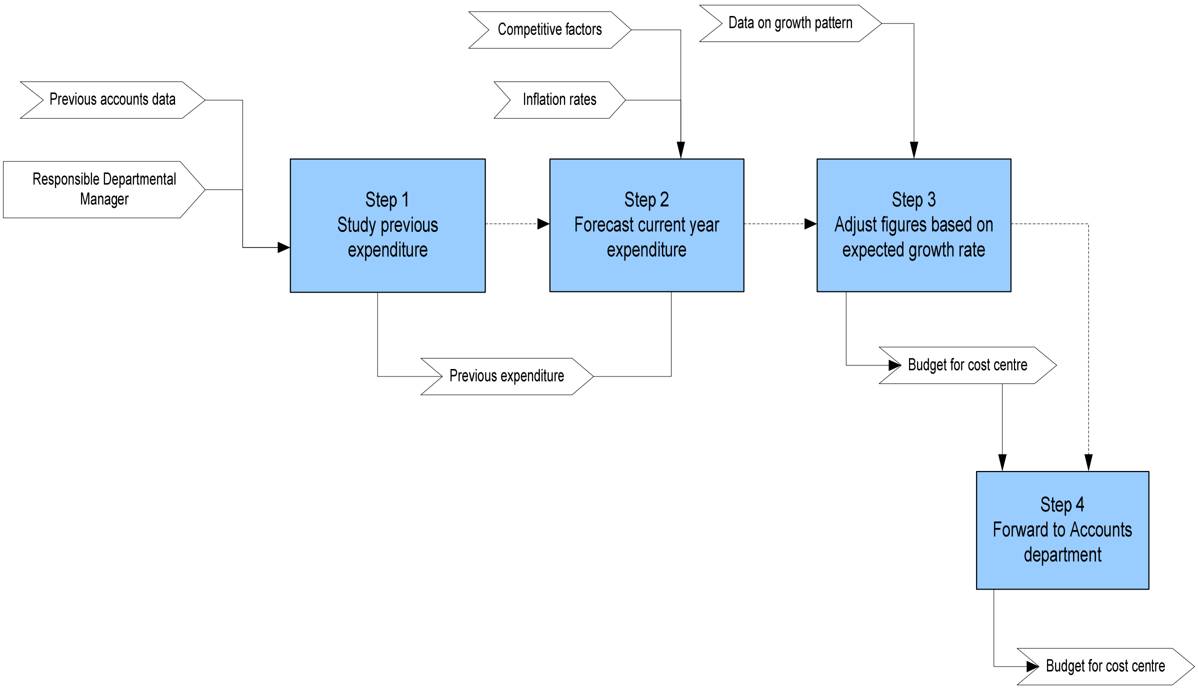


Figure 171: Cost centre budget derivation

After the budget for the cost centres have been derived by the account holders the account department will have to compile and distribute the agreed cost centres and their financial values as shown in figure 172.

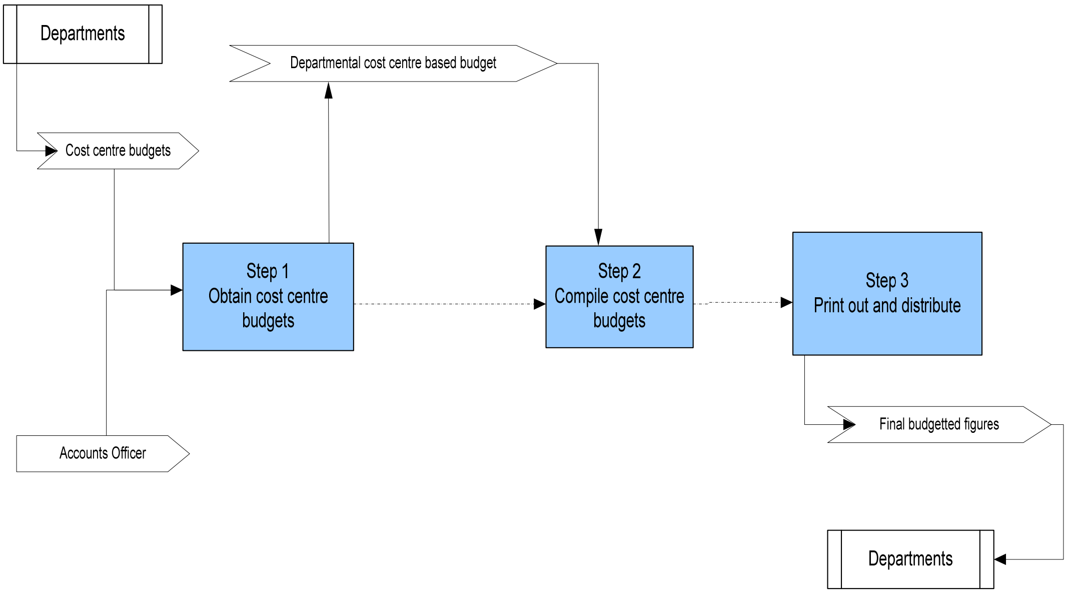


Figure 172: Compilation of cost centre budgets

Figure 173 also shows a revised process for approving purchases.

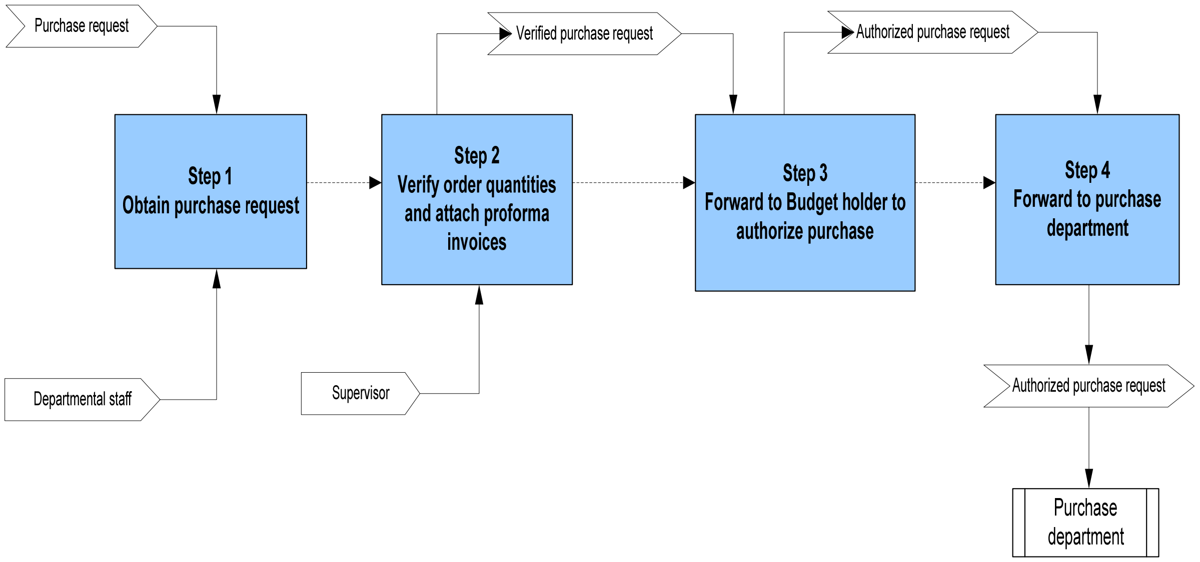


Figure 173: Revised approval of purchases

As a result a new approach to making payments based on the cost centre approach will be required. This approach also involves account holders authorizing invoices for payment and then debiting the right cost centre accordingly as shown in figure 174.

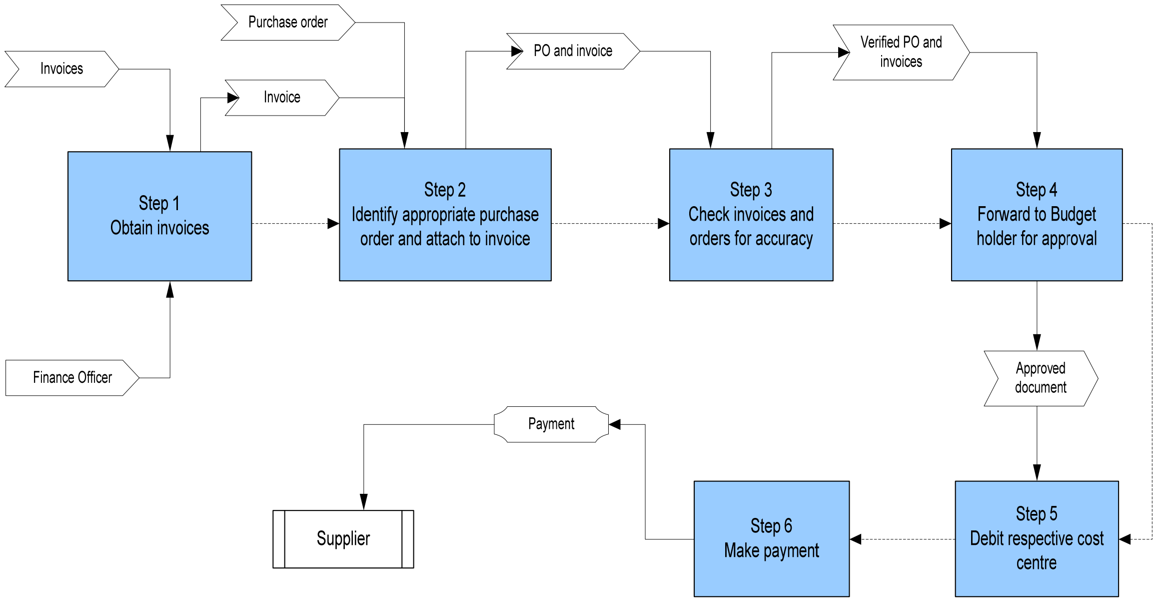


Figure 174: Revised payment procedure

These recommendations were well received and at the author’s last visit to AirCon China, reports submitted by relevant departmental heads on progress attained through the research showed clearly that some of the suggestions on cash flow had been implemented.

9.8 Redesign of AirCon China production processes for better cost and value realization

The foregoing discussions have shown which type of strategic decisions can be taken on various processes and departments to help improve cash flow in AirCon China. The strategic solutions proposed were considered vital by the Managers of AirCon China for the continuous improvement of their business. Mainly the solutions proposed were related to alternative ways in which cost effective purchases can be made, better management of internal cash flows and alternative payment policies. In addition to these recommendations, it was considered necessary to consider how the direct value adding processes could be designed to obtain high values and minimal cost. This involved revisiting the static cost and value stream models already created. Also based on the process-based product classification specified in section 9.4.3, it was possible to develop discrete event simulation models indicating how value is added to the separate materials required for the 5 product families realized by AirCon China.

The hierarchical approach described in Chapter 8 was used in modelling the direct value adding processes in AirCon China using the Simul8 discrete event simulation tool. Again in this application the material flow approach was adopted. Therefore a critical investigation was made to identify the main components of the A/C which are purchased and those which are made internally by AirCon China. Whilst investigating, it was realized that mainly steel plates, pipes, tubes, metal sheets compressors electronic controllers, fan motors among others are purchased. These materials are shown as entry work items in the model shown in figure 175. They are therefore fed into the purchase store shown in the model as a queue and transfer as per the production schedule to the respective make and assembly shops.

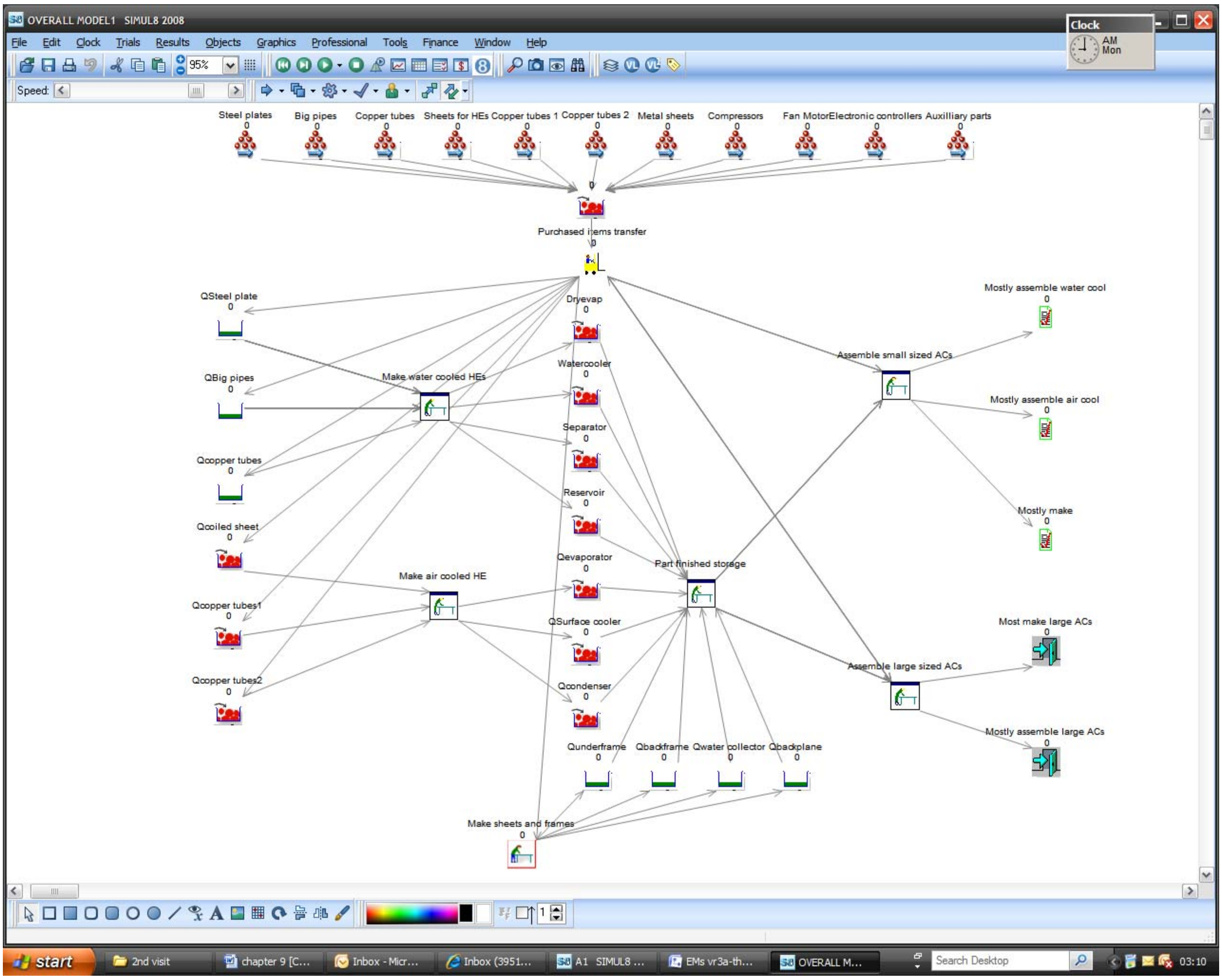


Figure 175: Top level dynamic cost and value stream model of aspects of AirCon China

A bottom level simulation model representing all the enterprise activities required to execute 'fabricate metal sheet (BP6.1), make air cooled heat exchangers (BP6.2.1), make water cooled heat exchangers (BP6.2.2), assemble water cooled A/Cs (BP6.3.1) assemble air cooled A/Cs (BP6.3.2) and assemble large sized A/Cs (BP6.4) was created and linked to the parent model through the 'sub-model' window command in Simul8. An example illustration of the model generated using such a modelling technique is shown in figure 176.

As shown in figure 175, steel plates, copper pipes and tubes are fed to the 'make water cooled heat exchangers' (BP6.2.2) whilst coiled sheets and copper tubes are transferred to the 'make air cooled heat exchangers' business process (BP6.2.1). The outputs of the air cooled heat exchanger process are evaporators, surface coolers and condensers whilst outputs of water cooled heat exchangers are dry evaporators, water cooler, separator and reservoir. These parts are transferred to the parts finished store. Another set of processes exist for the production of under frames, back frames, water collector and backplanes which are also transported to the parts finished stores. 'Made parts' in storage are transported to the assemble units for them to be assembled to together with purchased items such as electric controllers and fan motors depending on their product families. The work exit points show the various types of products produced by AirCon China.

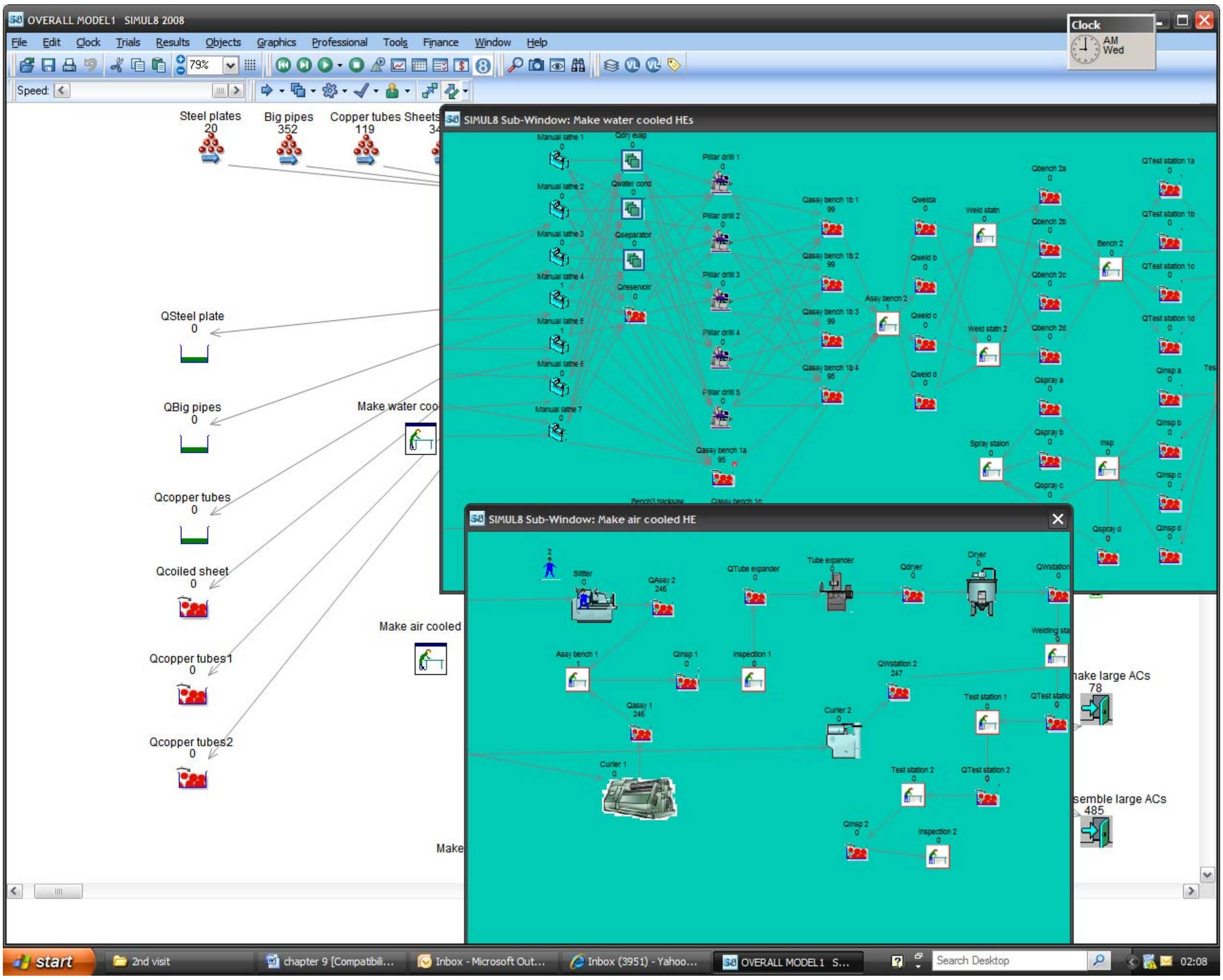


Figure 176: Illustration of hierarchical process models with Simul8

9.8.1 Testing and validation of initial models

Initial models were checked by the MSI Research team who visited AirCon China. These intial checks related to the robustness of the model especially in representing the sequence of product flow described in the static cost and value stream models. Significant revision was made in the water-cooled heat exchanger production processes and extra effort was used in ensuring that components and materials were routed based on defined labels such that sub assembly of parts and transformation of materials were evident.

At the next level of checking knowledge holders in AirCon China were tasked to verify if the model best represented the production operations. Operation times, inter-arrival times and material flows were thoroughly verified by the AirCon representatives. After the checks, they explained that there were essential quality checks which were not factored into the model. Since quality checks contributed to a larger percentage of work in AirCon China, the author decided to revise the current model to include the different quality control checks in the A/C production processes.

The modified model was run to see if outputs derived from the model was indicative of the real life situation. Data on product types, process sequences, delays, material arrivals and operation times were available for the period June-August 2008. Typical as-is results derived and verified are shown in Table 64. The Managers of AirCon China confirmed that these results were reflective of their real business scenario.

BP No.	Top level BPs	Total number of operators	Average utilization
BP6.1	Fabricate metal sheet (Metal sheet shop)	83	40%
BP6.2.1	Make air cooled heat exchangers	40	42%
BP6.2.2	Make water cooled heat exchangers	26	65%
BP6.3	Assemble small sized A/Cs	66	80%
BP6.4	Assemble large sized A/Cs	60	81%
BP6.5	Store materials	5	40%
	Total	280	58%

	Actual throughput	Expected throughput	Actual value realized (RMB)	Expected value (RMB)
Mostly assemble water cool A/C	5	13	501,000.00	1,302,600.00
Mostly assemble air cool A/Cs	50	118	6,995,000.00	16,508,200.00
Mostly make small size A/Cs	12	42	1,778,400.00	6,224,400.00
Mostly make large size A/Cs	50	78	11,835,000.00	18,462,600.00
Mostly assemble large A/Cs	120	485	33,456,000.00	135,218,000.00
			54,565,400.00	177,715,800.00

Table 64: Aspects of as-is model results

9.8.2 Simulation results and analysis

Studying the results derived from the model of the direct value adding processes in AirCon production system, it was realized that low outputs were generated which resulted in AirCon China obtaining low values. A review of the results from the model shows how parts are delayed in queues because appropriate assembly parts were not available either from purchasing store or the parts store. This indication has already been explained by the causal loop model in figure 157 . Through the use of the system dynamics model it was recommended strategically that appropriate purchasing and payment policies must be in place to enable healthy cash balances in AirCon China. Obtaining healthy cash balances will enhance payments of suppliers and hence timely supply of parts and materials.

In the quest to improve the design of the production system for better cost and value performance indications, it was assumed that earlier suggestions to improve material and parts arrival was adequate to ensure that needed materials and parts were always available at the time needed. This is an oversimplified assumption but it needed to be considered to observe how the current production system will perform when overloaded. This will ensure better design of the production system for optimal cost and value behaviours. As explained in Section 9.8, the dynamic cost and value stream model shown in figure 175 consist of sub models of 'fabricate metal sheet (BP6.1), make air cooled heat exchangers (BP6.2.1), make water cooled heat exchangers (BP6.2.2), assemble water cooled A/Cs (BP6.3.1) assemble air cooled A/Cs (BP6.3.2) and assemble large sized A/Cs (BP6.4), hence efforts were concentrated on optimizing these processes for better economic indications. The sub models were used for many other purposes and it is worth noting the tremendously input by other members of the MSI Research group. Particularly, research mate Zihua Cui pioneered the design and modelling of 'assemble large sized A/Cs' (BP6.4). Because of the need to integrate production system models for analysis, models created by the MSI Research team were integrated, enhanced and especially embedded with cost and value information by the author. These models were built from the activity diagrams of each of the six BPs (BPs 6.1, 6.2.1, 6.2.2, 6.3.1, 6.3.2 and 6.4).

The sub model representing detailed operational activities in the 'fabricate metal sheet' business process is shown in figure 177.

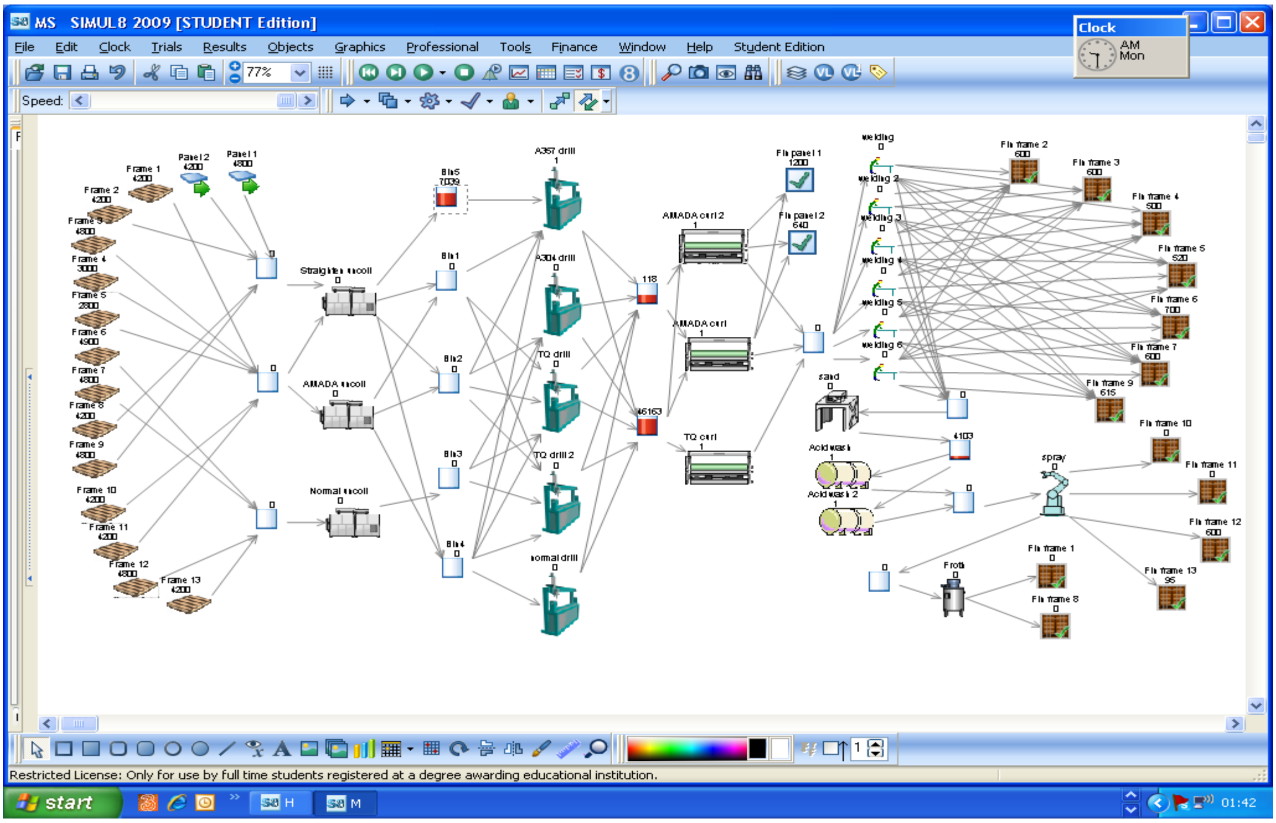


Figure 177: Dynamic cost and value stream model of 'fabricate metal sheets' (BP6.1)

To observe how work centres are utilized and hence develop a means of improving specific work centres, results related to time utilization during the 15 weeks simulation period was examined. Figure 178 shows the time view of all work centres in the 'fabricate metal sheets' business process.

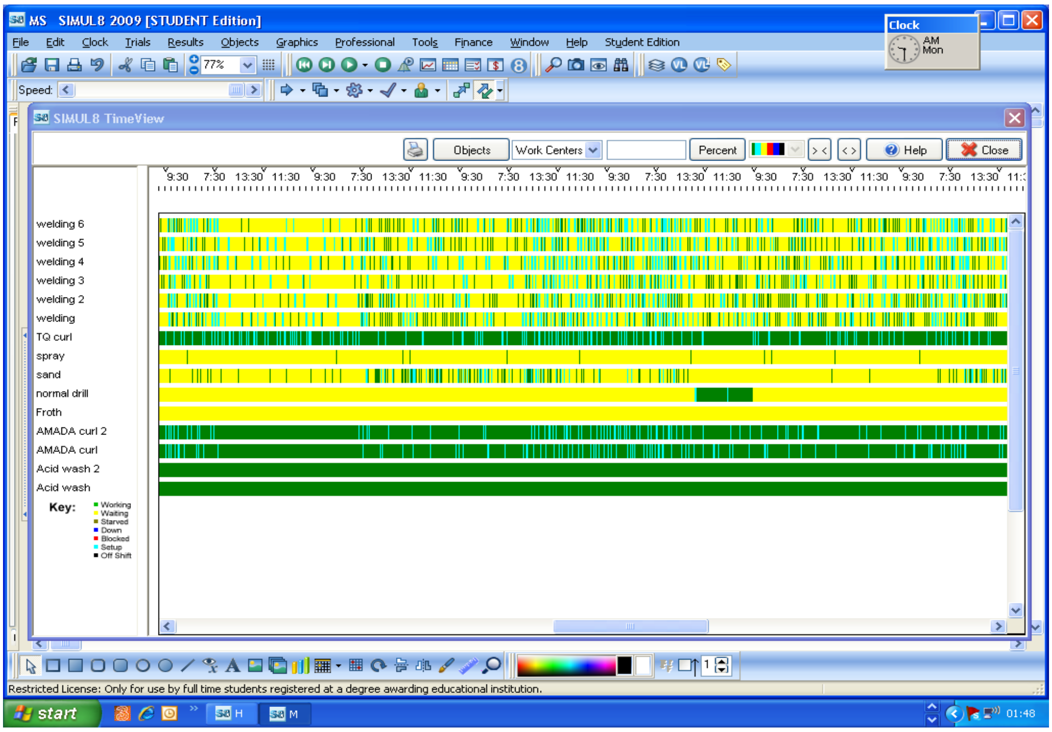


Figure 178: Time view of work centres

From the results displayed in figure 178, it was clear that work centres involved in spraying, drilling, sanding and frothing were grossly underutilized, whilst the welding resources were partly utilized. Machine resources for curling and acid washing were almost fully utilized. Detail percentage utilizations can be obtained by observing the performance of each of the work centres. For example performances of spray, curl and welding and uncoil work centres together with sample work exit results are shown in figure 178.

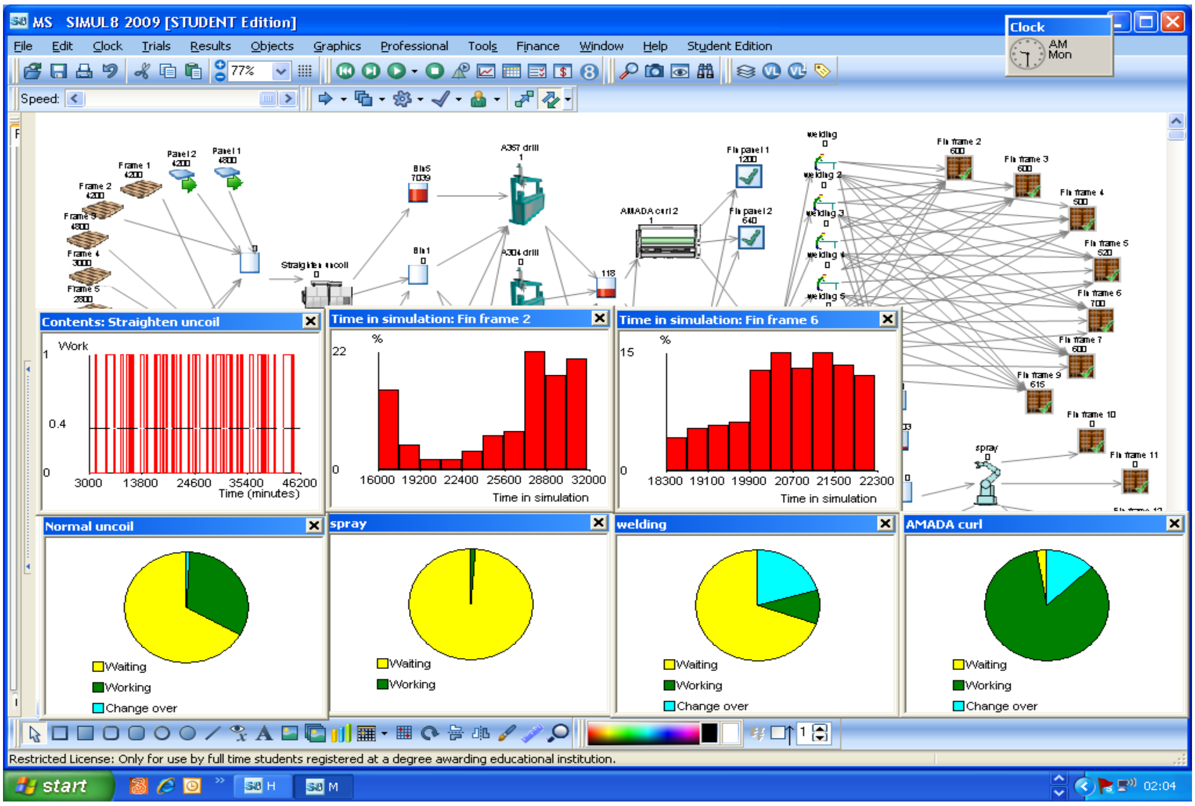


Figure 178: Sample work centre results

These results show the need to redesign processes so that work centres can effectively be utilized. Another set of results analysed were queue sizes, queuing time, current queue content and number of items which have entered each queue. A graph showing the different queue properties for each of the queues is shown in figure 179.

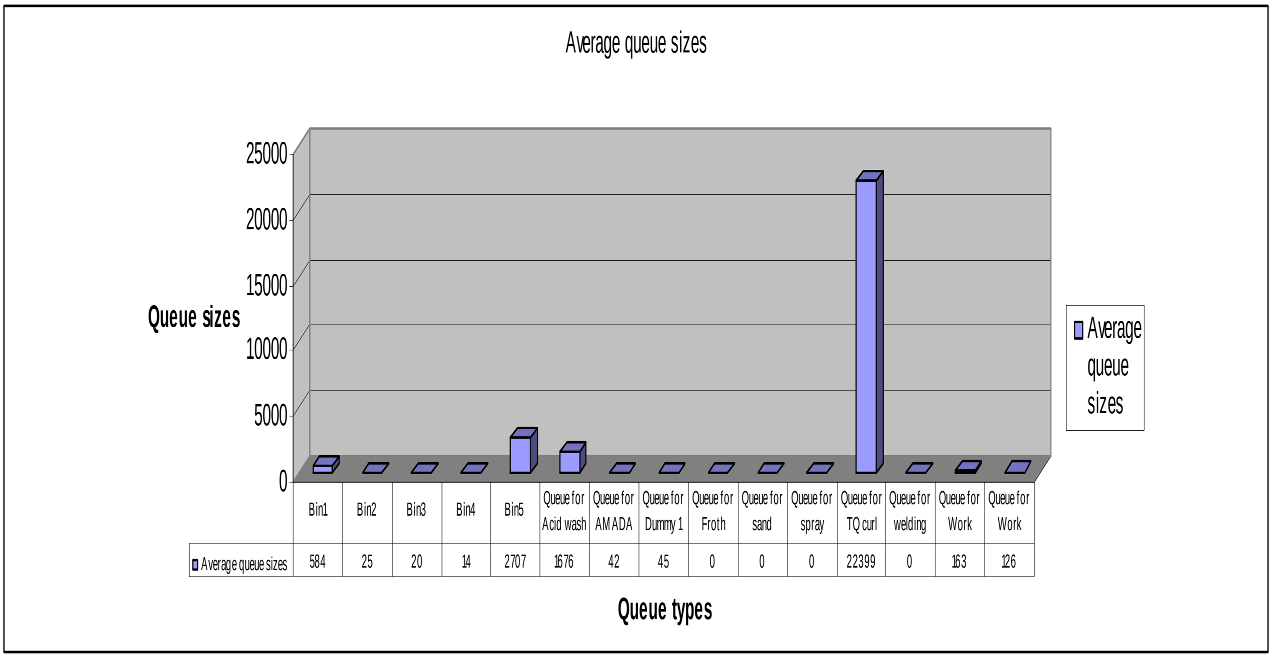


Figure 179: Queue properties

From the graph shown in figure 179, extremely high queue sizes are experienced at the curling and acid wash processes. The total time required for each of the parts realized through BP6.1 is shown as work exit properties in the model. These model results exported to MS Excel is shown in Table 65

Simulation Object	Performance Measure	Run 1	2	3	4	5	Average
Fin frame 1	Average Time in System	0.0	0.0	0.0	0.0	15591.8	3118.4
	Number Completed	0.0	0.0	0.0	0.0	516.0	103.2
Fin frame 10	Average Time in System	0.0	39059.0	0.0	18579.9	0.0	11527.8
	Number Completed	0.0	107.0	0.0	600.0	0.0	141.4
Fin frame 11	Average Time in System	0.0	18437.1	0.0	0.0	0.0	3687.4
	Number Completed	0.0	600.0	0.0	0.0	0.0	120.0
Fin frame 12	Average Time in System	18181.9	0.0	0.0	38308.1	0.0	11298.0
	Number Completed	600.0	0.0	0.0	88.0	0.0	137.6
Fin frame 13	Average Time in System	37142.4	0.0	18220.0	0.0	35416.5	18155.8
	Number Completed	95.0	0.0	600.0	0.0	199.0	178.8
Fin frame 2	Average Time in System	26030.2	24567.5	34046.7	0.0	15623.8	20053.6
	Number Completed	600.0	600.0	569.0	0.0	600.0	473.8
Fin frame 3	Average Time in System	11767.7	35674.8	3029.6	30753.7	31253.9	22495.9
	Number Completed	600.0	395.0	600.0	554.0	600.0	549.8
Fin frame 4	Average Time in System	9610.3	16948.6	7050.3	17313.9	23734.8	14931.6
	Number Completed	500.0	500.0	500.0	500.0	500.0	500.0
Fin frame 5	Average Time in System	12357.6	10535.3	17650.5	10430.4	12468.1	12688.4
	Number Completed	520.0	400.0	400.0	400.0	400.0	424.0
Fin frame 6	Average Time in System	20675.4	15177.7	35101.1	21851.8	16606.7	21882.6
	Number Completed	700.0	1400.0	564.0	1400.0	700.0	952.8
Fin frame 7	Average Time in System	4726.8	30965.6	8356.6	16961.7	33949.5	18992.0

	Number Completed	600.0	600.0	600.0	600.0	600.0	600.0
Fin frame 8	Average Time in System	0.0	0.0	38209.3	0.0	0.0	7641.9
	Number Completed	0.0	0.0	113.0	0.0	0.0	22.6
Fin frame 9	Average Time in System	3535.8	0.0	16947.5	7275.3	37418.3	13035.4
	Number Completed	615.0	0.0	600.0	600.0	259.0	414.8
Fin panel 1	Average Time in System	32366.1	10272.0	10585.2	13328.7	12938.2	15898.1
	Number Completed	1200.0	1936.0	1991.0	1800.0	1815.0	1748.4
Fin panel 2	Average Time in System	21453.0	13267.6	10867.6	15453.0	12293.5	14667.0
	Number Completed	640.0	1800.0	1800.0	1285.0	2400.0	1585.0

Table 65: Results collected from work exit points

The associated cost involved in realizing the throughputs shown in Table 65 is shown in Table 66

Category	Costs	Value
Queue for Work Center 1 Total Cost	109,387.16	
Straighten uncoil Total Cost	503.44	
Queue for Work Center 2 Total Cost	72,359.44	
Bin1 Total Cost	241,638.02	
Bin2 Total Cost	16,243.47	
AMADA uncoil Total Cost	192.16	
Normal uncoil Total Cost	507.57	
A357 drill Total Cost	1,269.76	
A304 drill Total Cost	694.84	
TQ drill Total Cost	1,040.31	
normal drill Total Cost	124.79	
Bin3 Total Cost	7,765.10	
Bin4 Total Cost	8,204.06	
AMADA curl Total Cost	1,503.01	
TQ curl Total Cost	1,376.02	
Queue for AMADA curl Total Cost	29,782.00	
Queue for TQ curl Total Cost	14,135,916.57	
welding Total Cost	138.10	
sand Total Cost	135.53	
Queue for sand Total Cost	102.51	
Acid wash Total Cost	1,654.76	
Queue for Acid wash Total Cost	1,021,101.65	
spray Total Cost	21.96	
Froth Total Cost	200.65	
Queue for Froth Total Cost	2.29	
Queue for Dummy 1 Total Cost	29,755.80	
welding 2 Total Cost	139.10	
welding 3 Total Cost	136.34	
Acid wash 2 Total Cost	1,652.38	
Bin5 Total Cost	1,476,843.24	
welding 4 Total Cost	138.17	
welding 5 Total Cost	137.14	
welding 6 Total Cost	139.06	
AMADA curl 2 Total Cost	1,501.20	
TQ drill 2 Total Cost	964.34	
Simulation Total Costs	17,163,271.93	

Revenue		
Fin frame 1 Total Revenue		1,032,000.00
Fin panel 1 Total Revenue		3,630,000.00
Fin panel 2 Total Revenue		4,800,000.00
Fin frame 2 Total Revenue		1,200,000.00
Fin frame 3 Total Revenue		1,200,000.00
Fin frame 4 Total Revenue		1,000,000.00
Fin frame 5 Total Revenue		800,000.00
Fin frame 6 Total Revenue		1,400,000.00
Fin frame 7 Total Revenue		1,200,000.00
Fin frame 9 Total Revenue		518,000.00
Fin frame 13 Total Revenue		398,000.00
Simulation Total Revenue		17,178,000.00
Profit		***14,728.07***

Table 66: Cost and value results for BP6.1

To investigate the performance of the ‘make air cooled heat exchanger’ business process (BP6.2.1) results related to the sub model shown in figure 180 was analysed.

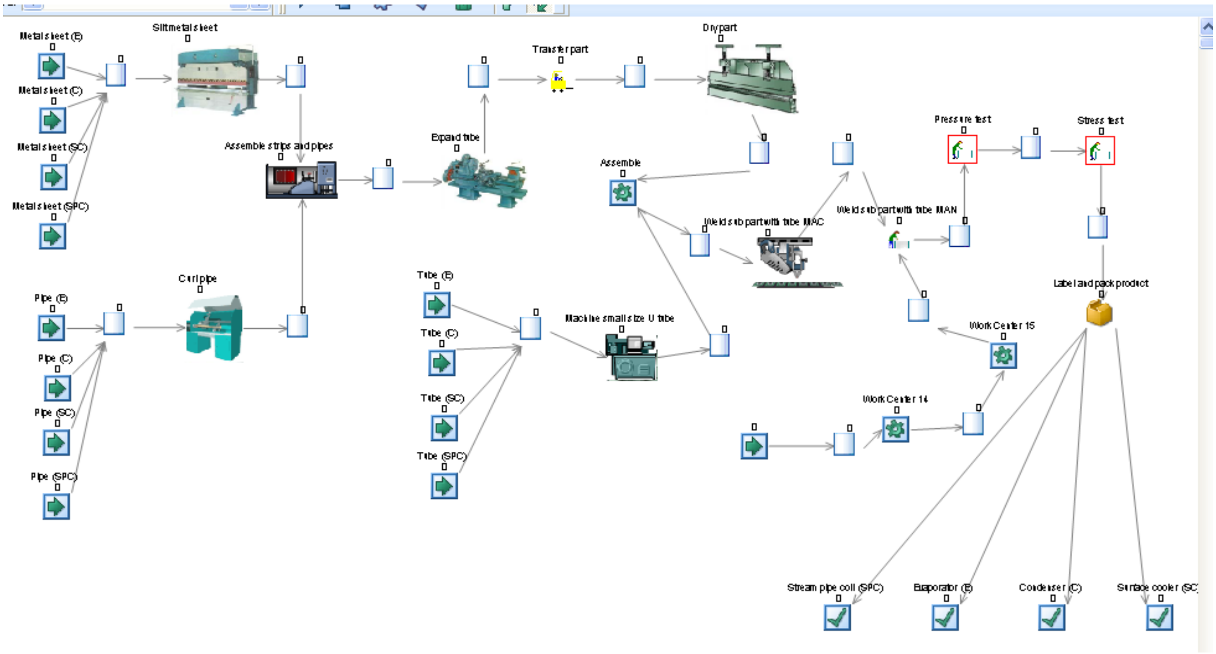


Figure 180: Screen shot of ‘make air cooled heat exchanger’ business process (BP6.2.1)

Similar result outputs as presented in the case of ‘fabricate metal sheets (BP6.1) were observed. For the lack of space, a few aspects of queue information and throughputs are shown in Table 66. Further graphs showing the time utilization of work centres is shown in figure 181.

Simulation Object	Performance Measure	Run 1	2	3	Average
Condenser (C)	Number Completed	665	684	695	681

Surface cooler (SC)	Number Completed	369	339	393	367
Stream pipe coil (SPC)	Number Completed	740	725	671	712
Evaporator (E)	Number Completed	1165	1182	1184	1177
Queue for Assemble	Minimum queue size	0	0	0	0
	Average queue size	232	248	223	234
	Average Queuing Time	8827	9421	8470	8906
	Current Contents	471	489	461	474
	Items Entered	3411	3420	3404	3412
Queue for Assemble strips and pipes	Minimum queue size	0	0	0	0
	Average queue size	3	11	8	7
	Average Queuing Time	126	464	336	309
	Current Contents	0	11	20	10
	Items Entered	2941	2944	2965	2950
Queue for Curl pipe	Minimum queue size	0	0	0	0
	Average queue size	0	0	0	0
	Average Queuing Time	0	0	0	0
	Current Contents	0	0	0	0
	Items Entered	2941	2944	2965	2950
Queue for Dry part	Minimum queue size	0	0	0	0
	Average queue size	0	0	0	0
	Average Queuing Time	10	11	10	10
	Current Contents	0	1	0	0
	Items Entered	2941	2933	2943	2939
Queue for Expand tube	Minimum queue size	0	0	0	0
	Average queue size	0	0	0	0
	Average Queuing Time	0	0	0	0
	Current Contents	0	0	0	0
	Items Entered	2941	2933	2945	2940
Queue for Label and pack product	Minimum queue size	0	0	0	0
	Average queue size	0	0	0	0
	Average Queuing Time	0	0	0	0
	Current Contents	0	0	0	0
	Items Entered	2939	2930	2943	2937

Table 66: Sample as-is results of BP6.2.1

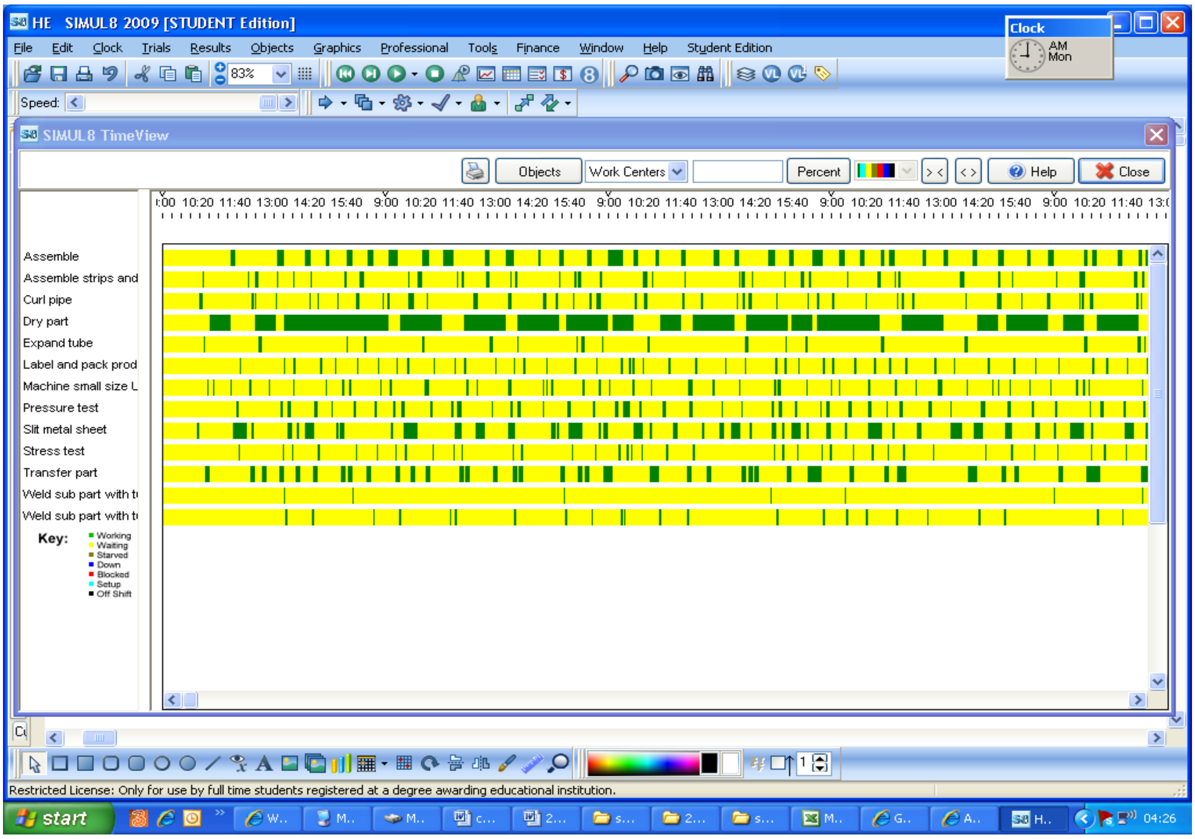


Figure 181: Time view performance of work centres

Again further analysis of other business processes required to fulfil the requirements of the six product families was conducted. Considering the time and space limits, only aspects of analysis related to 'assemble large sized A/Cs' (BP6.4) is presented in this Chapter. As shown in Table 11, assembly of large sized A/Cs is team based and historic operational times differ for most of the mostly assemble A/Cs.

team	Activities Op-time	Mostly assemble A/Cs			
		LS	LSF	LSQ	LSQF
team1	assemble under-frame	30	30	30	30
team1	assemble backbone	0	60	0	60
team1	assemble compressor	40	40	60	40
team1	assemble condenser	30	200	30	200
team1	evaporator	10	30	10	30
team1	assemble Fan motor	0	120	0	120
team2	tubing & welding	420	600	450	600
team2	Hydraulic pressure test	120	120	120	120
team3	Install electronic control	225	200	225	200
team3	assemble side panels	0	40	0	40
team4	test	180	180	180	180
team5	package	100	100	100	100

Table 67: Historic operation times for some mostly assemble A/Cs

A screen shot model of BP6.4 originally pioneered by Zihua Cui and enhanced by the author is shown in figure 182.

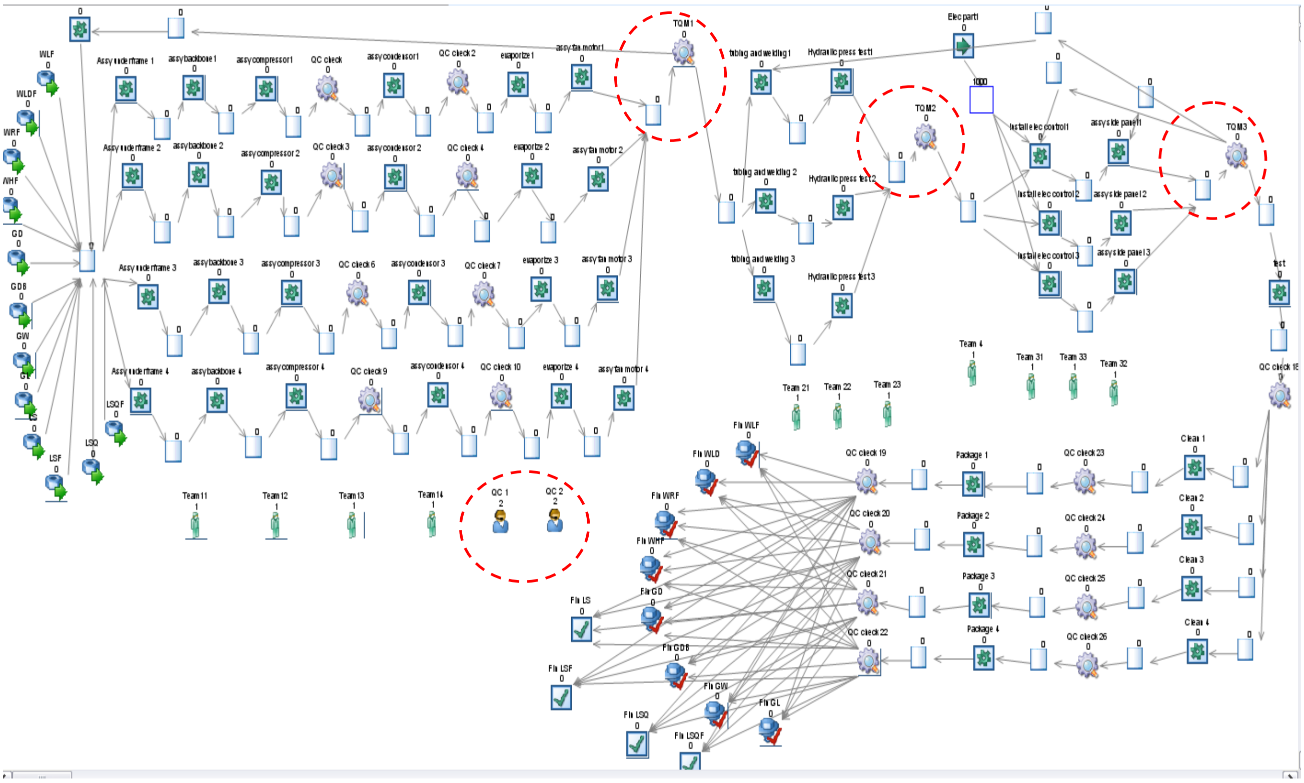


Figure 182 Screen shot of BP6.4

From a report received from the Managers of AirCon China, BP6.4 contributes to about 60% of the total value and hence improvements in these processes would have great economic benefit for the business. Therefore series of experiments were conducted on the BP6.4 model to see how best job could be designed for optimal performance. In a simulation experiment conducted over 15 weeks, a number of useful process indicators related to queues were used for analysis because from previous process analysis it was observed that the major cost influencing factor was queue sizes and queue times. Six simulation runs were conducted with alternative material arrival intervals, resource availabilities and introduction of parts at different intervals.

Queue elements	Run1	Run2	Run3	Run4	Run5	Run6
Production queue size	30	84	285	291	42	0
Production queue time (days)	2.2	7.5	27.5	19.0	2.9	0.6
Average queue time for welding (days)	0.2	0.2	0.1	0.2	0.1	0.2
Average queue time for install electrics (days)	3.7	5.4	6.5	7.3	1.0	0.2
Average queue time for	0.2	0.2	0.3	0.3	0.1	0.2

test (days)						

Table 68: Queue information for BP6.4

It was observed by studying Table 68 that runs 1 and 6 have better queue behaviours and hence potentially less cost indications.

The author conducted a number of experiments with the verified model of figure 175 to observe which combinations of resources and organization of processes best generate high values and low process cost. In principle, many parameters can be used as levers to manipulate the behaviour of virtual production models, but because the research has a specific focus, it was decided that:

1. The cost and value realized during the execution of as-is dynamic cost and value stream model will be examined
2. Changes related to product variance will be experimented to see the effect on cost and value generation
3. Changes related to mechanical and human resources will be experimented to see its impact on cost and values

The results derived out of the simulation experiments were used as basis for recommending specific operational solutions about AirCon China business processes.

A set of key performance indicators such as inventory cost, operation cost, queue sizes, average queuing time and values generated were chosen to benchmark one experimental result against the others. It was observed that when orders related to the production of mostly assemble A/Cs are prioritized over the others, AirCon China achieves very high values. Another relevant observation was that when materials are readily available, production is harnessed and overall throughput increase as shown in figure 181. Also observed was that when production plan is done well such that sub production models run at pace with the assembly shop models, inventories are minimized and production cost is reduced. Aspects of model requirements in support of planning of production facilities were covered by other colleagues in the MSI Research Team.

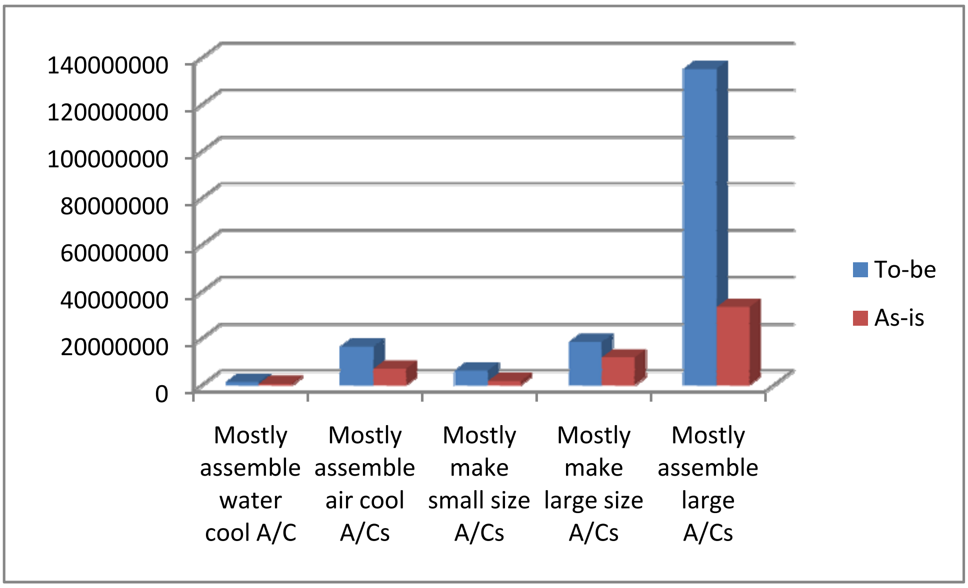


Figure 181: Value indications of 'to-be' and 'as-is' models

9.9 General observations and conclusions to Chapter 9

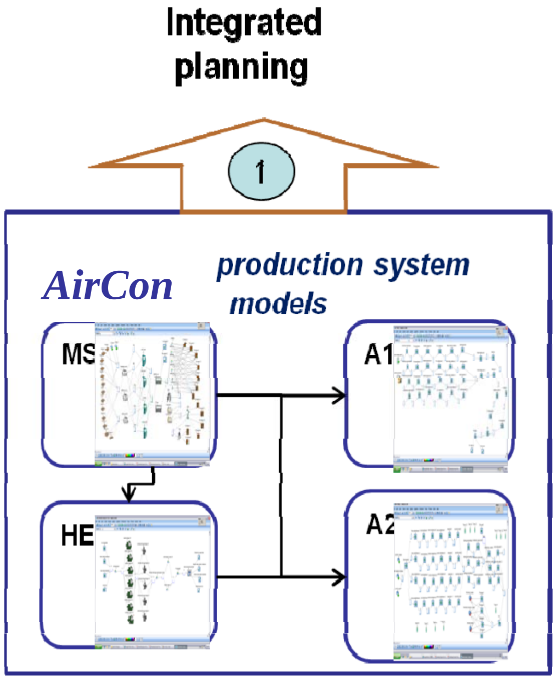
Previous sections in this chapter have illustrated how aspects of the multiproduct cost and value stream models were used to support analysis of business process and operations in AirCon China, a privately owned air condition manufacturing company based in the southern part of China. Although at the start of the research with this company, challenges facing the company were described as complex and almost unsolvable, the scientific approach adopted through the realization of the cost and value stream modelling technique allowed the challenges to be understood in an integrated manner limiting the tendency of shifting blames on each other in the company. Further to this, the iThink modelling technique provides further quantitative support to the observations qualitatively described by the causal loop models created. In all the modelling stages, it was observed that the static enterprise model served as a backbone.

Through the application of the modelling technique, key analysis on cash flow problems in AirCon China was conducted. This related to building cash flow models showing the sources and frequencies of cash inflows and outflows. Detailed analysis was made on the revenue sources and it became evident that the major source of income for AirCon China was through the realization of sales. Unfortunately payment patterns were not encouraging and therefore AirCon China is increasingly incurring debts at high rates as a result of borrowings from the bank.

Material purchase was also observed to be the most dominant expenditure node and in most cases the percentage of monies required for material purchases exceeded the value generated through sales. As a result, a number of recommendations were made which from the perspective AirCon China, was excellent. Before the end of the research many key portions of the suggestions for improvement had been implemented whilst others were awaiting further investigation and application. Some of the proposals considered worthwhile include the institution of contract based budgeting schemes, revision of purchase procedure, revision of payment of purchased items procedure, implementation of cost centre budgeting schemes, alternative customer and supply payments schemes. After these recommendations were made and accepted by AirCon China, further specific examples and documents describing how to achieve the recommendations specified were sent to them.

Specific process improvements were realized through the application of the discrete event simulation tool, Simul8. By conducting the experiments, possible process redesigns capable of generating improved cost and value conditions were obtained.

Whist conducting research with AirCon China other means of improving their current business included the development of an integrated planning suite to help achieve realistic plans. The stages required to achieve this are described in the diagrams shown in figures 182 and 183.



To achieve more realistic plans

*classify products with respect to process routes & operation time data

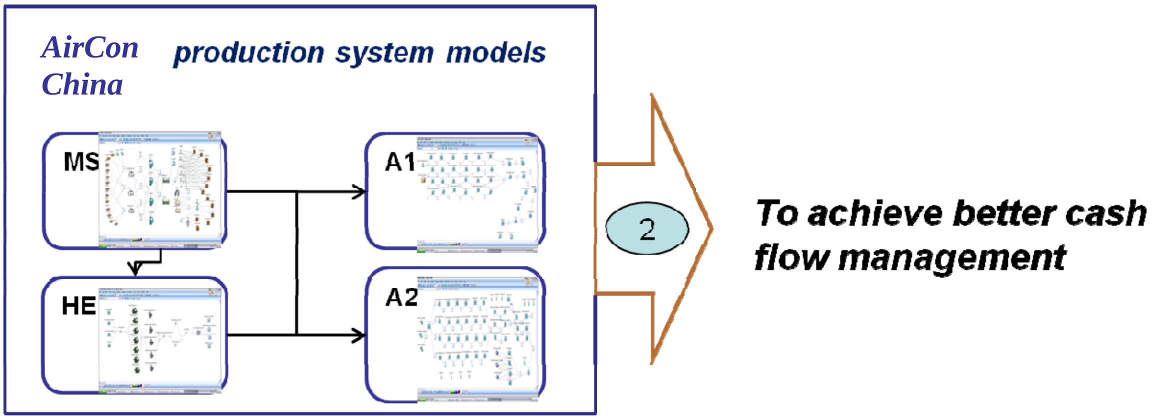
*classify products with respect to purchasing delays & uncertainty

*understand queuing times with respect to production workloads

*better understand source and impacts of design faults

Figure 182: Development of an integrated planning suite

Other recommendations required to maintain healthy cash balances requires the use of operation and resource cost data based on appropriate product classifications to estimate contract prices as described in figure 183. This can be achieved through further development of the dynamic simulation model shown in figure 175.



*achieve stated aims to use op time data & resource cost data when estimating contract prices

*regularly update mark-ups

*pursue cost centre budgets

Figure 183: Integrated use of production models to inform decision on cash flow

Reflecting on the application of the cost and value stream modelling methodology in case study 4, it was observed that the system dynamics tools provided great support in analysing problems related to cash flow. On the other hand, the CIMOSA based static cost and value stream models gave support on specific process improvements. These improvements were extended when the static models were transformed into DES models in the form of Simul 8. In brief, although at the start of the modelling exercise it was perceived that a sequential use of the techniques was necessary, it was learnt through the case study that specific portions of the technique can address certain problems without going through the overall rigorous modelling technique as specified in Chapter 4.

10. Reflections, future work and conclusions

10.1 Research Review

In Chapter 1 of this Thesis, general trends and developments in manufacturing industries were reviewed. Through the research, it was identified that in general terms, processes, technologies and management of manufacturing industries have evolved from the craftsman's technology to the latest IT based manufacturing technologies. Emerging technologies, competition, changing customer needs, globalization, legal and environmental requirements have forced many MEs to adopt many different manufacturing methods with potential to reduce production cost; improve quality; enhance customization and help MEs realize high values. Mainly, most MEs will have to operate in a manner that they can realize multiple values at low cost with limited complexities. In such instances, cost and value generation become key industrial performance indicators. These performance indicators are extremely necessary if any ME is to remain competitive over a long time.

The literature review showed that many Researchers and Industrialist have developed modelling techniques with the aim of reducing cost and improving values. In Chapter 3, these techniques were extensively reviewed and classified into: Process Mapping (PM), Enterprise Modelling (EM), System Dynamics (SD) modelling and Business Process Simulation Modelling (SM) techniques. During the review it was observed that tools developed under these broad categories were capable of solving problems only related to their unique viewpoints on Business Process Engineering, Enterprise Integration and Systems Thinking. Reviewing the needs of current Manufacturing Industries in the drive towards effective low cost but high value business processes, a set of modelling requirements for a dynamic ME realizing multiproduct flows were proposed. Matching the strengths of current best practice process modelling tools with the requirements, it was observed that none of the available techniques suitably matched the proposed modelling requirements. A number of limitations about current best practice in multi-product flow cost and value streams were reported in Chapter 3. It was noted that although the lean based Value Stream Mapping (VSM) technique has been reported as most suitable for designing and maintaining efficient manufacturing systems capable of adding value to inputs that flow through various aspects of manufacturing processes, there were clear limitations in the areas of designing and maintaining manufacturing systems deploying multiproduct flows. Also the VSM technique was observed not to be suitable for causal impacts and dynamic analysis; lacked decomposition formalisms; unsuitable for CIM systems design and it is not extended to cost estimations. It was however observed that suitable selection of tools belonging to EM, SD and SM domains could provide complementary support to the VSM technique. How to integrate these modelling techniques, to enable their practical application in manufacturing industries at large, had not yet been provided in literature.

Based on the limitations in current best practice approaches to dynamic multiproduct manufacturing process design and analysis, especially in capturing business processes responsible for generating cost and values, attention was focussed on developing a 'Multiproduct Dynamic Cost and Value Stream Modelling' technique with capability to meet the requirements specified in Chapter 3. The research therefore aimed to develop an enhanced approach for modelling multi product flow cost and value streams dynamics, to support business analysis related to manufacturing systems design, operation, process improvement and management.

Whilst conceiving a means to derive and test the 'Multiproduct Dynamic Cost and Value Stream Modelling' technique, general research approaches, styles and methodologies were reviewed and the descriptive case study research methodology was considered to be the best research approach for this application. Section 3.6 described the basis for the selection of a descriptive case study research method. Chapters 5-9 described the four case studies conducted during the period of the research. Analysis of the performance of the modelling technique in each of these case studies is given in Section 10.3.

10.2 Analysis of research results

In Section 3.3, requirements for cost and value stream modelling were specified for MEs realizing multi product flows. Fourteen different mapping tools were assessed against these modelling requirements. Among the 14 mapping tools, VSM was considered to be a useful tool but contained limitations in analysing processes realized by MEs engaged in multiple product flows. It was proposed that VSM could be enhanced to provide needed solutions in multiproduct flow business process designs and analysis. In view of the limitations of the VSM technique, five State of the Art public domain Enterprise Modelling (EM) tools were reviewed. The objective was to establish whether any of the EM tools could suitably replace or support the VSM technique. Among the 5 EM tools reviewed, the CIMOSA modelling methodology was observed to be the most suitable tool to enhance VSM especially in its decomposition formalisms and non-determisms in model generation. However the combination of CIMOSA and VSM results in a static description of a process without adequate constructs for modelling dynamic process variables, hence six system dynamics modelling tools were further reviewed to select the most suitable tool which could support dynamic system analysis of processes captured by the integrated CIMOSA-VSM technique. Although CLMs could not be directly simulated, it was considered to be a useful first stage qualitative analysis tool and essential for developing experiments during business process designs and analysis.

When the end benefit of alternative process designs and analysis as well as meeting CIM requirements was considered, iThink and Simul8 simulation modelling were considered useful to support the modelling schemes specified. Key strengths and weaknesses of the resultant multiproduct cost and value stream modelling technique when compared with VSM, CIMOSA, CLM, iThink and Simul8 are shown in Table 19. This comparison is based on the requirements specified in Section 3.3. A scale of 1 to 5 for each of the requirements was defined and assigned to the modelling techniques to help identify coverage provided by each of them. Although the scores are subjective, they fairly represent the relative strengths and weaknesses for each of the tools because they are borne out of the author's use of each of the tools in case studies described in this Thesis.

From a study of Table 68, based on the specific requirements for multiproduct flow dynamic manufacturing systems, VSM was the least in most of the factors used in measuring the performance of the modelling techniques. This is because of its expressed limitations in the area of multiproduct flow, complex and dynamic process analysis especially for simulation and CIM applications. CLMs basically are conventionally not used for process designs and hence scored very low in various factors. CLMs are basically for qualitative decision analysis. CIMOSA modelling technique is excellent in its defined scope of process decomposition, support for CIM design and complex process analysis. Its limitations are obvious in virtual simulation applications and multiproduct flow analysis, although CIMOSA models could serve as the backbone for virtual process simulation models. iThink and Simul8 models are excellent for virtual process analysis and complex process designs but they do not have a front end tool for modelling multiple product flows and specifying cost and value constructs. More so there are no mechanisms for decomposing processes and hence when used as standalone tools, their results could be interpreted out of context. In the case of iThink models further limitations are realized when the objective is to measure discrete distinctive process variables for different products since iThink results are cumulative.

The limitations of the above tools are overcome to significant extent by using the multiproduct dynamic cost and value stream modelling technique developed through this research. Where necessary, the strengths of the existing tools were integrated, but in instances where none of the existing techniques proved worthwhile, new methods were introduced to help meet the stated requirements. This is particularly shown in the cost and value estimation process, new constructs for static modelling of cost and values, enhanced strategic business analysis and detailed operation process analysis and optimization. The weaknesses however of the new integrated modelling technique are described in Section 10.5, whilst possible areas for future research are stated in Section 10.8

Modelling techniques	**Analysis of multiproduct flows and product dynamics**	**Identification and capturing of aspects of complexities and dynamics in MEs**	**Suitability for complex manufacturing systems and process redesign**	**Reflection of causal impacts of activities on financial indicators**	**Ability to measure process cost without distortions**	**Ability to quantify value added through processes**	**Availability of suitable constructs for value and cost modelling**	**Supporting business analysis in a virtual environment**	**Capability to decompose processes for easier analysis**	**Support of CIM principles and IT systems**
VSM	***2***	***1***	***2***	***1***	***1***	***2***	***1***	***1***	***1***	***1***
CIMOSA	***2***	***2***	***3***	***1***	***1***	***1***	***1***	***1***	***5***	***3***
CLM	***1***	***4***	***1***	***4***	***1***	***2***	***1***	***1***	***1***	***1***
iThink	***2***	***4***	***2***	***4***	***1***	***2***	***2***	***3***	***1***	***3***
Simul8	***3***	***3***	***4***	***3***	***2***	***2***	***1***	***3***	***1***	***3***
Multiproduct dynamic cost and value stream Modelling technique (MDCVSM)	***4***	***4***	***4***	***4***	***4***	***5***	***3***	***5***	***5***	***4***
Key:	***1-Low*** ***5-Highest***	***Totals: VSM-13/50; CIMOSA-20/50; CLM-17/50; iThink-24/50; Simul8-25/50; MDCVSM-42/50***								

Table 68: Analysis of research results

10.3 Case study analysis

To test the applicability of the proposed modelling technique, four main case studies were conducted. The first case study was related to a Make To Order furniture manufacturing company, called Brad Furniture Ltd. The multiproduct cost and value stream modelling technique was used to model multiple product flows in Brad Furniture Ltd. This supported business process analysis in Brad Furniture Ltd. Whilst deploying the technique, new conceptual manufacturing system designs with potential to solve key industrial problems related to high inventory sizes, high process cost, low value realization, long process lead times, bad investment decisions and improper combinations of human and mechanical resources were realized. A summary of how these case study problems were addressed is shown in Table 69. Based on these problems identified in Brad Furniture Ltd, only the aspects of the modelling technique which consists of the synergistic application of VSM, CIMOSA and SM techniques were used. A new cost and value stream modelling approach was specified and applied to model values and cost generated by the business processes of Brad Furniture Ltd.

In the second case study reported in Chapter 6, aspects of the technique involving the unified application of CIMOSA and SD techniques were used to solve complex dynamic cost and value stream problems in a Make to Order composite bearing manufacturing company called ACAM Ltd. Through the application of the technique, understanding about dynamics impacting on cost and values were enhanced. Alternative ways of reducing the impact of these dynamics on cost and value generation in ACAM Ltd was specified. The company benefitted by their enriched understanding of their business processes and also their ability based on the modelling technique to manage complexities associated with their business processes. Whilst meeting the research requirements, a method of capturing process dynamics and also a means of transforming qualitative CLMs to quantitative simulation models was derived.

The technique was fully applied in the third case study involving an Engineer to Order POP Manufacturing Company in UK. In this third case study the technique was used to develop strategic business solutions to manufacturing problems arising from BOM and design errors, high inventory levels and long production lead times. Other problems addressed at the strategic level included the lack of production flow, high production cost and low value addition. The output of the results proved worthwhile.

In the final case study involving AirCon China, similar industrial based problems were addressed. A typical example is the application of the modelling technique to solve problems of cash flow and recommend alternative strategic solutions to promote healthy cash balances. Quantitative production process models were used to specify how selected business processes can be improved, organized and resourced to enhance growth in AirCon, China.

A summary of the problems identified in the case study companies and how the modelling technique was enacted to solve these problems are show in Table 69. In addition to showing how the modelling technique was used, results provided through the application of the technique and the associated limitations are also shown.

Assessment of performance of the multiproduct cost and value stream modelling technique in solving case study company problems					
Case study no	**Company name**	**Problems in case study company**	**Solution offered by technique**	**Approach used**	**Limitations**
1	Brad Furniture Ltd	1. High inventory sizes	Typical inventory reductions of 87.94%. This led to the reduction of queues at the CNC operation centre without affecting output quantities.	Experimental and controlled changes of material inflows, people resource and related mechanical resources	Other practical limitations were not investigated
		2. High inventory and process cost	Total inventory cost was reduced by 30%	Experimental changes of material inflows, people resource and related mechanical resources	Other practical limitations were not investigated
		3. Low value generation	Overall value addition of 69.87% was realized	Generation of to-be models through alternative flow of materials and use of additional mechanical resources	Practical implications need to be investigated
		4. Inadequate analysis of investment options	The introduction of a second CNC router showed reduction in overall process lead times and overall value addition of 69.87%.	Introduction of additional mechanical resource	Detailed cost-benefit analysis is required before implementation

		5. Lack of proper combinations of resources for optimal performance	Human resource utilization rose from 62.08% to 72% and	Organization of work and alternative introduction of materials	Limitations of human resources on current work patterns not investigated
		6. Long process lead times	Delays at CNC centre and leg assembly avoided	Rate of flow of product components was altered and a second CNC introduced	In real life, adjusting rate of flow of materials might have some other impacts on the business worth investigating
2	ACAM, UK Ltd	1. Lack of understanding of process dynamics on cost and value generation	Recommended alternative ways of organizing production system to annex effect of dynamics	Through the synergistic use of SD tools	Because of time, limited numbers of dynamic factors was considered
3	POP Ltd	BOM and Design errors; long production lead times, high production cost, high inventory sizes and low value generation	Key business processes requiring improvements were identified and alternative means of improving them recommended. This resulted in a to-be model of better process performance	Complete use of all modelling stages	Product classifications was quite over simplified
4	AirCon China	Delays in purchasing and production leading to serious cash flow problems	Alternative cash flow management schemes recommended. Key BPs were redesigned for better cost and value indications	Detailed CLM, iThink and MS Excel analysis. Further detailed analysis through Simul8	Research was supported by Chinese translations and vital information could be lost in the process of transformation

Table 69: Summary of application of modelling technique in case study companies

Whilst utilizing the technique to address the above problems, it was realized that capturing and verifying data was time consuming and demanding. The total cost involved in creating and developing results from the multiproduct cost and value stream model were estimated and are shown in Table 70. In all the case studies, apart from the case study involving AirCon China, the research was not extended to investigating the practical implications of implementing the ‘to-be’ models specified. It is worth noting therefore that the results derived in the Thesis could be affected during the implementation stages, although they are good indications of what could potentially be achieved. Key concerns in risk assessment, net return on mechanical resource investment were not extensively considered. In the case study involving POP Ltd and AirCon China, process classifications were simplified to limit the degree of complexity that could have emanated in modelling multiple value streams from the material flow perspective. It was generally observed that there was a constraint whenever interaction between engineering and operational processes needed to be modelled.

To provide a means of justifying economically, the viability of the modelling technique, cost estimates for the modelling efforts for the four case studies are shown in Table70. From Table 70, it can be seen that for the Engineer to Order case companies (POP Ltd and AirCon China), data collection cost was very high. This was because, these were large sized companies with many engineering functions. In relative terms, the engineer to order companies were considered more complex to model than the make to order companies. Also the reason for the cause of the high data

Cost estimation of modelling efforts

	Case study companies			
Cost componets	**Brad, UK**	**ACAM, UK**	**POP Ltd**	**AirCon China**
Data collection				
Data collection time (hrs)	40	40	220	120
Resource cost @ £100/hr	4,000.00	4,000.00	22,000.00	12,000.00
Data support time	40	40	200	240
Data support cost @ 10/hr (£2.50/hr for AirCon China)	400.00	400.00	2,000.00	*600*
Total data collection cost	*4,400.00*	*4,400.00*	*24,000.00*	*12,600.00*
EM creation				
Creation of EMs (hrs)	24	24	40	40
Resource cost @£100/hr	2,400.00	2,400.00	4,000.00	4,000.00
Verification by Manager (hrs)	24	24	24	40
Verification cost @20/hr	480.00	480.00	480.00	800.00
Final editing of EMs @£100/hr	1,600.00	1,600.00	1,600.00	1,600.00
Sub total 2: cost of EM creation	*4,480.00*	*4,480.00*	*6,080.00*	*6,400.00*
Static cost and value streams(SCVS)				
Creation of static cost and value models (hrs)	40	40	40	40
Resource cost@ £100/hr	4,000.00	4,000.00	4,000.00	4,000.00
Sub total 3: cost of SCVS	*4,000.00*	*4,000.00*	*4,000.00*	*4,000.00*

SD model creation				
Creation of SD models (hrs)	0	160	160	80
Resource cost @100/hr	-	16,000.00	16,000.00	8,000.00
Sub total 4: Cost of SD models	*-*	*16,000.00*	*16,000.00*	*8,000.00*
DES model creation				
Creation of DES models	160	0	160	160
Resource cost @100/hr	16,000.00	-	16,000.00	16,000.00
Sub total 5: Cost of DES models	*16,000.00*	*-*	*16,000.00*	*16,000.00*
Other cost				
Travels	25.00	150.00	110.00	1,560.00
Hotel	-	-	-	600.00
Food and drinks	15.00	15.00	66.00	100.00
Entertainment	-	-	-	100.00
Translations				200.00
Sub total 6: Other cost	*40.00*	*165.00*	*176.00*	*2,560.00*
Total modelling cost	**28,920.00**	**29,045.00**	**66,256.00**	**49,560.00**

Table 70: Cost estimates for modelling efforts

collection cost for the two engineer to order companies is that 5 MSI Researches were involved in taking various data from POP Ltd whilst 4 MSI Researchers were involved in data collection at AirCon China.

Data support time was highest in AirCon China because of the additional time required for translation of Chinese to English language and vice versa. An internal team to support data collection and verification of models was created in AirCon China. Data support cost was low in AirCon China because of the low labour rate used in the estimation. On the contrary, travel, hotel, food and cost for recreational activities were highest because AirCon China is located in China. The cost involved in deriving static cost and value streams were the same for all the case studies because after the creation of EMs for the case companies and also with data on cost and values already collected, the same amount of effort was required in all the case studies. This essentially was because the modelling was also concentrated on the direct value adding processes for each of the case studies. No SD models were created for Brad Furniture Ltd and hence the estimate is shown as zero. In the same way, no DES models were created for ACAM, UK and therefore zero is shown on the table. In all, the highest cost was observed in the modelling exercise related to POP

Ltd, mainly, because of the cost associated with model data collection. Although the cost estimates are subjective, they fairly represent the direct cost involved in creating a multiproduct flow cost and value stream model for the different class of companies.

To provide a means of quantifying the benefits likely to be accrued by the case study companies as a result of the application of the multiproduct cost and value streams modelling technique, the benefits likely to be generated through the implementation of the ‘to-be’ model derived through the modelling technique, was used as a measure of the potential value of the technique. Although this is an exaggerated representation of the potential benefits of the modelling technique, it is assumed that the benefits to be derived from the implementation of the ‘to-be’ models are as a result of the application of the modelling technique. Hence the percentage cost savings and value generation were estimated in monetary terms and used for the analysis. Clearly, the values specified in Table 71 are within the simulation periods for each of the different case studies.

Potential benefits to be gained through deploying recommendations derived from the modelling methodology			
Case study	**Potential benefits**	**Value estimate (£)**	
Brad, UK	39.67% potential increase in value	Total cost savings and value added in 'to-be' model	11,479.90
ACAM, UK	23% potential increase in value	Total cost savings and value to be gained in implementing recommendations	124,000.00
POP Ltd	11% value increase	Value increase	59,763.30
	About 80% theoretical cost reduction	Cost reduction	717,982.20
		Total potential savings	777,745.50
AirCon, China	15% overall increase in value addition	Approximate total savings	150,000.00

Table 71: Potential benefits of multiproduct cost and value stream models

Comparing the potential values and cost estimates for the application of the modelling technique in each of the case study companies, it is evident that it is valuable to adopt the multiproduct cost and value stream modelling technique. A more informative economic analysis would however involve comparing the cost involved in developing the models with the cost and value involved in using other methods. It is important to however indicate that these benefits have not taken into consideration actual practical implications of implementing the ideas. The value estimates purely refers to potential benefits from conceptual system designs.

Although the benefits from deploying the multiproduct cost and value streams modelling technique are clear, it was observed during the case studies that adequate training is required in enterprise modelling before companies can benefit from techniques with enterprise models as their base. It was noted that enterprise modelling semantics were not common place in all the case studies. Simple process maps and flow charts were common in the case study companies but no knowledge on enterprise modelling was observed. The author is of the view that to provide proper footing for the technique specified in this Thesis, there is the need to create awareness on the strengths of enterprise, cost and simulation engineering in Industries.

10.4 Overall learning from case studies

Various aspects of the modelling methodology were applied in the different case scenarios presented in Chapters 5-9. Reflecting on the characteristics of the companies studied and how the modelling methodology was applied to solve salient industrial problems, it became evident that specific aspects of the modelling methodology can be applied under different business scenarios. A summary of this observation is shown in Table 72.

ME properties	**Application of modelling methodology**	**Possible solutions to be achieved**
1. Uncertain market demand	Integration of CLM and iThink	Prediction of market trend and hence better business forecast
2. High inventory and long lead times	1. Static cost and value stream modelling; 2. DES modelling	1. Identification of factors leading to high inventory sizes and long lead times. 2. Redesign of business processes.
3. High production cost and low value realization	Integration of static and dynamic cost and value stream modelling	1. Better estimation of process cost and values. 2. Redesign of business processes
4. Low resource performance	DES based dynamic value stream modelling	Redesign of production system
5. Inefficient manufacturing processes	Static cost and value stream modelling	Redesign of production system

Table 72: Usage of modelling methods based on specific business scenarios

10.5 Summary evaluation

In evaluating the overall research study, the author was of the view that three bases can be used for assessing the studies. These bases are: richness of data, capabilities of proposed technique and generality of technique. In each of the case study, (Chapters 5-9), methods for capturing primary and secondary data were described. Most essentially, these data were confirmed by key knowledge holders in the companies as being true reflection of their production records. More so ‘as-is’ results generated through the application of the technique was verified and validated by the Managers of the various companies. Because the data used was fairly accurate, results and hence recommendations provided in this Thesis are capable of meeting requirements of industries.

In section 10.2, the multiproduct cost and value streams technique was compared with other proprietary modelling techniques and it was found to exhibit high potential for meeting the requirements of process engineering in dynamic multiproduct flow Manufacturing Enterprises.

The generality of the modelling technique is proven in the four different case companies in which it was applied. This shows the applicability of the modelling technique in ‘Make to Order’ and ‘Engineer to Order’ MEs. The application of the technique is yet to be conducted in other classes of MEs but it is predicted that the modelling technique will have utility in the other classes of MEs, probably with minor adjustments.

10.6 Research achievements and weaknesses

Table 73 shows the achievements and weaknesses of the research in relationship with the research objectives. From the summary of the benefits offered by the research outcome, it implies that major achievements in relation to the modelling technique solving key industrial problems have been achieved. Also comparing the modelling technique with other proprietary modelling tools, the multiproduct dynamic cost and value stream technique is most suitable for managing complexities and dynamics which impact on cost and value generation in Industries. Through the available resources and MSI company collaborating schemes, this technique was successfully tested in case study companies. Also essential knowledge addition on current best practice of business process cost and value modelling has been provided.

In addition to the weaknesses mentioned in Table 73, considering the research scope, objectives, resources and time available for a PhD study, the research is likely to have weaknesses in the following areas:

1. Costing of processes was simplified to include only direct operational cost elements. However other indirect cost elements are key in determining the actual business process cost. Unplanned and breakdown maintenance, rework, human attitudes towards work, work culture, etc are importance factors which also impact on cost
2. Tools deployed were not specifically designed for cost and value stream modelling hence many iterations and adjustments needed to be done to enable the provision of best results for the research. Thus actual design capabilities of the tools were not utilized.
3. Results provided in this Thesis are yet to be tested physically by the case study companies and there are the likelihoods that some of the models may need to be modified or their results adjusted
4. Since most MEs are dynamic, most often EMs and SMs require regular update. There is therefore the likelihood that changes have occurred in the operations of the companies as of the time when the Thesis was written. Notwithstanding the data and models created best represented the 'as-is' situation of the companies.
5. Data required for creating effective cost and value stream models from the enterprise perspective requires a lot of time and resource commitments. It is economically difficult to convince managers of companies to commit their resources to such investments. Hence process improvement in many companies is considered overheads. Therefore although the methodology is useful, there are key concerns in marketing the tool. An alternative approach which worked during the research was to use the technique as a check over results provided by existing VSM techniques.
6. The technique requires thorough understanding of many modelling tools and interfaces and therefore may be of interest only to Consultants, Researchers and Academicians. This is because in comparison with the VSM technique, VSM is simpler to construct and understand although results provided through the use of VSM are not exhaustive.
7. The research depended mostly on value indices from accounting experts in the case study companies. These value ratios were reliable but for a small scale industry where previous valuation of resources had not been done, it will be an exhaustive exercise to perform. The same applies to creating EMs of companies before cost and value stream models can be generated. The later is true but the benefit to be derived always far outweigh the cost.

Research Objectives	**Achievements**	**Assumptions**	**Weaknesses**
To specify a modelling technique suitable for capturing aspects of complexities and dynamics in MEs realizing multiple products	The research utilized the strengths of the system dynamics modelling to capture various aspects of complexities and dynamics. This was demonstrated in the three of the case studies presented in the Thesis.	It was assumed that many companies will function in similar ways as the case study companies.	Dynamics and complexities in MEs may differ largely from one ME to the other. Knowledge of modelling complexities and dynamics is required by an in-house company expert to be able to model and suggest means of controlling and managing complexities and dynamics on ongoing basis
To help specify a modelling scheme to support process design and optimization	The process decomposition formalism as well as the virtual engineering strengths in the research outcome supports complex process designs and optimizations. Through simulations, processes can be redesigned and optimized based on experimental test of different business scenarios.	Processes may be designed or optimized based on many other performance indicators such as lead time, throughput, quality, etc but it was assumed that these other performance indicators can conveniently be quantified in cost and value terms	Depending on an industry, cost and values may not be the prime focus. But the technique has not clearly shown how other performance indicators can be used for business process analysis, although it is implied in the cost and value estimations
To be able to test alternative business and process improvement scenarios	This is clearly achieved through the iThink and Simul8 simulation applications	It was assumed that all business and process improvement scenarios can be conveniently tested by either a discrete event or continuous simulation tools	Based on the assumption, research was not extended to other statistical, parametric or other mathematical modelling methods to access their potential
To estimate values and cost and use to identify 'value and non-value adding'	A method for estimating cost and values has been specified and used in	It was assumed that value indices which was used as basis for estimating values	In companies where value ratios have not been previously determined, it will

processes and use as basis to determine cost effectiveness of manufacturing processes	exemplary cases to determine value and non-value adding processes and products for economic decision making in four case companies	generated by processes were accurate and that operational cost elements were accurately identified	be a heavy task to estimate value indices for purposes of value stream analysis
To test the derived technique in a number of case companies	Test of the modelling technique was conducted in four different companies	It was assumed that data obtain from companies were current and accurate	The technique may be limited to the cases investigated and may require further improvements in different manufacturing environments
To verify and validate 'as-is' models	All 'as-is' models created were verified by key knowledge holders in the case study companies. Initial results was compared with historic data and observed patterns	It assumed that views and recommendations provided by responsible people in the case study companies best represented the real manufacturing cases	The validity of the models depend on how accurate the verification of the Knowledge holders was
Derive what-if scenarios and recommend alternative process improvement schemes in case companies	Three main change types were experimented: process changes, product change and mechanical and human resource change. These changes became the backbone for many of the recommendations made for process improvements in the case study companies.	It was assumed that the changes were not occurring at the same time	Limited numbers of changes were experimented for the sake of time. In reality many changes could occur at the same time
Outline the limitations of the developed methodology and recommend further areas of improvement	The observed limitations and areas of improvement are specified in Sections 10.5 and 10.8	Despite the observed limitations, the author is of the view that key process improvements and business process analysis especially based on cost and values can be performed using the multiproduct flow dynamic cost and value stream modelling technique	Many other limitations could assist which have not yet been identified

		specified in the Thesis	
To test the developed technique as a tool for design, organization and reengineering of business processes in MEs	Although it was only four different case studies which was conducted, the author is of the view that the technique is capable of modelling and analysing processes with the view of improving cost and values generated in other manufacturing environments	It is assumed that other MEs operating in different environments will exhibit similar behaviours which have been modelled through this research	Real differences in other MEs is yet to be tested

Table 73: Summary of research achievements and weaknesses

10.7 Contribution to knowledge

The achievements of this research relative to specified research objectives are shown in Table 73. In addition to that, key solutions provided by the modelling technique for the case study companies are shown in Table 69. When the technique was compared with current best practice to modelling cost and value streams, it was confirmed to be better than any of the currently available tools. Essential contributions to knowledge have been made in these specific areas:

1. The development of static multiproduct cost and value stream models. This consist of the introduction of new resource, cost, queues and value constructs in value stream modelling. A new definition for value and a new approach for estimating values generated by processes have been introduced.
2. The development of dynamic cost and value stream models. A contextual derivation of cost and value related system dynamics and discrete event simulation models have been introduced. A new approach for transforming qualitative CLMs to simulation models was achieved through this research.

10.8 Possible future extensions to the multiproduct flow cost and value streams modelling methodology

In view of the limitations of the modelling technique specified in Section 10.5, future research extensions related to modelling cost and value streams may be required in the area of:

- Modelling detailed cost and value elements for short term decisions
- Deriving modelling platforms which will ensure 'life updates' for process models such that operation cost and values can be estimated at short intervals

- Enhancing the concepts of conceptual and detailed process-resource design schemes referred in this thesis as ‘producer units’ and by some earlier MSI authors (Weston, Rahimifard et al. 2009). This will systematize the design of processes and ensure that analysis which determines best process-resource configurations are scientifically proven. A lead is necessary to further develop constructs for different resource types based on capabilities and competence and their cost and value indications.
- Developing a cost and value modelling technique where ‘tactical operations’ such as engineering, planning, designing, etc can be clearly integrated with operational or ‘direct value’ adding process for business analysis.
- Detailed application of modelling technique to appropriate paradigm selection for different process segments in Manufacturing Industries. Key illustrations of how lean can be implemented in specific portions of manufacturing processes are required.

In addition to the above possible extensions of the technique, further work on the selection of modelling tools can be conducted to reduce the element of subjectivity as described in Chapter 3. The different tools reviewed in Chapter 3 can be applied on specific case studies and on the basis of their observed strengths and limitations, necessary recommendations which will impact on the choice of tools can be made.

10.9 Conclusions

A methodology for modelling value streams and process cost in a Manufacturing Enterprise engaged in systems that generate multiple products meeting varying customer requirements was conceived after realizing the limitations in best practice process mapping techniques, especially the lean based value stream mapping tool. The technique took into consideration the limitations of current best practice value stream mapping technique and enhanced it with complementary strengths of state of the art enterprise, system dynamics and discrete event simulation modelling techniques. The proposed modelling technique was tested in four different case studies involving Brad Furniture Ltd, UK; ACAM Bearing Manufacturing Company, UK; POP Manufacturing Ltd, UK and AirCon Manufacturing Ltd, located in China. During the test of the applicability of the modelling technique in these case companies, it was observed that the proposed unique dynamic multiproduct cost and value stream modelling technique is capable of:

1. Modelling multi-product flows in complex manufacturing environments. This is based on proper process-based product classifications and the utilization of material flow, process logics and simulation ‘labels’ to connect various different types of product flows

2. Defining and estimating values and cost generated by business processes and using these economic indicators to specify processes which are inefficient and hence requires re-engineering. Process analysis are further conducted to generate ‘to-be’ manufacturing systems models of better cost and value indications
3. Modelling aspects of complexities and dynamics in processes in an ME such that causal and temporal effects of changes in process states can be visualized, controlled and managed to ensure that MEs remain stable within their life time
4. Conducting experiments on business ideas, scenarios and process improvement suggestions to determining best options before their implementation. This has the enabled benefit of facilitating process (re) design and optimization. The technique is strongly supported by IT systems and CIM principles and hence also applicable in advanced manufacturing environments.
5. Decomposing processes into their elemental levels such that processes can be chained to their parent processes for detailed analysis and observation of changes in processes and their impact on other processes, resources and outputs

An extension however, of the technique described in this thesis, is required to further model in detail many process cost indicators especially for life cycle cost of processes. Also it is important to indicate that results shown in this thesis only represent one instance of the production processes and there are many other instances which will need to be considered when process optimization becomes the focus. User of this technique may require knowledge in many different modelling tool applications and may therefore remain a technique in use among modelling experts until a simplified approach to modelling multiproduct flow cost and value streams is derived.

References

Aguilar-Save´n, R. S. (2004). "Business process modelling: review and framework." International Journal of Production Economics., **90**: 129-149.

Agyapong-Kodua, K., J. O. Ajaefobi, et al. (2009). "Modelling dynamic value streams in support of process design and evaluation." Int. J of Computer Integrated Manufacturing **22**(5): 411-427.

Agyapong-Kodua, K., B. Wahid, et al. (2007). Process cost modelling in Manufacturing Enterprises. 4th International Conference on Digital Enterprise Technology, Bath, United Kingdom.

Ajaefobi, J. O. (2004). "Human Systems Modelling in support of Enhanced Process Realisation." PhD Thesis, Loughborough University, UK.

Akkermans, H. A. (1995). "Developing a logistics strategy through participative business modelling." International Journal of Operations and Production Management **15**(11): 100-112.

AMICE (1993). "CIMOSA: Open System Architecture for CIM, 2nd extended and revised version, Springer-Verlag, Berlin."

Ashworth, C. M. (1988). "Structured systems analysis and design method (SSADM)." Information Software Technology **30**: 153-163.

Askin, R. (1993). Modelling and analysis of manufacturing systems, John Wiley & Sons.

Baines, T. S., D. K. Harrison, et al. (1998). "A consideration of modelling techniques that can be used to evaluate manufacturing strategies." International Journal of Advanced Manufacturing Technology **14**: 369–375.

Baker, P. (2003). "We’re all in this together." Works Management **56**: 30-33.

Barfield, J. T., C. A. Raiborn, et al. (1994). Cost Accounting; Traditions and Innovations. USA, West Publishing.

Barlow, J. (1998). From craft production to mass customisation? Customer focussed approaches to housebuilding. Proceedings of 6th Annual Conference of International Group for Lean Construction, IGLC-6, Guaruja, Brazil.

Batur, C., A. Srinivasan, et al. (1991). "Automated rule based model generation for uncertain complex dynamic systems." Proc. of the 1991 int. symp. on intelligent control: 275-279.

Bauman, C. (1968). "Fundamentals of Cost Engineering in the Chemical Industry." Reinhold, NY.

Bermus, P. and L. Nemes (1996). "A framework to define a generic enterprise reference architecture." International Journal of Computer Integrated Manufacture.

Bernus, P. and L. Nemes (1996). Enterprise integration-engineering tools for designing enterprises. Australia, Chapman & Hall.

Berztiss, A. (1996). Software methods for Business Reengineering. Springer Verlag, New York.

Bicheno, J. (2000). The Lean Toolbox. Buckingham, England, PICSIE Books.

Binder, T., A. Vox, et al. (2004). Developing system dynamics models from causal loop diagrams. 22nd International Conference of the System Dynamic Society, Oxford.

Bititci, U. S. and D. Muir (1997). "Business process definition: a bottom-up approach." International Journal of Operations & Production Management **17**: 365-374.

Boeing, C. (2000). "Lean Manufacturing [http://www.boeing.com/] (19th February)."

Braglia, M., G. Carmignani, et al. (2006). "A new value stream mapping approach for complex production systems." International Journal of Production Research **44**(18): 3929-3952.

Brimson, J. A. (1991). Activity Costing—An Activity-Based Costing Approach. New York, Wiley.

Browne, J., P. Sackett, et al. (1995). "Industrial requirements and associated research issues in the Extended Enterprise." Integrated Manufacturing Systems Engineering, Chapman & Hall, London: 13-28.

Bryan, F. (1990). Beyond the Model T: The Other Ventures of Henry Ford Wayne State Press.

Burbidge, J. L. (1991). "Production flow analysis for planning group technology." International Journal of Operations and Production Management **10**: 5-27.

Burgess, T. F. (1994). "Making the leap to agility-defining and achieving agile manufactuirng through business process redesign and business network redesign." International Journal of Operations and Production Management **15**: 23-34.

Burns, J. R. (2001). Simplified translation of CLDs into SFDs. Proceedings of the 19th Int. Conference of the System Dynamics Society, Atlanta, GA.

Burns, J. R. and O. Ulgen (2002). A component strategy for the formulation of system dynamics models. Proceedings of the 20th Int. Conference of the System Dynamics Society, Palermo, Italy.

Camarinaha-Matos, L. M. and H. Afsarmanesh (2001). "Virtual enterprise modeling and support infrastructure: applying multi-agent system approach." Lecture Notes in Artificial Intelligence (LNAI)(2086): 335–364.

Carrie, A. (1988). Simulation of Manufacturing Systems. USA, John Wiley & Sons.

Cavalieria, S. and P. Maccarrone (2004). "Parametric versus neural network models for the estimation of production costs: A case study in the automotive industry." Int. Journal of Production Economics **91**(2): 165-177.

CEN (1994). "Enterprise integration - Constructs for modelling."

CEN/ISO (19440). "Enterprise integration - Constructs for modelling."

Chan, S. L. and C. F. Choi (1997). "A conceptual and analytical framework for business process reengineering." International Journal of Production Economics **50**: 211-223.

Chatha, K. A. (2004,). "Multi-process modelling approach to complex organisation design, PhD. Thesis." Loughborough University.

Chatha, K. A. and R. Weston (2005). "Combined Enterprise & Simulation Modelling in support of Process Engineering." Int. J of Computer Integrated Manufacturing **18**(8): 652-670.

Chatha, K. A., R. H. Weston, et al. (2003). "An approach to modelling dependencies linking engineering processes." Proceedings of Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture.

Chen, C.-K. and C.-H. Tsai (2008). "Developing a process re-engineering-oriented organizational change exploratory simulation system (PROCESS)." International Journal of Production Research, **46**(16): 4463-4482.

Chen, J. C., Y. Li, et al. (2008). "From value stream mapping toward a lean/sigma continous improvement process: an industrial case study " International Journal of Production Research.

Cho, H., M. Jung, et al. (1996). "Enabling technologies of agile manufacturing and its related activities in Korea." Computers and Industrial Engineering **30**(3): 323-334.

Chopra, S. and P. Meindl (2004). Supply Chain Management, Strategy Planning and Operation, Pearson Education, New York, NY.

CITEC, M. A. T. S. (2008). Lean Manufacturing, http://www.citec.org/lean_manufacturing.html.

Cohen, L. and L. Manion (1994). Research Methods in Education. Routledge, London.

Cooper, R. and R. S. Kaplan (1992). Activity-based system: Measuring the cost of resource usage. Accounting Horizon. September**:** 1-13.

Cox, J. (1998). "Labour Theory of Value." The concise guide to Economics.

Coyle, R. (1983). "The technical elements of the system dynamics approach." European Journal of Operational Research **14**: 359-370.

Creese, R. C., M. Adithan, et al. (1992). Estimating and Costing for the Metal Manufacturing Industries. New York Marcel Dekker, Inc.

Curran, T. and G. Keller (1998). SAP R/3 Business Blue Print understanding the business process reference model, Prentice Hall, Upper Saddle River, N.J.

Davenport, T. H. (1993). Process Innovation: Reengineering work through information technology. Boston, Mass, Harvard Business School Press.

Davenport, T. H. (1998). Putting the enterprise into enterprise systems. Harvard Business Review 76(4): 121-131.

Davenport, T. H. and M. C. Beers (1995). "Managing information about processes." Journal of Management Information - System dynamics review **12**: 57-80.

DeVor, R. and J. Mills (1995). "Agile Manufacturing." American Society of Mechanical Engineers, Manufacturing Engineering Division (MED) **2**(2): 977.

DoD (1999). Joint Industry/Government Parametric Estimating Handbook, US Department of Defense.

Doumenigts, G., D. Chen, et al. (1992). GIM- a GRAI integrated methodology. A method for designing CIM systems. France, GARI/LAP, University of Bordeaux.

Drury, C. (1991). Management and Cost Accounting. London, Thomson Learning.

Dubensky, R. G. (1992). "Simultaneous automotive engineering – fact and fiction." SAE 922115.

Duggan, K. (2003). Creating mixed model value streams. USA, Productivity press.

Duverlie, P. and P. Castelain (1999). "Cost estimation during design step: Parametric methods versus case based reasoning." Journal of Advanced Manufacturing Technology **15**: 895-906.

Dwivedi, S. N., R. Sharan, et al. "Simultaneous Engineering –Why and What?" Institute of Electrical and Electronics Engineers, Computer Society: 142–148.

Earl, M. J., J. Sampler, et al. (1995). "Strategies for business process reengineering: evidence from field studies." Journal of Management Information Systems **12**: 31-56.

Feng, C. X., A. Kusiak, et al. (1996). "Cost evaluation in design with form features." Computer-Aided Design **28** (11): 879–885.

Foner, Eric, et al. (1991). The Readers Companion, Houghton-Mifflin Co.Inc.

Ford, D. and J. Sterman (1998). "Dynamic modelling of product development processes." System dynamics review **14**(1): 31-68.

Forrester, J. W. (1961). Industrial Dynamics, MIT Press, Cambridge, MA.

Gardner, E. J. and B. Derrida (1988). "Optimal storage properties of neural network models." Journal of Physics **A**(21): 271–284.

George, C. S. J. (1968). The History of Management Thought., Prentice Hall.

Goldhar, J. D. and M. Jelinek (1983). "Plan for economies of scope." Harvard Business Review, November-December.

Goldman, L., R. L. Nagel, et al. (1995). "Agile Competitors and Virtual Organizations - Strategies for Enriching the Customer."

Goldstine, H. (1972). The Computer from Pascal to Von Neumann, Princeton University Press.

Gou, H. (2000). "Petri-Net based business process modeling for virtual enterprises: Systems, Man, and Cybernetics,." IEEE International Conference **5**: 3183-3188.

Gregory, A. (2003). "Look before you leap." Manufacturing Company Solutions: 30-31.

Grover, V., K. D. Fiedler, et al. (1999). "The role of organizational and information technology antecedents in reengineering." Decision Science **30**: 749-781.

Guha, S., V. Grover, et al. (1997). "Business process change and organizational performance: exploring an antecedent model." Journal of Management of Information System **14**: 119-154.

Gunasekaran, A. (1998). "Agile manufacturing: enablers and an implementation framework." International Journal of Production Research **36**(5): 1223-1247.

Gunasekaran, A. and B. Kobu (2002). "Modelling and analysis of business process reengineering." International Journal of Production Research **40**: 2521-2546.

Gunasekaran, A. and Y. Y. Yusuf (2002). "Agile manufacturing: a taxanomy of strategic and technological imperatives." International Journal of Production Research **40**(6): 1357-1385.

Gupta, U. G. and R. O. Mittal (1996). "Quality, time, and innovation based performance measurement system for agile manufacturing." Proceedings - Annual Meeting of the Decision Sciences Institute **3**: 1511-1513.

H'mida, F., P. Martin, et al. (2006). "Cost estimation in mechanical production: The Cost Entity approach applied to integrated product engineering." Int. J. Production Economics **103**: 17–35.

Hammer, M. and J. Champy (1993). Reengineering the corporation: A manifesto for business revolution.

Hammer, M. and J. Champy (2001). Reengineering Management: A manifesto for business revolution.

Harrison, B. D. and M. D. Pratt (1993). "A methodology for reengineering businesses." Plan. Rev **21**: 6-11.

Haung, X. G., Y. S. Wong, et al. (2004). "A two stage manufacturing partner selection framework for virtual enterprise." International Journal of Computer Integrated Manufacturing **17**(4): 294–304.

Hengst, M. D. and G. J. D. Vreede (2004). "Collaborative business engineering: a decade of lessons from the field." Journal for Management of Information Systems **20**: 85-113.

Hills, P. (1992). Simultaneous engineering. Seminar on Simultaneous Engineering. Savoy, Management and Design Division, Institution of Electrical Engineers.

Hines, P. and R. Nick (1997). "The seven value stream mapping tools." International Journal of Operations and Production Management **17**(1): 46-64.

Hines, P. and D. Taylor (2000). Going Lean. Lean Enterprise Institute. Cardiff Business School, UK.

Hirano, H. (1990). 5 Pillars of the visual workplace. Portland, OR: Productivity Press.

Hitchins, D. K. (2003). Systems Engineering: A 21st Century Systems Methodology, Wiley, Chichester.

Ho, S. K. (1995). TQM An Integrated Approach. UK, Kogan Page Limited.

Homer, J. and R. Oliva (2001). "Maps and models in system dynamics: a response to Coyle." System dynamics review **17**: 347-355.

Humphreys, K. (1987). Project and Cost Engineers Handbook. New York and Basel, Marrel Dekker.

Imai, M. (1997). Gemba Kaizen: A commonsense, low-cost approach to managment. New York, McGraw-Hill.

ISEE (2007). isee systems,USA

Jang, K. J. (2003). "A model decomposition approach for a manufacturing enterprise in business process reengineering." International Journal of Computer Integrated Manufacturing **16**: 210-218.

Johnson, H. and R. Kaplan (1987). Relevance Lost – The Rise and Fall of Management Accounting. Boston, MA, , Harvard Business School Press.

Jones, D. and J. Womack (2003). Seeing the Whole. Brookline, Massachusetts, USA

Junankar, P. N. (1982). Marx's economics, Oxford:Philip Allan.

Jung, J. Y. (2002). "Manufacturing cost estimation for machined parts based on manufacturing features." Journal of Intelligent Manufacturing **13**: 227-238.

Kettinger, W. J., J. T. C. Teng, et al. (1997). "Business process change: A study of methodologies, techniques, and tools." MIS Quarterly **21**: 55-80.

Kim, C., Y.-J. Son, et al. (2008). "A virtual enterprise design method based on business process simulation." International Journal of Computer Integrated Manufacturing **21**(7): 857 — 868.

Koonce, D., R. Judd, et al. (2003). "A hierarchical cost estimation tool." Computers in Industry **50**(293-302).

Kosanke, K. (1996). "Process oriented presentation of modelling methodologies." Proceedings of the IFIP TC5 Working conference on models and methodologies for Enterprise Integration: 45-55.

Kumar, R. (1999). Research methodology: A step-by-step guide for beginners. London, SAGE Publications.

Laudon, K. C. and J. P. Laudon (2002). Management Information Systems: Organization and Technology in the Network Enterprise, Upper Saddle River NJ.

Layer, A., E. Ten Brinke, et al. (2002). "Recent and future trends in cost estimation." International Journal of Computer Integrated Manufacturing **15**(6): 499-510.

Lee, G. (2005). Strategos guide to Value Stream and Process Map. Strategos International, USA, Engineering and Management Press USA.

Lian, Y.-H. and H. Van Landeghem (2007). "Analysing the effects of Lean manufacturing using a value stream mapping-based simulation generator." International Journal of Production Research **45**(13): 3037-3058.

Liker, J. K. (1998). Becoming Lean. Portland, OR, Productivity Press.

Lu, S. C.-Y. (1991). Computer tools for Concurrent Engineering: Challenges, Requirements and Solutions. Proceedings of the Berlin Symposium on International Trends in Manufacturing, Berlin, Germany.

Lummus, R. R. and R. J. Vokurka (1999). "Defining supply chain management: a historical perspective and practical guidelines." Industrial Management & Data Systems, **99/1**: 11–17.

Lutherer, E., S. Ghroud, et al. (1994). "Modelling with CIMOSA: a case study." Proceedings of the IFIP WG5.7 Working Conference on Evaluation of Production Management Methods **B-19**: 195 - 203

Macintosh, R. (1997). "Business process re-engineering new applications for the techniques of production engineering." International Journal of Production Economics **50**: 43-49.

Marca, D. A. and C. L. McGowan (1988). SADT: Structured Analysis and Design Technique. London, Prentice Hall.

Marx, K. (1865). "Value, price and profit." www.marxists.org.

Maskell, B. (1991). Performance measurement for world class manufacturing: a model for American companies. Cambridge, Productivity Press.

McDonald, T., E. M. Aken Van, et al. (2002). "Utilising Simulation to Enhance Value Stream Mapping: A Manufacturing Case Application." International Journal of Logistics: Research and Applications **5**: 2.

McManus, H. L. and R. L. Millard (2002). Value stream analysis and mapping fpr product development. 23rd International Council of the Aeronautical Sciences, Toronto, Canada.

Meadel, L. M., D. H. Liles, et al. (1997). "Justifying strategic alliances and partnering:a prerequisite for virtual enterprising." International Journal of Management Science **25**: 29-42.

Melan, E. (1993). Process management methods for improving products and services. McGraw Hill, New York.

Melville, S. and G. Wayne (1996). Research methodology: An introduction for Science and Engineering Students. Kenwyn 7790, Juta and Co Ltd.

Meyer, U. B., S. E. Creux, et al. (2007). Process Oriented analysis
Design and optimization of Industrial Production Systems. Boca Raton, CRC Press, Taylor and Francis Group.

Minsky, M. and S. Papert (1969). An Introduction to Computational Geometry, MIT Press.

Monfared, R. P. (2000). "A Component Based Approach to Design and Construction of Change Capable Manufacturing Cell Control Systems." PhD Thesis, Loughborough University, UK.

Morecroft, J. and J. Sterman (1994). Modelling for learning. Portland, Productivity press.

Moser, J. (1997). "The origin of the Austrian School of Economics." Humane Studies Review **11/1**.

Muhlemann, A., J. Oakland, et al. (1992). Productions Operation Management. London, Pitman.

Naylor, J., N. Ben, et al. (1999). "Leagility: integrating the lean and agile manufacturing paradigms in the total supply chain." International Journal of Production Economics

Nicholas, J. M. (1998). Competitive Manufacturing Management. New York, Irwin McGraw-Hill.

Nielsen, A. (2005). "Value Stream Mapping with Lean Modeler." Visual 8 Cooperation.

Osada, T. (1991). The 5-S: Five Keys to a Total Quality Environment. Tokyo, Asian Productivity Organization.

Otswald, P. F. (1992). Engineering Cost Estimating. Englewood Cliffs, NJ, Prentice Hall.

Ou-yang, C. O. and T. S. Lin (1997). "Developing an integrated framework for feature-based early manufacturing cost estimation." International Journal of Advanced Manufacturing Technology **13**: 618-629.

Oyarbide, A. (2003). Manufacturing systems simulation using the principles of system dynamics, Cranfield University, UK. **PhD Thesis**.

Özbayrak, M., M. Akgü, et al. (2004). "Activity-based cost estimation in a push/pull advanced manufacturing system." International Journal of Production Economics., **87**: 49-65.

Pandiarajan, V. and R. Patun (1994). "Agile manufacturing initiatives at Concurrent Technologies Corporation." Industrial Engineering: 46-49.

Pandya, K. V., A. Karlsson, et al. (1997). "Towards the manufacturing enterprises of the future." International Journal of Operations and Production Management **17**: 502–521.

Parks, C. M., D. A. Koonce, et al. (1994). "Model based manufacturing integration: a paradigm for virtual manufacturing systems engineering." Computers & Industrial Engineering **27**: 357-360.

Partovi, F. Y. (1994). "Determining what to benchmark: An analytical Hierachy Process Approach." International Journal of Operations and Production Management(14(6)): 25-39.

Pavnaskar, S. J., J. K. Gershenson, et al. (2003). "Classification scheme for lean manufacturing tools." International Journal of Production Research **41**(13): 3075-3090.

Peach, T. (1993). Interpreting Ricardo. Cambridge, Cambridge Univeristy Press.

Pearl, J. (1985). Bayesian Networks: A Model of Self-Activated Memory for Evidential Reasoning. Proceedings of the 7th Conference of the Cognitive Science Society,, University of California, Irvine, CA.

Pearl, J. (2000). Causality: Models, Reasoning, and Inference, Cambridge University Press.

Peterson, J. L. (1981). Petri net theory and the modelling of systems. Englewood Cliffs, NJ, Prentice, Inc.

Pluto, D. M. and B. A. Hirshorn (2003). "Process Mapping as a Tool for Home Health Network Analysis',." Home Health Care Services Quarterly **22**(2): 1-16.

Qian, L. and D. Ben-Arieh (2008). "Parametric cost estimation based on activity-based costing: A case study for design and development of rotational parts." International Journal of Production Economics **113**(2): 805-818.

Ramsay, D. (1992). "From Marx to Misses: Post-capitalist society and the challenge of economic calculation." La Salle: Open Court.

Rand, A. (1993). "The fountain head." Ayn Rand Institute.

Randers, J. (1980). Elements of the system dynamics method. Cambridge, MA, MIT press.

Ranky, P. (1986). Computer-Integrated Manufacturing, Prentice-Hall, Englewood Cliffs, NJ.

Rashid, S., K. Agyapong-Kodua, et al. (2008). Business process value analysis using an analytical hierarchical process. 6th International Conference on Manufacturing Research, Brunel.

Ricardo, D. (1823). "Absolute value and exchange value." The works and correspondence of David Ricardo **4**(Cambridge University press, 1951).

Richardson, G. P. (1999). "Reflections for the future of system dynamics." Journal of Operational Research Society **50**: 440-449.

Roboam, M. (1993). La Me´thode GRAI. Principes, Outils, De´marche et Pratique. Toulouse, France, Teknea.

Roll, D. (2003). An introduction to 6S, Vital Enterprises, Hope, Maine 04947.

Rolstadås, A. A., Bjørn (editors) (2000). Enterprise Modelling, Improving global industrial competitiveness, Kluwer Academic Publishers.

Rother, M. and J. Shook (1996). Learning to See.

Rumelt, R. P. (1974). "Strategy, structure and Economic performance." Harvard Business School.

Russel, R. S. and B. W. Taylor (1999). Operations Management. Upper Saddle River, NJ, Prentice Hall.

Saaty, T. L. (1980). The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation, McGraw-Hill.

Salvendy, G. (1992). Handbook of Industrial Engineering. New York, Wiley.

Samid, G. (1990). Computer-organized Cost Engineering. New York and Basel.

Schal, T. (1998). Workflow management Systems for Process Organizations.

Scheer, A. W. (1992). Architecture of Integrated Information Systems, Foundation of Enterprise Modelling. Springer-Verlag.

Scholz-Reiter, B., M. Freitag, et al. (2004). "Modelling and control of production systems based on nonlinear dynamics theory." int. J. of Production Research.

Serrano, I., C. Ochoa, et al. (2008). "Evaluation of value stream mapping in manufacturing system redesign." International Journal of Production Research **46**(16): 4409-4430.

Shalliker, J., C. Rickets, et al. (2005). An Introduction to SIMUL8 (Release 12), SIMUL8 Corporation.

Shingo, S. (1992). The Shingo Prize Production Management System: Improving Process Functions. Cambridge, MA, Productivity Press.

Shtub, A. and Y. Zimerman (1993). "A neural-network-based approach for estimating the cost of assembly systems." International Journal of Production Economics., **32**(2): 189–208.

Smith, A. (1776). "An inquiry into the nature and causes of the wealth of nations."

Smith, I. and T. Boyns (2005). "Scientific management and the pursuit of control in Britain to c.1960." Accounting, Business & Financial History **15**(2): 187-216.

Sohlenius, G. (1992). "Concurrent engineering." Keynote paper, Annals of the CIRP **41/2**: 645-55.

Soliman, F. (1998). "Optimum level of process mapping and least cost business process re-engineering." International Journal of Operations and Production Management **18**: 810-816.

Son, Y. K. (1991). "A cost estimation model for advanced manufacturing systems." International Journal of Production Research **29**(3): 441-452.

Son, Y. K. and C. S. Park (1987). "Economic measure of productivity, quality, and flexibility in advanced manufacturing systems." Journal of Manufacturing Systems **6**: pp. 193–206.

Spencer, J. E. (1996). "Robotics technology and the advent of agile manufacturing systems in the footwear industry " Assembly automation **16**(10-15).

Spooner, J. T., M. Maggiore, et al. (2002). Stable Adaptive Control and Estimation for Nonlinear Systems: Neural and Fuzzy Approximator Techniques, John Wiley and Sons, NY.

Sraffa, P. and D. Maurice (1951). "The works and correspondence of David Ricardo." Cambridge University Press **1**.

Sterman, J. (2000). Business Dynamics: Systems thinking and modeling for a complex world, McGraw Hill.

Stewart, R. D. (1991). Cost Estimating. NJ, Wiley.

Stoddard, D. B. and S. L. Jarvenpaa (1995). "Business process redesign: tactics for managing radical change." Journal for Management of Information Systems **12**: 81-107.

Taylor, D. and D. Brunt (2001). Manufacturing Operations and Supply Chain Management: The Lean Approach. London, Thomson Learning.

Taylor, F. (1911). The Principles of Scientific Management.

Taylor, F. W. (2003). "Principles of Scientific Management." Scientific Management **1**(1): 235.

Tayur, S., R. Ganesher, et al. (1999). Quantitative models for supply chain management, Kluwer Academic Publishers.

Thietrart, R.-A. (2001). Doing management research: a comprehensive guide. SAGE, London.

Thong, J. Y. L., C. S. Yap, et al. (2000). "Business process reengineering in the public sector: the case of the housing development board in Singapore." Journal for Management of Information Systems **17**: 245-270.

Tu, Y. (1997). "Production planning and control in a virtual one-of-a-kind production company." Computers in Industry **34**(3): 271-283.

Vail, P. S. (1998). Computer-Integrated Manufacturing, PWS-KENT Publishing Company, Boston, MA.

Vastag, G., J. D. Kasarda, et al. (1994). "Logistical support for manufacturing agility in global markets." International Journal of Operations & Production Management Science **14**: 73-85.

Vernadat, F. B. (1996). Enterprise modelling and integration; Principles and Applications, Chapman & Hall, London.

Vernadat, F.B and G. Bermus (1999). "New developments in enterprise modelling using CIMOSA." Computers in Industry **40**(2): 99-114.

Visual8Co. (2006). Lean Modeler Software Manual. Ontario, Canada, Visual8 Simulation Solutions.

Waldner, J.-B. (1992). CIM: Principles of Computer-Integrated Manufacturing, John Wiley & Sons, New York, NY.

Walliman, N. (2001). Your research project. London, Sage Publications Ltd.

Wang, L. (1992). "Analysis and design of fuzzy systems." USC-SIPI report **206**.

Wang, Z. Y., K. P. Rajurkar, et al. (1996). "Architecture for agile manufacturing and its interface with computer integrated manufacturing." Journal of Materials Processing Technology **61**: 99-103.

Weston, A. Rahimifard, et al. (2007). Next Generation, Change Capable, Component Based Manufacturing Systems: Part 1 Dynamic Producer Unit Loughborough University, UK.

Weston, R. (1999). "A model-driven, component-based approach to reconfiguring manufacturing software systems." Int. J. of Operations and Production Management, Responsiveness in Manufacturing **19**(8): 834-855.

Weston, R. (2005). Unified Modelling of Complex Systems - to facilitate ongoing organisation design and change Loughborough University, UK.

Weston, R., A. Rahimifard, et al. (2009). "On Modelling Reusable Components of Change Capable Manufacturing Systems." Proceedings of Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture. **223**(3): 313-336.

Weston, R. H. (1999). "A model-driven, component-based approach to reconfiguring manufacturing software systems." Int. J. of Operations and Production Management, Responsiveness in Manufacturing **19**(8): 834-855.

Wetherell, M. (1996). Attitudes, Social Representations and Discursive Psychology,Identities, Groups and Social Issues. Sage Publications, London Singer.

Wiendahl, H. P. and H. Scheffczyk (1999). Simulation based analysis of complex production systems with methods of nonlinear dynamics. Institute of production systems, University of Hannover Hannover, Germany, CIRP.

Williams, T. J. (1992). The Purdue Enterprise Reference Architecture. Instrument Society of America, North Carolina.

Williams, T. J. (1998). "PERA and GERAM – Enterprise Reference architecture for Enterprise Integration."

Williams, T. J. (2002). "The Purdue Enterprise Reference Architecture." Instrument Society of America. Research Triangle Park, North Carolina, USA.

Wolstenholme, E. F. (1982). "System dynamics in perspective." Journal of Operational Research Society **33**: 547-556.

Wolstenholme, E. F. (1999). "Qualitative verses quantitative modelling: the evolving balance." Journal of Operational Research Society **50**: 422-428.

Womack, J. P., D. Jones, et al. (1990). The Machine that Changed the World: The Story of Lean Production. New York, Rawson Associates.

Womack, J. P. and D. T. Jones (2003). Lean thinking - Banish Waste and Create Wealth in Your Corporation. New York, Free press.

Wong, J. P., I. N. Imam, et al. (1992). A Totally Integrated Manufacturing Cost Estimating System (TIMCES). Economics of Advanced Manufacturing Systems. H. R. Parsaei and A. Mital. Englewood Cliffs, NJ., Prentice-Hall, .

Wu, B. (1996). Manufacturing Systems Design and Analysis: Context and Techniques. London, Chapman and Hall.

Xinyu, S. (2006). "Workflow modeling for virtual enterprise: a Petri-Net based process-view approach." Proceedings of the 10th International Conference on Computer Supported Cooperative Work in Design, IEEE.

Yester, J., J. Sun, et al. (1993). "Design and automatic tuning of fuzzy logic control for an active suspension system." Proc. of the 12th IFAC World Conference.

Yin, R. (1994). Case study research design and methods. Newbury Park, CA, Sage Publications.

Yogesh, M. (1998). "Business process redesign: Business change of mythic proportions." MIS Quarterly: 121-127.

Youssef, M. A. (1992). "Agile manufacturing: a necessary condition for competing in global markets." Industrial Engineering: 18-20.

Yusuf, Y. Y., M. S. Sarhadi, et al. (1999). "Agile Manufacturing: the drivers, concepts and attributes." International Journal of Production Economics **62**(1-2): 23-32.

Zelm, M., et al (1995). "The CIMOSA Modelling process." Computers in Industry.

Zhou, M. C. and K. Venkatesh (1999). Modeling, simulation and control of flexible manufacturing systems- A Petri Net Approach. Singapore, World Scientific Publishing Co. Pte. Ltd.