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Conceptual Design and Simulated Operation of Economies of Scope and Scale Manufacturing Enterprises

By

Zihua Cui

A Doctoral thesis
Submitted in partial fulfilment of the
Requirements for the award of

Doctor of Philosophy
of Loughborough University

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M e

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W o n d e r f u l

W o r l d ! !

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Abstract

Much of industry is seeking scope economies, but this requires more complex and flexible product realisation. Modelling technologies have potential to support the life cycle engineering of both Economies of Scope and Scale (EoSS) manufacturing systems. However when companies operate in dynamic environments it is not sufficient to model manufacturing systems in isolation. Rather a holistic modelling methodology is needed which can create structural and behavioural models of dependencies between the manufacturing systems, and the business and engineering environments in which they operate; so that a suitable balance between economies of scope and scale can be achieved. This thesis describes the conception and development of a step wised Extended Modelling Methodology (EMM) which facilitates reasoning, and related decision making, about EoSS manufacturing systems. The EMM was conceived from exploratory research in two SMEs, following which it was applied and case tested in a large manufacturing company.

Little academic attention to date has been paid to theorising about the link between 'Economies of Scope and Scale (EoSS) phenomenon' and 'manufacturing systems design'. Hence many questions about EoSS manufacturing remain unanswered, such as: (1) academic communities need to know what EoSS actually means and how state-of-the-art modelling can support qualitative and quantitative analysis of EoSS system phenomenon; and (2) industry needs to know how they can benefit from EoSS, what attended costs they might incur, and what best balance between scope and scale economies can be achieved. With these general requirements in mind the thesis reports on the conception and industrial application of the

EMM. This has: (A) developed new ideas about EoSS, which can be used to characterise EoSS phenomenon; (B) introduced a new way of visualising architectural aspects of EoSS at multiple-levels of abstraction; and (C) with reference to case studies has illustrated the use of multi-level modelling to enable predictions to be made about EoSS benefits and costs.

Key words:

Economies of scope, Economies of scale, Enterprise modelling, Simulation modelling, Enterprise Architecture, Manufacturing systems engineering, Systems integration, Conceptual Design, Simulated Operation

List of Abbreviations

ALBP: Assembly Line Balancing Problems

AMC: An aerospace company the author has collaborated with as a member of the MSI research group

AMICE: A European consortium for CIM development initiated under ESPRIT R&D programme. It was instrumental in the development of CIMOSA

A/C: Air-conditioner

BE: Balance Efficiency

BGF: a UK based privately owned furniture company (please see page 72)

BoM: 'Bill of Material'

BP: 'Business Process'

CE: Concurrent Engineering

CIMOSA: 'Computer Integrated Manufacturing Open System Architecture'

CLM: Causal Loop Modelling

CM: Cellular Manufacturing

CU: Customised products (please see page 183)

DES: Discrete Event Simulation

DL: Drop Leaf table product

DM: 'Domain'

DP: 'Domain Process'

DPD: Delayed Product Differentiation

EA: 'Enterprise Activity'

EI: Enterprise Integration

EM: Enterprise Modelling

EMM: Extended Modelling Methodology that author defined in chapter 7

EoSS: Economies of Scope and Scale (please see list of definitions)

ETO: 'Engineer to Order'

FE: 'Functional Entities'

FFMS: Focused Flexibility Manufacturing Systems

FH: Farm House table product

FMS: Flexible Manufacturing Systems

FO: 'Functional Operation'

GALBP: Generalised Assembly Line Balancing Problems

GT: Group Technology

HE: Heat exchanger

IMM: Initial Modelling Methodology that the author defined in chapter 4

IPPD: Integrated Product and Process Development

ISO: 'International Standards Organisation'

IT: Information Technology

iThink®: Proprietary dynamic simulation software by 'isee systems'

JIT: 'Just in Time'

KPI(s): Key Performance Indicator(s)

LE: Line Efficiency

LT: 'Lead Time'

NPI: New Product Introduction (please see page 57)

MA A/Cs: Mostly Assembled air-conditioners (please see page 145)

MDF: Particularly refer to 'MDF flat panel item' products (please see page 101)

ME(s): Manufacturing Enterprise(s)

MM A/Cs: Mostly Make air-conditioners (please see page 145)

MS: Metal Sheet (please see page 187)

MSI Research Institute: 'Manufacturing System Integration Research Institute' at Loughborough University, UK founded by Professor Richard Weston in early 1990s

OEM: 'Original Equipment Manufacturer'

PD: Product Dynamic (please see list of definitions)

PERA: 'Purdue Enterprise Reference Architecture'

PhD: 'Doctor of Philosophy'

PMD: Product Mix Dynamic (please see page 57)

PPC: 'Production Planning and Control'

PV: Product Variance (please see list of definitions)

QT: Queuing Time

RMS: Reconfigurable Manufacturing Systems

RPP: Reconfiguring Process Plans

SALBP: Simple Assembly Line Balancing Problems

SM: Simulation Modelling

SME: Small to Medium sized Enterprise

SP: Special products (Please see page 183)

ST: Standard products (please see page 183)

TOGAF: 'The Open Group Architecture Framework'

TQM: Total Quality Management

VD: Volume Dynamic (please see list of definitions)

WC: 'Work Centre'

WIP: Work in Process

W-T: Wood Team furniture company (please see page 93)

5S: A workplace organizing method that uses a list of five Japanese words, which translated into English, starts with letter S. The letters are 'seiri' (or sorting), 'seiton' (or straighten or set in order), 'seiso' (or sweeping or shining), 'seiketsu' (or standardizing) and 'shitsuke' (or sustaining the discipline)

List of definitions

Economies of Scope and Scale (**EoSS**) **manufacturing systems**: Panzar and Willig (1981) argued that 'economies of scope occur when the cost of multi-product production is less than the cost of producing each product individually'. This thesis develops new ideas about EoSS manufacturing systems where detailed explanation is provided in sections 4.1.2 and 7.2.5.

Enterprise Model: 'This is a consistent set of special purpose and complementary models describing the various facets of an enterprise to satisfy some purpose of some business users' (Vernadat 1996).

Model: 'A Model is a simplified representation of a system for purposes of studying the system' (Banks et al 2001). The models that have been used in this thesis are representations that describe key aspects of the organisational structure and reachable behaviours of ME systems.

Process: 'A sequence of interdependent and linked procedures which, at every stage, consume one or more resources (employee time, energy, machines, and money) to convert inputs (data, material, parts, etc.) into outputs (BusinessDictionary.com, accessed: 16/02/2011). In the research context of this thesis, a 'process' means a organised set (or chain) of activities that flows through an organization, and/or sections of that organization, that require resources for their execution.

Product Dynamics: MEs are required to operate within their specific business environment. Often that business environment gives rise to changing customers' demands. This has been viewed as inducing 'Product Dynamics' which impact on MEs in form of variable work entries to ME systems. Four types of Product Dynamics were classified by Cui & Weston (2008), namely: ***Product (family, type and feature) Variance***; ***Volume Dynamic***; ***Product Mix Dynamic*** and ***New Product Introduction***.

Product Variance (PV): is defined as the change between 'aspects of products' within a 'product family' or within a 'particular group of product families'. Aspects of PV of prime concern to this author are those that will impact upon the process and resource sub-systems.

Product Mixed Dynamics: In manufacturing systems capable of realising a family of products or more than one family of products. As customer order patterns change, typically the mix of products that must be realised in a given timeframe will change. PMD will be causally related to both PV and VD.

Simulation Model: A simulation model is a specific type of mathematical model that uses symbolic notation and mathematical equations to describe a system and its behaviours over time (Banks et al 2001).

Volume Dynamics (VD): VD is the change in production volume of any product type with respect to time. A VD will typically arise from variation over time of customer demand for a particular product type or family.

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Chapter 1 Introduction

1.1 General trends and challenges in manufacturing industry

Typically the operation of Manufacturing Enterprises (MEs) involves complicated interactions between causally related variables within and between three kinds of environment, namely a business environment, an engineering environment and a production environment. Most business environments and their related product markets give rise to changing customer demands. Dependent on the competency and capacity of any given ME it can align its 'internal' business, engineering and production systems to address some fraction of that demand. It follows that to remain competitive MEs need to conceive and develop their systems such that within suitable timeframes they can obtain and fulfil a sufficiency of contracts and orders (comprising types and quantities of products as specified by customers) so that defined strategies and acceptable profit levels can be realised. Changing customer's demands can be viewed as being a 'product dynamic' which impacts on MEs in the form of variable 'work inputs'; the specification of which is in part likely to be outside of the MEs control. Because of competitor actions and changing customer demands, even to retain a market share most MEs will need to make system changes on an ongoing basis (Goldman et al 1995, Henderson 2000)

A variety of architectural concepts are widely used to facilitate the life-cycle engineering of systems used by MEs. From the business world have come many organisational models pertaining to hierarchy, function, distribution, process, value and cost, culture, leadership styles, empowerment, people behaviours, commands and decisions, supply chains, market forces and so forth (Ducker 1969, Buchanan 1994). From the manufacturing world have come methods to realise quality products and services in Lean and Agile ways (Loe., 1998 and Mason et al., 2000). Those methods can be realised using concepts and techniques which include: total quality management, concurrent engineering, just in time manufacture, postponement, cellular manufacture, group technology and economy of scope and scale production (Weston, 2009). While architectural models generated and widely used by the IT community include: communication architectures, service architectures, many software system structures and related data structures, information and knowledge structures; component systems architectures and intelligent systems architectures (Jones and McLean

1986, Weston 1993). From the systems engineering community have come organisational models related to life-phases of programmes, projects, products, systems and system entities (Tolio et al, 2010).

By selecting and adopting one or more of these advances any given ME may be able to improve its competitiveness short and long term. But deciding which 'theory' suits a specific ME best is far from trivial thing to do. Further making the wrong decision can lead to catastrophic failure of the ME. With a view to resolving the diversity of architectural concepts from different disciplines, the Enterprise Integration and Modelling (Vernadat, 2002) (EI&M) community world-wide has developed reference architectures and methods to inform and support aspects of ME life-cycle engineering. In theory the EI&M community has also developed modelling techniques that can usefully underpin the application of many forms of (business, manufacturing, IT and Systems engineering) reference architecture (Zachman 1987, Togaf 2010. But current generation EI&M concepts and tools have yet to be viewed by industry at large as being ready, or possibly even being needed, to satisfy their current needs. Whereas simulation modelling can allow MEs to understand and predict the behaviours of manufacturing systems and can provide model users with new insights into complex system functions and how variables interact with each other (Agyapong-Kodua et.al. 2009). This can assist in supporting long-term strategic, medium term tactical and short term operational decisions with MEs. However the current use of simulation modelling in industry is normally piecemeal rather than holistic and therefore is currently limited (Rahimifard and Weston 2007),

This research and thesis is set within the above context of industry need and emerging theories and modelling but has a definitive focus on (1) better understanding economy of scope and scale phenomenon and (2) enabling enterprise managers and engineers to systematically deploy emerging architectural and behaviour modelling concepts to help them to reason about and simulate potential scope and scale economies they might achieve.

It follows that this research study considers ways of developing and using models of ME systems and of the environments that impact on them. Therefore this study concerns the modelling of complicated systems and interactions between those systems. A system has been defined as 'a collection of entities (people or machines) that act and interact together toward the accomplishment of some logical end' (Schmidt and Taylor, 1970). The states of

the system need to change over time, in order to obtain insights into relationships among those entities or to predict system performance; which in turn can lead onto system (re)design, but a model of such a system is then required (Law2007). According to Law (2007) a model of a system is defined as a representation of that system for the purpose of studying it. For most of the studies, the level of detail in the model is determined by the number of aspects that affect the problem under investigation, a model is therefore considered as a simplification of a system (Banks et. al. 2005, Law 2007). It follows that a model of a system doesn't have to capture the entire system states, nor need it include all components of the system; indeed specific issues and appropriate performance measures are important for any study.

1.2 Research problem defined

Manufacturing industry is complex and is changing continuously; therefore, many Manufacturing Enterprises (MEs) are seeking competitive advantage by realizing 'economies of scope'. This typically means that they will make varying quantities and mixes of cognate (or similar) products over significant time-frames, such that the total quantity of products realised becomes large (Viswanadham, 2000, and Willig, 1979). Figure 1.1 graphically illustrates the complexity of a manufacturing system operating within its specific business environment. As indicated this commonly requires the use of production systems that implement processes with sufficient flexibility to cater for product variety within a product group or family, and possibly within a number of product families.

Manufacturing Enterprises (MEs) have to operate within a specific business environment; which in general is subject to many dynamic factors linked to customer, supplier and competitor and/or market related change (Watkins 1997). Changing internal factors also dictate a need for MEs to demonstrate various and changing behaviours (Weston 2003). It follows that responding rapidly and cost effectively is often critical to business success and even survival.

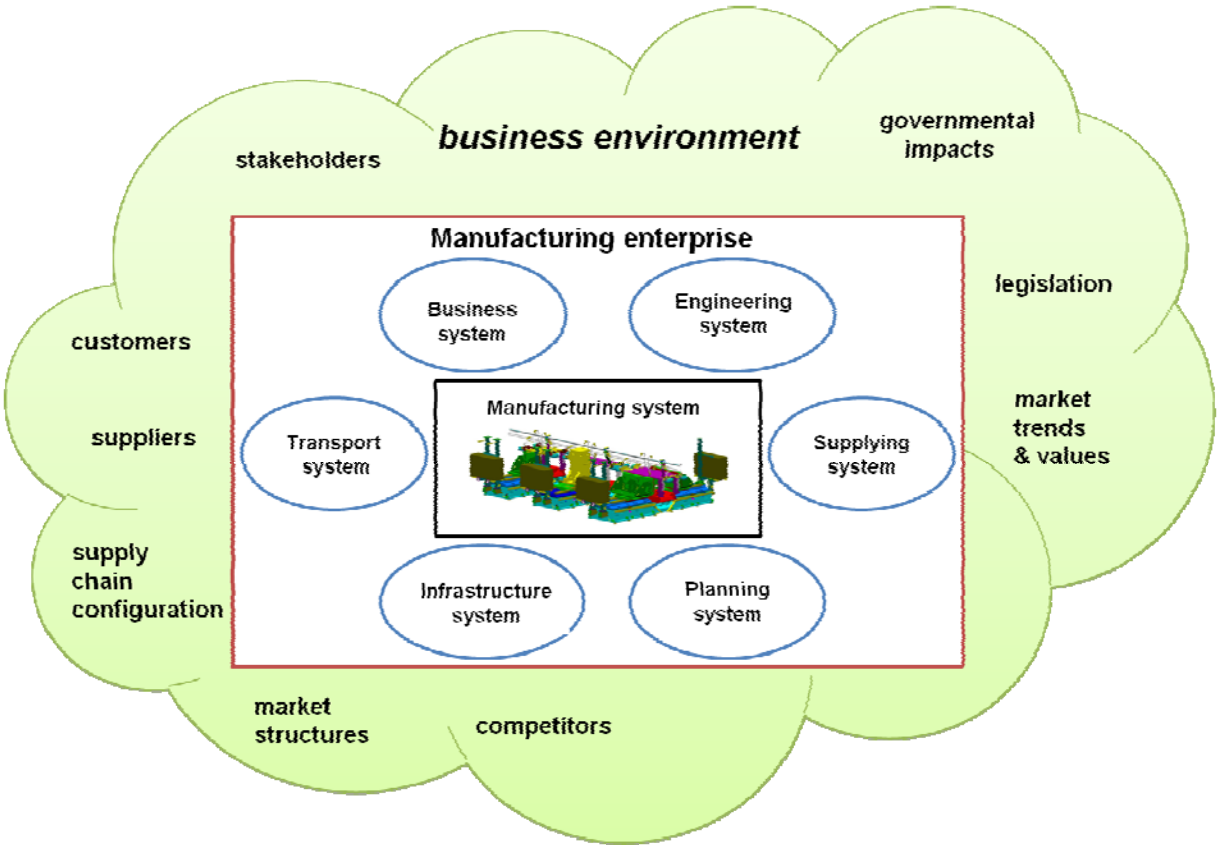


Figure 1.1 conceptualisation of working environment of manufacturing systems

Because in general the life-time of a product family will be greater than that of any single family member, then at least in theory multi-value stream production systems can be developed progressively such that effective work-organization and resource utilization leads to effective, reliable and low-cost product and service realisation.

It is reported that growing business fluidity and related increases in complexity are driven by many factors (Handy 1999) that include: increasing customer desire for product customization; driving down of unit costs, mainly because of global competition; emergence of new engineering methods, advanced technologies and materials; and innovative organizational development of MEs. Figure 1.2 is a causal loop created by the present author as a simplification of a model of change proposed by Weston (2007); this figure illustrates the causal impacts of business fluidity on production systems. These effects have driven down average product life-times and reduced effective life-times of production systems; so as to reduce opportunities for pay back on investments in production plants (which previously was often achieved by realizing economies of scale over lengthy product and production

systems life-times). Hence there has been a growing need world-wide to seek economies of scope to compensate for increasing market uncertainties (Cui and Weston, 2010)

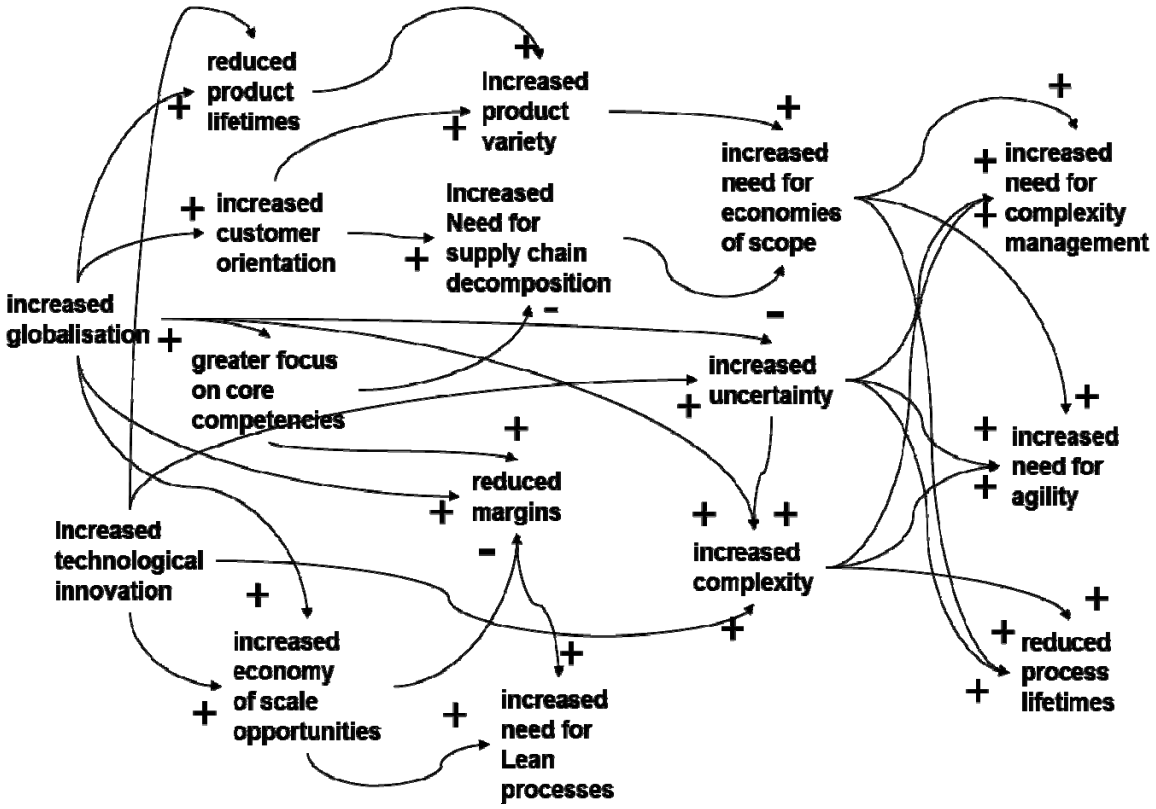


Figure 1.2 causal effects that lead to complexity of economies of scope production

But despite significant advance in areas of 'Lean' and 'Agile' manufacture, this thesis reports that; there is insufficient established 'theory' in the current literature regarding economy of scope systems; and particularly in respect of how effective design of economy of scope systems is influenced by changes associated with products (which will be referred to as ('***Product Dynamics***') through the useful lifetimes of any given economy of scope system.

1.3 Modelling in manufacturing systems engineering

The use of model driven engineering of manufacturing systems is emerging in many industries. Model driven approaches are often based on the use of manufacturing paradigms, supply chain models and process planning concepts, methods and tools. Industrial engineers,

as well as academic researchers, have developed and applied these ideas to make system improvements in terms of: reduced cycle time; reduction in cost, increased resource utilisation and capacity; and elimination of bottlenecks. Many types of modelling technique have been deployed during academic research on manufacturing systems (Rahimifard and Weston 2007) and the use of various modelling tools has become commonplace in industry (Vernadat, 2002). If the various decision makers in any manufacturing business are supported by 'fit for purpose' models that share a coherent vision and structural view of that business, in theory that business can gain a significant competitive advantage (Law 2007). However choosing the right modelling techniques and methods of integrating the use of those models remains a subject of needed further research (Weston et al 2009).

1.4 Research Scope

With a view to addressing aspects of research problems outlined in the forgoing, the scope of the author's research was determined as follows:

1) With a particular focus on investigating economies of scale and scope phenomenon, understand the essential concepts, application domains, benefits and limitations of existing manufacturing philosophies and technologies; as well as those enabling techniques designed to support manufacturing paradigm selection, application and development.

2) Understand current 'big systems[1]' and 'big systems integration[2]' theories, concepts and methods.

[1] 'Big systems': this term has been used because MEs comprise many system types and their constituent system elements; which need to function as a whole to realise the purposes of a given ME. Very commonly ME system elements can be grouped into classes of systems like 'business', 'engineering', 'production' and 'logistical' systems. Typical business system elements are sales order entry or sales order processing systems which at runtime may be realised by a combination of people and IT systems building blocks. Other examples include: CAD/CAM, EPR and purchase planning systems, which can be considered to be engineering system elements; and robots, machine tools, PLCs and other types of automation or semi-automation which can be considered to be production system elements. Much of the focus in this thesis has been on the conceptual design and simulated operation of alternative configurations of smaller system elements of various types that are used by a subject ME. Hence the term big system is used to imply the above.

[2] 'Big system integration': system elements need to interact with each other to form bigger systems which have needed competencies, capabilities and capacities to realise business, engineering and production and logistical operations performed by typical MEs. These interaction may take many and complex forms and may be realised by various means. Generally big systems integration implies that many system building blocks and/or complex systems interactions need to be handled between smaller systems (which typically will have constrained reachable states and lesser behavioural abilities).

3) Study how manufacturing system engineering can facilitate effective responses to factors that arise from within changing environments and to review gaps in the provision of model driven methods of facilitating that engineering.

4) Develop and case study test a new modelling methodology which addresses gaps in provision identified under 3), to support key aspects of 1) and 2).

Hence this thesis is structured as shown in table 1.1.

Table 1.1 thesis plan

Chapter 1	**Introduction**
Chapter 2	**Literature review**
Chapter 3	**Gap Analysis and research design**
Chapter 4	**Initial modelling methodology define**
Chapter 5	**Exploratory research –case 1**
Chapter 6	**Exploratory research –case 2**
Chapter 7	**Extended modelling methodology definition**
Chapter 8	**Implementation and testing of the extended modelling methodology: part I**
Chapter 9	**Multiple level extended modelling of AirCon hybrid EoSS systems: part II**
Chapter 10	**Reuse of modelling methodology**
Chapter 11	**Conclusion and future work**

Chapter 2 Literature Review

As discussed in Chapter 1 the prime focus of this study is on engineering manufacturing systems that are subject to a changing 'work dynamic'. Furthermore of more particular concern in this thesis is to seek improved methods of creating and re-using 'models' of:

(1) 'Manufacturing systems' that realise multiple product types and

(2) 'Ways in which multiproduct manufacturing systems can be engineered and changed'; so that in conformance with defined economic and lead-time performance criterion they realise multiple product types in partially predictable quantities and mixes.

Therefore this chapter provides a review of the literature on existing theories on manufacturing system engineering. Specific initial attention is paid to a range literature on manufacturing philosophies and technologies (and their supporting techniques) which can be viewed as being 'reference models of ways of reasoning about manufacturing systems and how such systems should be designed and changed.

Also as discussed in chapter 1, this thesis is particularly concerned with the 'fit' of any given multiproduct manufacturing system to: its host manufacturing enterprise (ME); and to the environment that its host ME needs to operate in. Therefore this review also considers the state of the art in general systems engineering as well as manufacturing systems engineering and modelling.

It follows that this thesis is concerned with the following study domains:

- The life cycle engineering of Manufacturing systems
- Manufacturing systems engineering paradigms and technologies
- Interactions between and interactions within ME systems
- Interactions between MEs and customers driven changes
- General methods and technologies that facilitate modelling in the above domains

Also noted is that the thesis scope emphasises complex systems interactions, hence suitable decomposition ideas need to be researched which can help to cut through high levels of

complexity faced when modelling. Therefore it was determined that the following areas of literature should be reviewed.

2.1 System life cycle engineering

Systems Engineering is 'an interdisciplinary engineering design and management process that involves and verifies an 'integrated life-cycle balanced set of system solutions that satisfy customers needs' (Solhenius 1992 and Mintz 1994). There are three major activities involved (as illustrated in figure 2.1):

1. Development phasing: it manages the design process and design errors copping process; which possesses three distinct levels: concept; system and element level.

2. Systems engineering process: it transfers requirements for sets of product and process descriptions and generates information for decision makers involved in various levels of development.

3. Life Cycle Integration: it ensures that customers' needs are satisfied as well as to ensure the system development is viable during its life cycle and/or life time.

Development phasing connects the design efforts and technical management and overall acquisition effort. It generates design baselines that govern each level of development; the system engineering process is the heart of systems engineering management, which provides a flexible structure for transforming requirements into specifications, baselines and architectures. Life cycle integration includes the planning of associating product and process development, as well as the multiple functional concerns into design and engineering processes. Hence this concurrent consideration of all life cycle can greatly reduce manufacturing system design costs.

As reported by in 'Systems Engineering Fundamentals' (2001): 'System engineering is a standardised, disciplined management process for the development of system solutions that provides a constant approach for system development in an environment of change and uncertainty.

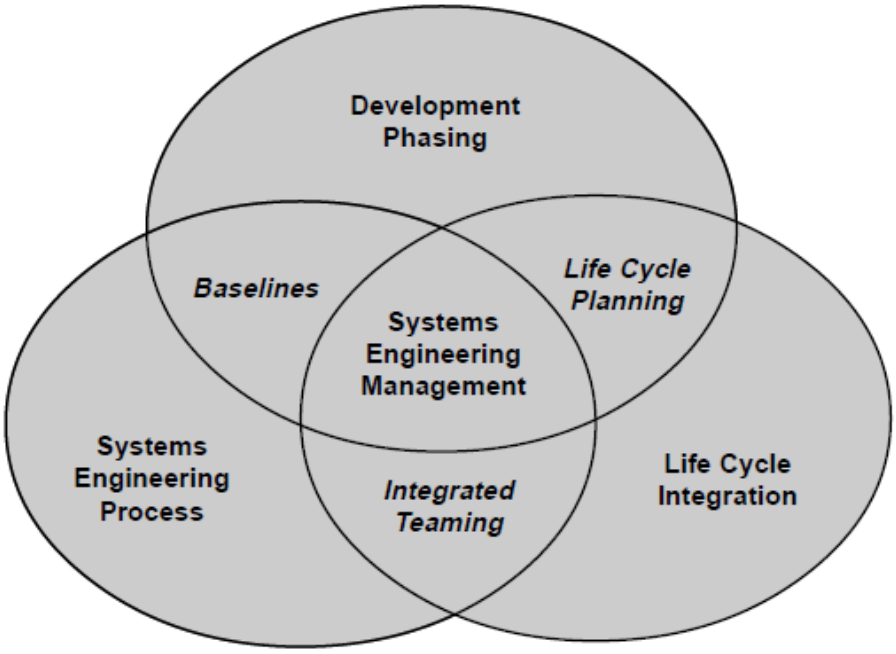


Figure 2.1 three activities of system engineering management (source from Defence Acquisition University Press, 2001)

In the author's research, the main focus is the life cycle integration aspect of system engineering, hence further literature research was conducted within this filed.

The needs of users of any manufacturing systems are emphasised since they perform the system life cycle functions which generate the requirement for designing systems. Therefore systems engineers are required to consider primary functions of life cycle integration as defined as follows (Systems Engineering Fundamentals, 2001):

- Development provides the identification and documents of transforming the customer needs to product or process solutions.

- Manufacturing/Production/Construction includes the modelling and testing the manufacturing system; ramp-up and ramp down of production of systems and establishing building blocks of the system.

- Deployment (Fielding) includes the activities necessary to 'initially deliver, transport, receive, process, assemble, install, checkout, train, operate, house, store, or field the system to achieve full operational capability'.

- Operation is the activities that involve users performing objective functions that satisfy system requirements.
- Support provides physical support for system engineering including maintenance, logistics, and management.
- Disposal includes the end-of-life system activities that meet all applicable regulations and directives.
- Training provides activities that ensure system resources are at required skill levels and maintain the knowledge possession.
- Verification includes the activities that evaluate the design matching with the product and process requirements as well as the effectiveness of system performance throughout its life time.

Life cycle engineering in manufacturing domains is also known as 'Integrated product and process development (IPPD) or Concurrent Engineering (CE); which is an engineering method that integrates process and product development as much as possible in parallel (Solhenius 1992).

Figure 2.2 illustrated the phases involved in product realisation (Keys, 1990). In respect of life cycle engineering ideas this means that product realisation includes: product planning, product and design modelling, material selection, manufacturing process design, prototype testing, implementation and logistics, production and distribution (Yan and Zhou, 2003).

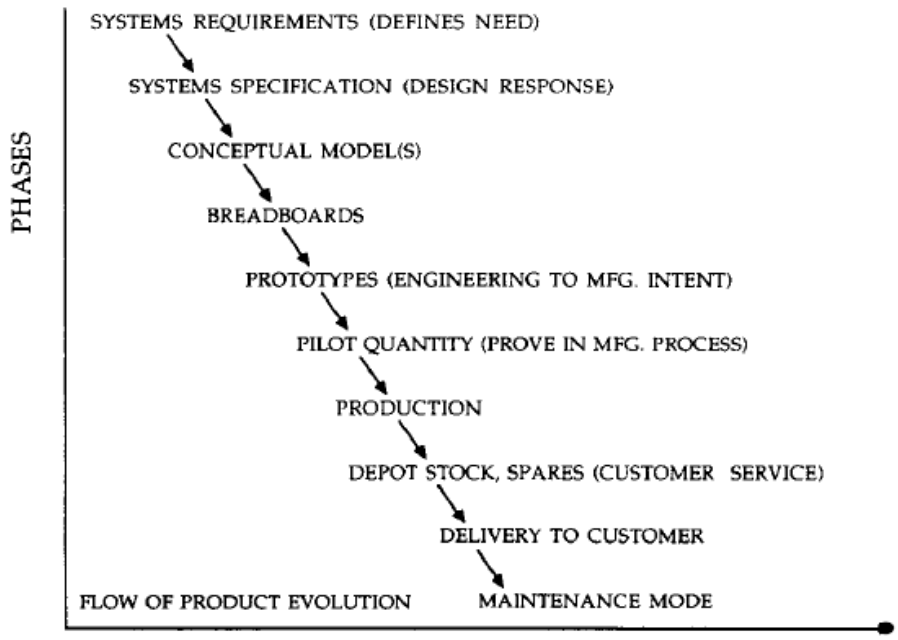


Figure 2.2 Product realisation phases (source from Keys 1990)

2.2 Literature review on Manufacturing Philosophies

This thesis section presents a comprehensive literature review on current manufacturing philosophies and technologies that shows how industrialists and academics have reasoned about ways of achieving different life cycle stages of manufacturing system engineering. As indicated previously this reasoning can be considered to constitute 'reference models' of life-cycle engineering.

2.2.1 Lean Manufacturing

Lean was defined by Womack et al (1990), as a strategic and systematic methodology aimed at driving down the cost of production development by achieving single piece production flow; giving rise to low inventory; eliminating non-productive activities; maximizing active involvement in root activities and making needed organizational and cultural change in enterprises (Vernadat, 1996).

According to Womack, lean manufacturing means manufacture without waste. Waste (Muda) (Ohno, 1995) is defined as non-value adding activities, the opposite of value, in terms of: a) *Process waste* (changeover time; planning time; evaluation time, etc) b) *Business waste* (policies; untapped potential, etc); c) *Pure waste* (materials; energy; waster, etc)

In order to reduce such waste by implementing lean, five core principles should be followed by everyone in the organization involved in the lean manufacturing：

1) *Value*: specify value as defined by customers.
2) The *value stream*: Identify all the processes required to bring a product or service to the customers.
3) *Flow*: smooth progression of products or services.
4) *Pulled*: Produce a product or service when ordered by the next in-line customer.
5) *Perfection*: Strive to perfection by removing successive layers of waste as they are uncovered.

Lean techniques tend to suit the highly efficient producer, particularly the production of high variety commodity items at a minimum cost. In the control of Lean production, issues of Efficiency and Responsiveness were emphasised by Fisher (1997) described how some businesses compete on the basis of price.

To achieve increased competitiveness, lean practitioners can adopt the use of a number of 'Lean tools' designed to minimize such waste. These tools are:

Total Quality Management, TQM (Ittner and Larcker., 1995) is a proven systematic approach used to continually improve performance in much of the enterprise.

5S/ Workplace organization, this tool is a systematic method that increases efficiency at a micro-level by keeping the workplace clean and orderly. 5S is short for sort, shine, set, standardize and sustain (Ohno, 1995).

Work Cell system, this as a technique of arranging operations and people in a work cell such as a U-shape unit, etc, rather than in a traditional straight assembly line. Among other things, the cellular concept allows for better utilization of people and improves communication.

Pokayoke and One-piece Flow are methods have emerged to support and implement Lean (Ohno., 1995, Nicholas., 2006 and Salvendy., 1992).

Just In Time (JIT) manufacturing concepts were largely superseded by Lean ideas (Levinson, 2002). Therefore in many respects JIT provided a foundation idea that was later developed

into current Lean concepts and tools. However JIT was itself a significant manufacturing philosophy with the origin of JIT having been attributed to the Toyota factory in Japan (Toyota Motor Cop., 1996). But JIT strategies have since been used in industry around the world. The philosophical base of JIT is to produce the required items, in the required quality and in the right place at the required time (Yasuhiro, 1996). Ford production systems have been considered by some authors to be early practitioners of a combination of Just-In-Time and Lean manufacturing philosophies (Yasuhiro., 1996 and Levinson., 2002). JIT philosophy can be linked to terms like lead-time and changeover.

Kanban: A 'Kanban' is an important system for signalising and synchronising the pull between interdependent units in a factory and for controlling the call-off from suppliers (Bicheno, 200). A Kanban can take the form of a card-based system, such that production is only initiated when there is a pull signal from a down-stream work station.

2.2.2 Agile Manufacturing

Adopting a 'Lean' approach to production is very distinct from that of adopting an 'Agile' one. According to Jones et al (2000), agility is the ability to rapidly reconfigure the production system (here we assume that the production system can incorporate associated supply and distribution systems) to meet new product requirements. It stresses different values to Lean: and emphasizes learning, rapid reconfiguration and change (Anderson, 2002).

Agility has a *responsiveness* dimension which makes the agile system behave quite differently from a Lean one, for example as part of a supply chain. It may typically have an inventory store (possibly of modular products) that is as close to customer needs as possible and it may well use *postponement* concepts (Loe, 1998).

Another feature of an agile system is *forecasting*: not of end user items but usually of capacity requirement. This capacity is then arranged to be as flexible as is possible (Fisher, 1997).

Agility concepts are synonymous with flexibility concepts. Harrison et al (2001) having reviewed the flexibility literature with a view to quantifying the degree to which production systems can enable change of different types introduced the following flexibility definitions,:

Change Capability is the ability of systems to enable change. This capability can be realised by one or all of the following: 'system re-composition', 'configuring system components' and 'programming system components'.

Programming: is concerned with predefining a sequence of reachable states of a 'process', 'resource system' or 'set of work structures'. For example a robot can be programmed so that it moves through predefined states that are within its working envelope. Generally programmable system components will require a well defined programming technique and well defined reachable states.

'Configuring system components': concerns the reuse of system blocks (or modules) in a wider scope system that will inherit competencies and behaviours of its building blocks. The system configured will normally possess a greater set of competencies and possible reachable states than individual components. For example a robot and feeder conveyor will have complementary functional and change capability competencies, but to realise them suitable sequences of interaction need to be defined. Generally for a system component to possess configurability competencies, also required will be an associated well defined configuration method (for attributing suitable structures that define relationships between the components of configured systems), and well defined interfaces (via which components can deliver the [functional and change capability] competences they possess). Sometimes such configuration methods and interfaces are defined as part of a so called 'component systems architecture' (Frühwirt and Blazek, 2006).

System composition: is concerned with defining a system composed of reusable and programmable components; such that the (functional and change capability) competences and reachable states possessed by the composed system suitably match the requirements of the application (or applications) in which it will be deployed. In general system composition will require a suitable systematic process, which can be enacted when required to recompose systems as application requirements change. In the case of the robot and feeder conveyor example the composed system must to able to attain the reachable states and changes in reachable states needed to perform an application specific set of tasks (Cui & Weston 2010).

Change Capability Rate: can be used as a quantitative measure of the programmability, configurability and composability of systems of components. In general this relates to the speed with which any given system change can be realised with a unit resource.

2.2.3 Pull and push systems

Definition of Push system

A push system is a type of production in which materials and part finished goods are delivered into system based on a prediction of customer demands (Orlicky, J.A. 1975). This type of systems is often operated within a MRP environment, where forecasting the quantity and the due dates of customer's demands.

Definition of Pull system

While in Pull systems, a final product will not be withdrawn until a customer order were placed (Monden, Y. 2002). In a pull system, each of the process steps can be treated as an individual isolated station; the upstream station can be viewed as a 'supplier' while the downstream station can be viewed as a 'customer'. Raw materials or parts will not be released until the downstream station 'give an order' for the upstream process to do so (O.Ghrayeb, N. Phojanamongkolkil. 2009).

Hopp and Spearman (2008) have defined the distinction between Push and Pull as 'A pull system establishes an a priori limit on the work in process, while a push system does not.' The effectiveness of Pull system is coming from the limitation of WIP rather than the pulling itself; however Pull system requires 'better' manufacturing environment e.g. unlimited availability of product than a equivalent Push system (Spearman and Zazans 1990). Therefore, in the real world, manufacturing systems are quite often operated as a hybrid of Push and Pull systems (Hopp and Spearman, 2008 and O.Ghrayeb, N. Phojanamongkolkil. 2009). In a combination of Push and Pull system, the upstream of the production system is controlled by a push type system where large among of raw materials can be delivered into the earlier production; the downstream part of the production is controlled by a pull type system, where the final product will not be released until a customer order was placed.

J. Hagel and J. S. Brown (2005) have produced a working paper to compare the performance of Push and Pull systems, table 2.1 shows a summary of characteristics comparison of Push and Pull systems from them.

Table 2.1 Push and Pull characteristics summary (J. Hagel and J. S. Brown, 2005 www.hohnhagel.com)

Push Systems	**Pull Systems**
Demand can be anticipated	Demand is highly uncertain
Top down design	Emergent design
Centralized control	Decentralized initiative
Procedural	Modular
Tightly coupled	Loosely coupled
Resource centric	People centric
Participation restricted Few participants	Participation open Many diverse participants
Efficiency focus	Innovation focus
Limited number of major re-engineering efforts	Rapid incremental innovation
Zero sum rewards Extrinsic rewards dominate	Positive sum rewards Intrinsic rewards dominate

2.2.4 Line-balancing Methods

A significant body of literature reports on line balancing and production optimisation methods and techniques. Here relevant definitions are given to underpin discussion on line balancing best practice. The Assembly line balancing problem (ALBP) as defined by Scholl (1999) concerns 'the decision problem of optimally partitioning the assembly work among the work stations'. Stevenson (2002) defined line balancing as 'the process of assigning tasks to workstations in such a way that workstations have an approximately equal time requirement. Becker and Scholl (2006), characterised line balancing problems as follows: given a set of operations and task times, and a set of precedence constraints among the tasks, and a set of workstations, it is necessary to assign each task to exactly one workstation in such a way that no precedence constraint is violated and the assignment is optimal. An extensive review of line balancing problems and some of their related concepts (including simple assembly line balancing problems (SALBP); generalised assembly line balancing problems (GALBP); cost and profit-oriented objectives; parallel stations; U-shaped line layout; and mixed-model lines) is presented by the aforementioned three sets of authors.

Meyers and Stephens (2000) stated that the purpose of assembly line balancing techniques is commonly to: equalise the work load among workstations; to identify bottlenecks; to determine the needed number of workstations and their related labour and production costs; to determine and predict the likely utilisation of resources; and to support plant layout planning. Meyers and Stephens (2000) also presented a step-by-step procedure based on the completion of assembly line balancing forms with a given example plant layout. Many authors have defined performance measures when implementing line balancing techniques. However, terms reported in the literature are far from precise and are not standardised. Generally speaking, key performance indicators (KPIs) in terms of assembly line balancing can be categorised into two aspects:

1) *Cycle time (in line)*: which normally relates to the time for each workstation to complete its task (which only sometimes is equal to the make span). In assembly lines, when batching and moving are considered, the average line cycle time is equal to the sum of a number of cycle times at each stations (including processing, setting up and moving cycle times) less any time that overlaps two or more stations.

2) *Utilisation (of workstations)*: which refers to the fraction of time a workstation is not idle, such as because of a lack of parts. Utilisation can be computed as U= Arrival rate / effective production rate.

Both aspects are important to revenue generation and production costs. Also they can help determine the throughput (or production rate) of the assembly line.

Industrialists and academic researchers have been seeking improved ways to develop and implement line balancing techniques. The following paragraphs report on some cases deployed in the field.

Driscoll and Thilakawardana (2001) report on two assessment, or quality, measures when balancing lines, namely ***line and balance efficiency (LE and BE)***. They based their measures on traditional balance solutions: balance delay and smoothness index, which they consider are sophisticated enough to represent line efficiency. LE can represent positive achievement in line utilisation while BE is used to indicate work distribution, with individual satisfaction associated with increased opportunities for greater output. A software package for assembly line balancing entitled 'A line' is also presented in their paper. Especially this software can

only be used to determine a static line balance, as it does not take into account any stochastic time based heuristic.

2.2.4 Flexible Manufacturing Systems

A Flexible Manufacturing System (FMS) is a production system that enables reaction to some types of predictable and unpredictable change (Toni and Tonchia., 1998).

According to Y. Koren (1983), there are two aspects of FMS flexibility. The first category, *machine flexibility*, covers the system's ability to be changed to produce different (previously defined) product types and its ability to change the order of operations executed on a part. The second category is called *routing flexibility*, which concerns an ability to use multiple machines to perform the same operation on a part, as well as the system's ability to absorb large-scale changes, such as changes in product volumes, average capacity or required functional capabilities (Koren et al 1999).

Claimed benefits from implemented FMSs are:

1. Productivities increase;
2. Shorter cycle time for new product introduction;
3. Reduced labor costs;
4. Quality of products can be improved;

But a general question that remains unanswered is: under what conditions will 1 to 4 be true. Evidently FMSs cannot be used cost effectively in many forms of production system, particularly where there is significant production demand change and/or where production demands are uncertain.

2.2.5 Cellular Manufacturing (CM)

CM has been viewed as an application of Group Technology (GT), where GT principles are used to design a manufacturing system comprising a number of manufacturing cells (Suresh and Kay, 1998). The first published discussion about the manufacturing cell concept has also been attributed to the Production Engineering Laboratory at the University of Trondheim in Norway. In their work a Manufacturing Cell was defined as being a cluster of dissimilar machines (and the processes they realise) that are located in close proximity and are dedicated to the manufacture of a family of parts. Each cell is responsible for the manufacture of a specific part family. Within such a cellular manufacturing scheme, parts with similar attributions are grouped using group technology principles (Brandon, 1996).

A prime aim of CM is to reduce: (a) Setup Times (by using part-family tooling and scheduling); (b) manufacturing cycle times (by reducing setups, movement times, wait times and using small transfer batches); so that consequently (c) Work-In-Process (WIP) inventory can be lower (Colin et al, 1995). From a research of the literature (Angra et al., 2008) operational benefits claimed for cellular manufacturing include:

The manufacturing processes can be better balanced in terms of operation times so that;

1. Productivities can be increased via reorganization and tidying up of work flows; reducing work items movements and waiting time and reducing the WIP inventories.

2. Over production can be eliminated.

However a number of problems of Cellular Manufacturing have been observed (Angra et al., 2008, Suresh., 1998 and Brandon, 1996):

(i) The costs of set-up and stoppage can be increased significantly;

(ii) The requirement for a given machine or other resource might be the same for different cells, which leads to duplicate investment and reduced machine utilisation.

Once again any potential user of CM is left with an unanswered question, namely: for what types of production and range of production demand will the use of CM provide operational and commercial benefits.

2.2.6 Group Technology (GT)

GT is a manufacturing philosophy which advocates simplification and standardization of similar entities which include (parts, assemblies, process plans, tools and instructions). The underlying idea of GT is to take advantage of similarities that exist among items to increase effectiveness during production (Angra et al., 2008). In order to reduce complexity and achieve economies of scale, similar entities are grouped to realise benefits of batch manufacturing (Apple, 1977). Grouping allows similar, recurring activities to be conducted more efficiently, like part family scheduling. Here a *part family* is all parts in a family that require similar treatment and handling methods (Pierre de lit and Alain Delchambre 2003). Efficiencies are achieved by processing the parts together (Colin et al., 1995), so that productivity can be increased by reducing set-up times, realising benefits of part family scheduling, achieving improved process control and by using standardised process plans (Apple 1977)..

An approach to part family grouping can be implemented via techniques such as: production flow analysis (Burbidge, 1991, and Burbidge., 1970) and cluster analysis (Waghodekar, and Sahu, 1984). Burdige (1991) stated that PFA is a technique which can help to identify GT groups and their associated product families by analysing information about different process routes needed to realize components. This information includes: operations needed to make each part and the machines to be used for each operation. These techniques help identify families of machines and parts by a progressive analysis of the information contained within route sheets.

Unlike FMS, GT is a philosophy rather than a solution, but like FMS and CM, the potential user cannot readily quantify operational, engineering and business benefits that can be gained by using one entity grouping, rather than another.

2.2.6 Reconfigurable Manufacturing Systems (RMS)

RMS is a relatively new manufacturing approach which is considered to be cost-effective and responsive. This is because the machines in RMS are designed with an adjustable structure to enable the system to be scalable in response to market demands. RMS also allows system adjustability to meet the needs of new products introduction (Koren, 1999 and Landers, et al 2001).

The definition of RMS is attributed to Y. Koren (1999), who explained that any RMS is designed at the outset for rapid change in structure, as well as in hardware and software components. By adopting an RMS design philosophy it becomes possible to quickly adjust production capacity and functionality within a part family in response to sudden changes in the market or in regulatory requirements. RMS principles seek to combine the high throughput of Dedicated Manufacturing Lines with the flexibility of Flexible Manufacturing Systems (Koren 1983 and 1999). This is achieved by (1) optimising the design of a manufacturing system so that it specifically suits a given variation in production demand over some time period and (2) enabling the manufacturing system to be redesigned (and hence re-optimised) when significant change in production demand occurs, while also enabling the elements of the redesigned production system to be reconfigured and reprogrammed accordingly.

From the study of RMS, it is evident that there are some outstanding advantages which can benefit industry:

- The adjustability of RMS machines allows flexibility not only in producing the variance of parts, but also the reconfiguration of the system itself.
- The customized flexibility of RMS can lead to faster throughput and higher production rate.

Once again however, potential industrial users of RMS cannot readily quantify the benefits of adopting RMS principles in any specific production system with a given range of production scenarios.

2.2.7 Mass customisation

Mass customisation combines mass production and customisation, which means manufacturers develop, produce products that meets specific customers requirement in a low cost and timely fashion (Jiao et al 2007, Tseng and Jiao 2001, Westbrook and Williamson, 1993 and Ross, 1996). Customer purchasing decisions are based on a set of complicated interacting factors. To be able to stay within the competitive environment of low cost, high quality and quick delivery, manufacturing enterprises must personalise products to meet

customer needs and stimulate market demand, this is what mass customisation offers. Mass customization can provide advantages of high-volume production while at the same time satisfying individual customer needs (Jiao 2007, Tseng and Jiao 2001).

Mass customisation is reported to be beneficial of (Lampel and Mintzberg., 1996 and Kotha, 1995).

- Quick response to changing market preference;
- Timely delivery;
- Wider range product variety for customers;
- Low cost production

2.2.8 Evolving families and Reconfiguring Process Plans

Within the current changeable manufacturing environment, final products often require changes and a higher level of customisation. ElMaraghy (2007) proposed a method of 'Evolving Parts/Products Families'. Two distinctive ways in which companies evolve their designs were observed, namely 'chronological' and 'functional'. Also observed was that with many new parts/products emergent, the old design of a process plant is likely to be influenced significantly.

The term 'Product Family' has been discussed and defined by a number of authors with reference to alternative manufacturing contexts. According to Fan and Liu (1999) a product family is a group of products based on a specific design concept or a standard product. Laakko and Mantyla (1994) explained that products within a product family share the same core technology and a common manufacturing resource; as they can be processed via similar process routes and manufacturing operations. Products within a family are normally aimed at the same market segment (Meyer and Lopez 1995; Meyer and Utterback 1993).

Thus an approach to 'Reconfiguring Process Plans' (RPP was introduced to cope with the challenges raised by 'Evolving Parts/Products Families' (Azab and ElMaraghy, 2007a and 2007b).

Terkaj et al (2009a) observed a need to support production system design with Focused Flexibility Manufacturing Systems (FFMSs) to define the extent to which production systems should be flexible in a specific application. FFMS architectures were developed to provide a cost effective way of specifying the dedicated flexibly requirements of manufacturing systems that can outperform traditional FMS and RMS approaches (Tolio et al 2010, W. Terkaj et al, 2009b).

Another related manufacturing strategy is 'Delayed Product Differentiation' (DPD) which is designed to postpone processing activities that make the difference between products (He et al., 1998 and Xuehong et al, 2003). With this strategy in mind, ElMaraghy (2009) proposed the application of cluster theory to 'Reconfigure Process Plans' (RPP) with the aim of realising a DPD environment

2.2.9 Economies of scale and scope

The importance of achieving economies of scale and economies of scope has been discussed primarily by researchers within 'Economics' and 'Business' schools. There is consensus agreement that economies of scale can be generated when a manufacturing system is used to realise a single product type in large quantities; while economies of scope can be generated through the production of two or more product types using a common manufacturing system.

Willig (1979) observed that 'with the presence of economies of scope, the joint production of two goods by one enterprise is less costly than the sum of the costs of two specialty productions'. Therefore this early definition considered delivered economies from a product-oriented point of view. In 1980, Teece (1980) argued that it is essential for multi product enterprises to gain business advantage by realising economies of scope. Panzar and Willig (1981) developed a similar argument, stating that 'economies of scope occur when for all outputs and the cost of multi-product production is less than the cost of producing each product individually'. Like Teece, therefore these authors stressed the importance of delivered economies from an enterprise-oriented point of view. The 1981 publication of

Panzar & Willig also pointed out that economies of scope can occur when some input is shared by two or more product lines without complete congestion' (Panzar and Willig, 1981). The studies of Panzar and Willig provided baseline definitions and useful insights into economies of scope outcomes. Within multi-product manufacturing environments, they also emphasised the importance of understanding technological competency requirements and benefits that may be gain from adopting marginal pricing policies.

In 1998, J. Clark (1988) sought to further classify economy of scale and scope outcomes by arguing the following:

(1) There are two outcomes of economies of scale, namely:

1.1) 'Product specific economies of scale', where economies arise for a particular product from increasing the quantity of production of that product;

1.2) 'Overall (namely enterprise level) economies of scale', where enterprise economies arise over time, because a greater increase in value generation is achieved than the corresponding increase in total cost of production.

Clark also developed a similar argument in respect of economies of scope outcomes, stating that:

2.1) Product–specific economies of scope that occur when the production efficiency is enhanced by adding one or more products to a given product mix;

2.2) Global (or enterprise wide) economies of scope, that occur when the total cost of joint production of a given product mix is less than the sum of the costs when those products are realised individually.

The reader can deduce that the previous literature on economy of scale and scope outcomes is based primarily in the early 1980's and being founded in economic and business schools is naturally focussed on likely cost conditions which can arise (from a product or enterprise perspective) when realising scale and/or scope economies. But to date relatively little literature has characterised economy of scope and scale phenomenon: such that any given enterprise can determine how best it can organise itself to achieve potential economy of scope and scale outcomes.

2.3 Enabling technologies

In this section of the literature study, the author has reviewed a range of enabling techniques that can be used to support systems integration and the design and engineering of manufacturing paradigms.

2.3.1 Enterprise Integration and Enterprise Modelling

Significant advancement in IT, data and communication technologies has brought dramatic changes to the manufacturing world. Many of the foundation ideas and applications in manufacturing systems of IT and communication concepts emerged in the early 1980s under that banner computer integrated manufacturing (CIM). Claimed aims of CIM are to integrate complex manufacturing activities; such as in ways that facilitate communication and interaction within MEs based on the use of IT solution techniques like computer networking and database systems engineering (Vernadat, 1996, AMICE, 1993, Ranky, 1986 and Waldner, 1992). Consequently on these developments MEs can now distribute and integrate their operations giving them to access growing and changing market demands worldwide (AMICE, 1993). 'Enterprise Integration' is concerned with the coordination of operations performed by enterprise elements in order to achieve the fulfilment of the enterprise mission. In general this requires: use of process & enterprise modelling techniques (to help specify and implement application architectures) and the use of computational infrastructures (Womack, 1991 and Viswanadham 2000).

Vernadat (2002) has defined the Enterprise Integration (EI) as follows: 'It concerns breaking down organisational barriers to improve synergy within the enterprise so that business goals are achieved in a more productive and efficient way'.

Various existing literature has illustrated that MEs can be usefully described as an integrated network of dependent processes. Common processes (sets of activities carried out by human and technical resources or supporting IT systems) that are utilized within MEs have been classified in various ways (Rahimifard and Weston, 2006). Two such classifications of ME processes are shown in Figure 2.3.

The modelling technique known as Enterprise modelling (EM) is reported as being 'the art of externalising enterprise knowledge which adds value to the enterprise or needs to be shared' (Vernadat 2002 and 2006).

A number of Enterprise Modelling (EM) architectures and methodologies have been proposed to enable enterprise modelling and engineering (Vernadat, 2002). These EM techniques enable enhanced understandings about ME processes to be gained to facilitate key aspects of process oriented organization design and change. Some of the best known and comprehensive EM methodologies includes CIMOSA (AMICE, 1993) (Computer Integrated Manufacturing Open System Architecture); ISO work on the GERAM Enterprise Modelling framework (ISO 1990); GRAI/GIM – a methodology to analyse and conceptually design manufacturing systems (Doumeingts, et al 1992); PERA – The Purdue Enterprise Reference Architecture (Williams, 1992) and the Architecture for Integrated Information Systems (ARIS) (Scheer, 1992) etc.

Also commonly quoted public domain Enterprise Frameworks that are closely related to EM architectures include the Zachman Framework (Zachman 1987) and TOGAF (TOGAF 2010).

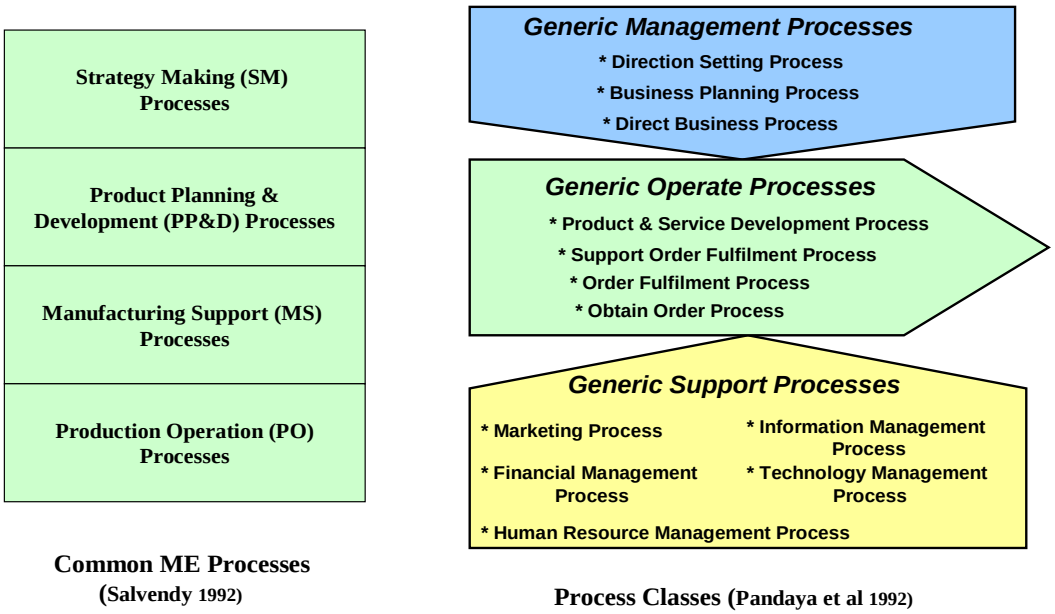


Figure 2.3 Common processes classification (Salvendy 1992, Pandaya 1997 & Weston et. al. 2007)

2.3.2 CIMOSA Enterprise Modelling

According to Vernadat (1996), CIMOSA provides a comprehensive architectural framework for helping companies to organize the system changes they make so that improved performance can lead to competitive advantage in terms of price, quality and delivery time. CIMOSA promotes the descriptive modelling of enterprise operations. The CIMOSA modelling framework (illustrated in figure 2.4) is widely also known as the CIMOSA Cube, as this has three orthogonal axes, which correspond to:

1. *The derivation principle*, which concerns three successive levels of Enterprise Modelling: (1) model enterprises: requirements definition model; (2) design specification model and (3) implementation description.

2. *The instantiation principle*, which is based on three generic layers: namely generic, partial and particular.

3. *The generation principle*, which states that manufacturing enterprises need to be modelled from at least four basic complementary aspects: organization view; resource view; information view and function view.

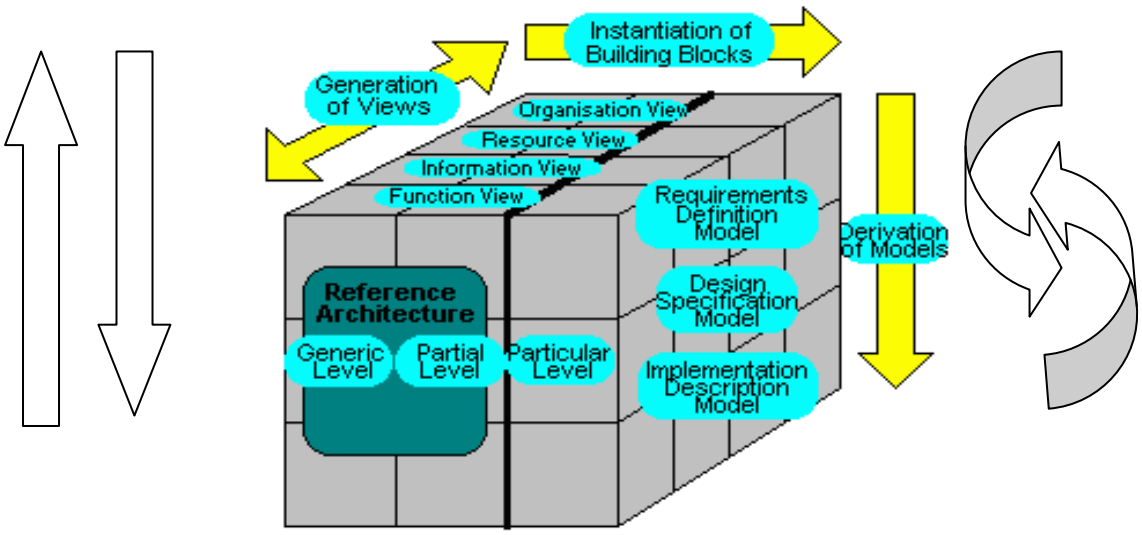


Figure 2.4 CIMOSA modelling framework (CIMOSA cube) (Source from http://cimosa.cnt.pl)

When creating a CIMOSA model of any ME, during requirements definitions four kinds of modelling template can be populated with specific case data about the ME being modelled. These four types of modelling template are: Context diagrams; Interaction diagrams; Structure diagrams; and Activity diagrams. Within those diagrams CIMOSA requires the use

of well defined modelling concepts, such as Domain Processes (DPs) which are top level processes, which are considered to comprise lower level Business Processes (BPs) and Enterprise Activities (EAs). Having defined the requirements of any ME (as a network of DPs and their constituent BPs and EAs) the enterprise modeller can use further CIMOSA defined modelling constructs to link ME requirements to various candidate resource system (or solution) designs. To do this the modeller needs to decompose the required EAs of any subject ME using two low level modelling concepts, namely: a) Functional Operations (FOs) and b) Functional Entities (FEs). FEs are elemental building blocks of candidate resource systems; some form of which will be need to be assigned to an EA (or grouping of EAs) to realise FOs so that the required behaviours of ME processes can be achieved. In this way FEs can be linked to functional competencies and capabilities possess by people, machines and IT systems; such that the design of alternative MEs systems can be systemised and visually modelled (Ajaefobi and Weston 2009). Generally therefore CIMOSA enforces a hierarchical structure as a means of coping with high levels of complexity, such that specific process elements (or process requirements) of concern to the modeller can be well defined with respect to the specific ME context in which they must operate. Examples of CIMOSA constructs are shown in figure 2.5.

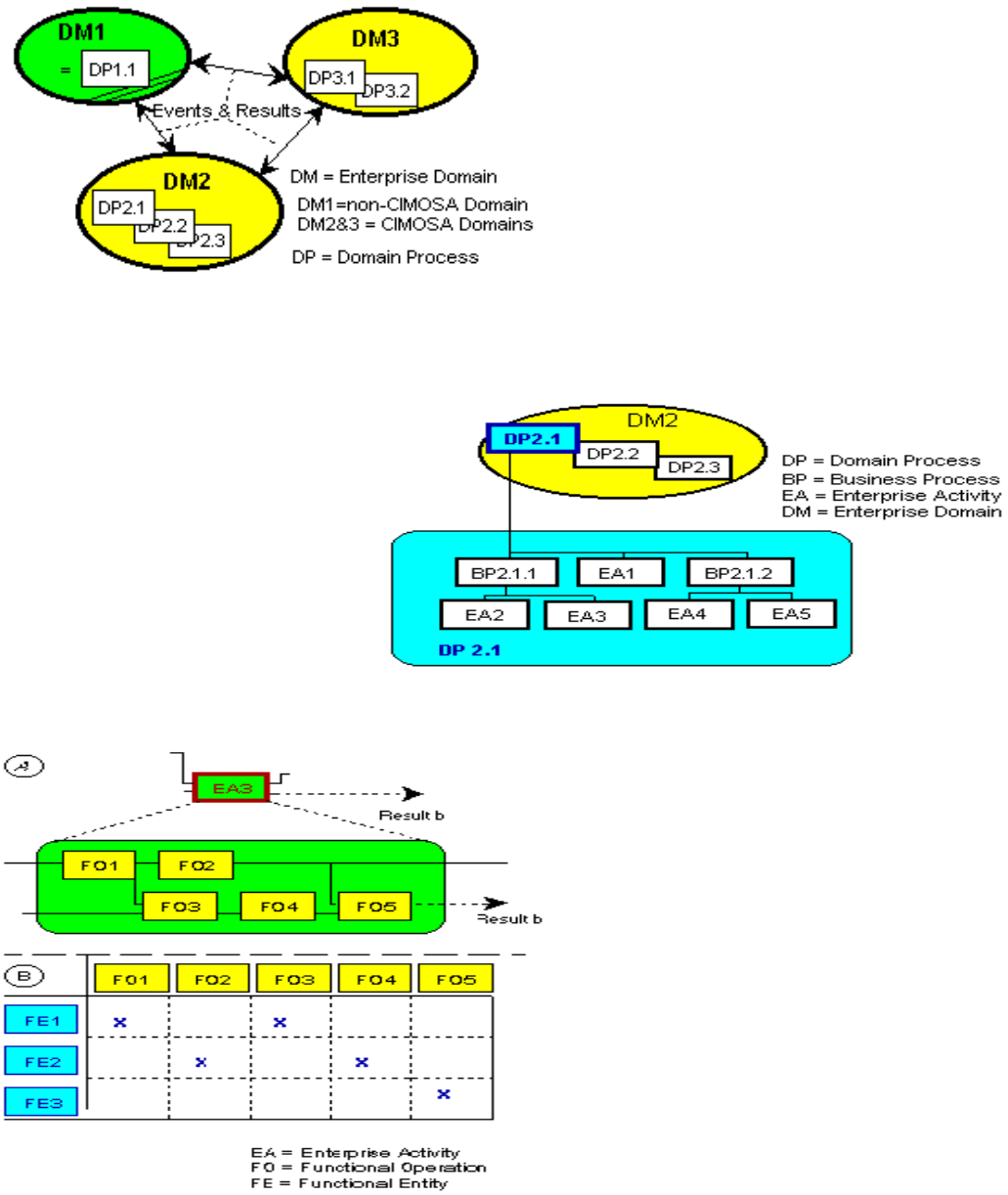


Figure 2.5 CIMOSA modelling architecture (Source from http://cimosa.cnt.pl)

Using EM techniques like CIMOSA can facilitate process benchmarking, standardization and model reuse in support of the lifecycle engineering of human and technical resource systems. However to maintain the scalability of CIMOSA models, CIMOSA requirements modelling diagrams do not model time based behaviours; in the sense that they do not encode sufficient information about specific instances of material and products flows such that changes in their states during process runtime (or operation) can be captured. Therefore like other EM techniques, the use of CIMOSA modelling techniques does not lead to the capture of EMs that facilitate quantitative analysis and futures prediction about subject MEs. Thus CIMOSA

cannot be used to determine what process and activity instantiations and specializations will be required over time and what and how resources need to be re-configured over time (Weston et al, 2006).

As discussed section 2.3.6, by contrast simulation modelling technologies can be used to facilitate process re-design and ME change specification. The simulation of process behaviours can lead to an analysis and predictions about operating events, such as the build up of queues, stochastic events and breakdowns or absences of resources.

2.3.3 Zachman framework

In the late 1980's John Zachman an IBM researcher proposed the now popularly used Zachman framework. This is an analytic tool for conceptualising and organising the architecture of descriptive representations within an enterprise (Zachman., 1987 and Sowa and Zachman, 1992). Zachman primarily used the term 'architecture' in the field of Enterprise Engineering and Enterprise modelling; this was because he pointed out that an enterprise does not have a single architecture but usually has a significant number of documents representing different aspects and different life phases of the enterprise concerned (Zachman, 1987). An application of the Zachman framework within enterprises can provide significant benefit when managing systems engineering aspects of the enterprise (Bernus and Nemes, 1996). Figure 2.6 shows an overview of the Zachman enterprise framework (Zachman, 1987).

Abstractions (Columns) →

Perspectives (Rows) ↕

The Zachman Framework	DATA *What (Things)*	FUNCTION *How (Process)*	NETWORK *Where (Location)*	PEOPLE *Who (People)*	TIME *When (Time)*	MOTIVATION *Why (Motivation)*
SCOPE (Contextual) *Planner*	List of things important to the business *Entity = Class of business thing*	List of processes the business performs *Function = Class of business process*	List of Locations in which the business operates *Note = Major business location*	List of Organizations Important to the Business *People = Major organizations*	List of Events Significant to the Business *Time = Major business event*	List of Business Goals/Strategies *Ends/Means = Major bus. goal/Critical success factor*
BUSINESS MODEL (Conceptual) *Owner*	Semantic Model *Ent = Business entity* *Rein = Business relationship*	Business Process Model *Proc = Business process* *I/O = Business resources*	Business Logistics System *Node = Business location* *Link = Business linkage*	Work Flow Model *People = Organization unit* *Work = Work product*	Master Schedule *Time = Business event* *Cycle = Business cycle*	Business Plan *End = Business objective* *Means = Business strategy*
SYSTEM MODEL (Logical) *Designer*	Logical Data Model *Ent = Data entity* *Rein = Data relationship*	Application Architecture *Proc = Application function* *I/O = User views*	Distributed System Architecture *Node = I/S function (Processor, Storage, etc.)* *Link = Line characteristics*	Human Interface Architecture *People = Role* *Work = Deliverable*	Processing Structure *Time = System event* *Cycle = Processing cycle*	Business Rule Model *End = Structural assertion* *Means = Action assertion*
TECHNOLOGY MODEL (Physical) *Builder*	Physical Data Model *Ent = Segment/Table, etc.* *Rein = Pointer/Key*	System Design *Proc = Computer function* *I/O = Data elements/ sets*	Technology Architecture *Node = Hardware/ System software* *Link = Line specifications*	Presentation Architecture *People = User* *Work = Screen format*	Control Structure *Time = Execute* *Cycle = Component cycle*	Rule Design *End = Condition* *Means = Action*
DETAILED REPRESENTATIONS (Out-of-Context) *Sub-Contractor*	Data Definition *Ent = Filed* *Rein = Address*	Program *Proc = Language statement* *I/O = Control block*	Network Architecture *Node = Addresses* *Link = Protocols*	Security Architecture *People = Identity* *Work = Job*	Timing Definition *Time = Interrupt* *Cycle = Machine cycle*	Rule Specification *End = Sub-condition* *Means = Step*
FUNCTIONING ENTERPRISE	Actual Business Data	Actual Application Code	Actual Physical Networks	Actual Business Organization	Acutal Business Schedule	Actual Business Strategy

Figure 2.6 Zachman Enterprise Architecture Framework (source Zachman, J.A., 1987)

'The framework for Enterprise Architecture is a two dimensional classification scheme for descriptive representations of an Enterprise' (Zachman, J.A., 1987). The first vertical column of the framework classifies users of model types described by cells in the framework and the perspective they have on the architecture of an enterprise; while in the remaining columns classify model types that can usefully describe and enterprise (Sowa and Zachman, 1992).

The perspectives and their prime users are:

1. 'SCOPE' the planner's perspective; contextual
2. 'BUSINESS MODEL' is the owner's view; conceptual
3. 'SYSTEM MODEL' is the designer's perspective; logical
4. 'TECHNOLOGY MODEL' is the builder's perspective; physical
5. 'DETAILED REPRESENTATION' represents the sub-contractor's view

6. ‘FUNCTIONING ENTERPRISE’ describes the actual elements of an enterprise;

It is important to state that normally the primary end purpose of using the Zachman framework is to create a large scale IT system. Therefore the model user classes identified by Figure 2.6 align best with user groups typically involved with IT projects. Additionally for that reason the example model types recommended by Zachman relate most readily to large scale IT systems development.

The ‘abstractions’ starting from the left of Figure 2.6 describe:

1. The data: what is made of?
2. The function: how does it work?
3. The network: where are the elements’ locations?
4. The people: who does it?
5. The time: when does it happen?
6. The motivation: why does it happen?

The purpose of using such a framework is focus thinking on a selected perspective without losing sight of the holistic ‘big picture’.

A set of advantages of applying Zachman Framework is summarised as follow (Frankel et al, 2003):

- Easy to understand and use;
- It addresses the entire perspectives of an enterprise;
- Can facilitate ideas and data sharing between different users within an enterprise;
- Can be used for planning, and positioning alternatives;
- It enables working with high level abstractions down to details;
- It can be used to support the use of other methodologies or tools

2.3.4 Causal Loop Modelling

Causal loop dynamic modelling (CLM) belongs to a group of tools which are used to represent and analyse support system dynamics. System dynamics is an approach used to understand the behaviours of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of an entire system (Hnberman, 1994). The foundations of Systems Dynamics in the late 1950s have been attributed to Jay W. Forrester of the MIT Sloan School of Management, following the establishment of the MIT System Dynamics Group (Forester, 1962). An illustration of a CLM is shown in figure 2.7.

For nearly half a century now, Causal Loop diagrams (CLDs) have been used in standard system dynamics practice for purposes connected with simulation modelling. Today they are mostly used prior to simulation analysis, to depict the basic causal mechanisms hypothesized which are believed to underlie some reference mode of behaviour over time, that is, for articulation of a dynamic hypothesis of the system as endogenous consequences of the feedback structure (Senge et al, 1994). CLMs can also usefully form a connection between structure and decisions that generate system behaviour. CLDs have also started to be used for purposes not necessarily related to model building, namely, for detailed system description and for stand-alone policy analysis (Sterman, 2000).

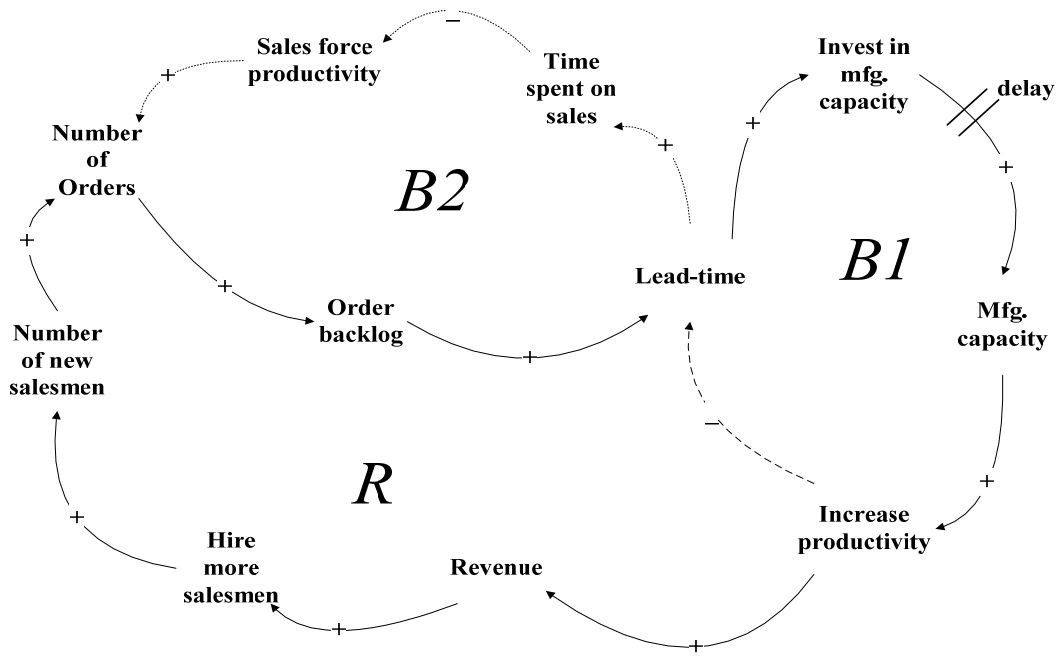


Figure 2.7 Example of CLM of Sales model in MGI Company (Weston R.H., 2006)

Regenerating loop ⟶

Balancing loop - - - - - - - - - - ▸

According to the causal loop of MGI, we can realize that the reason why MGI is losing market share despite the fact that sales are growing, is that in a responsive mode the company triggers the adding of manufacturing capacity by the occurrence of a set lead-time.

As the order backlog rises the lead-time will grow. In turn this will lead to the following behavioural phenomenon:

- The needed increase in manufacturing productivity is achieved too late.
- The time salespersons spend on winning new orders increases, because unsatisfied customers will order less meaning that sales productivity will reduce.

If the market is expanding rapidly, MGI will lose market share unless competitors behave equally badly. Because (investment in people and machine) manufacturing capacity will likely take a significant period of time these bad behaviours will occur unless MGI become proactive; e.g. by adopting a policy of predicting when new capacity is needed.

The forgoing example shows how CLDs can facilitate qualitative thinking about a complex causes and effects which result in difficult to understand behaviours, that are commonplace in our every day world.

2.3.5 Traditional simulation optimisation

Traditional optimisation methods have been centred on mathematical formulations that heavily reply on assumptions and simplifications upon which those formulations are based. Industry and academia has widely reported however that 'real world' manufacturing environments are often too complex for practically applicable OR methods to be deployed (April et al, 2006). Many authors argue that an integration of optimisation and simulation ideas is essential for evaluating different configuration of stochastic systems. An emergent combining these two technologies has been developed over the last two decades. The resultant major advances made in simulation optimisation are categorised as follows (Fu et al 2000):

1) *Stochastic approximation algorithms*, which are based on the use of Gradient-based procedures and Random search algorithms. The gradient-based approach tries to mimic its real system counterpart to achieve deterministic optimisation (ref Fu, Glover and April). However Gradient-based approaches are only applicable for continuous variable cases. This is distinct from random search algorithms which are designed to handle discrete input variables (Swisher et al 2001).

2) *Mathematical programming based approaches*, such as the sample path method (SP). SP optimisation is also known as a stochastic counterpart as it is initially based on many simulations, then tries to optimise resulting estimates (Rubinstein and Shapiro 1993).

3) *Statistical search techniques*, such as the sequential response surface methodology (RSM). This method is aimed at obtaining an approximate functional relationship between relevant input variables and an output objective function (April et al 2006).

4) *Evolutionary algorithms and metaheuristics*. Methods such as genetic algorithms, tabu search, scatter search all use metaheuristics, in which combinatorial optimisation is used based on evolution strategies (April et al 2006). They are methods that particularly support complex optimisation problems, as they guide other procedures to enable them to overcome the trap of focussing on local optimality (Fu et al 2005).

An integration of optimisation and simulation has become crucial for most commercial vendors of DES software. Most of them now include some types of optimisation routine. In terms of DES software implementation, metaheuristics approaches have been applied successfully. Especially the tabu search and scatter search have proven successful at the core of simulation optimisation software that is now widely used (Fu et al 2005). Those approaches are based on viewing any simulation model as a function evaluator. In this context Law and Kelton (1991) stated that a simulation model can be thought of as a mechanism that turns input parameters into output performance measures.

2.3.6 Simulation Modelling

Having studied enterprise modelling it was observed that this is a static modelling technique. But in order to understand complex ME system's behaviours, the author deduced that it was necessary for her to understand and use simulation modelling.

Banks et al (2001) defined that 'a model is a representation of a system for purpose of studying the system'. There are two types of model have been classified: mathematical and physical. Simulation model is a specific type of mathematical model that uses symbolic notation and mathematical equations to describe a system (Banks et al 2001).

Simulation models can therefore be classified as follows (Law and Kelton 2000, Banks 2001):

- *Static model*: represent a system at a particular point in time
- *Dynamic model*: represent a system as it evolves over a period
- *Deterministic model*: where a model has a unique set of outputs that are generated by a set of 'specified' inputs.
- *Stochastic model*: stochastically modelled systems are like most queuing and inventory models.
- *Continuous model*: model of a subject system status changes over a continuously specified time frame.
- *Discrete-event simulation model*: modelling state variable changes in a system instantaneously at discrete points in time.

Both continuous and discrete-event simulation have been popularly applied in modelling manufacturing systems, hence further review of these two techniques follows.

2.3.6.1 Continuous simulation

Continuous simulation concerns the rate of changes of state of variables in a subject system over a continuous period; hence it requires that observations be collected non-stop at every point in time (Law and Kelton, 1991, Elizandro and Taha 2008).

Continuous simulation models are often used to capture manners of queuing or inventory systems, one example of a continuous system given by Banks (Banks et al 2001) is that of the head of water behind the dam. For example, Figure 2.8 shows the possible movement of the water level when water is drawn from dam for flood control and electricity generation.

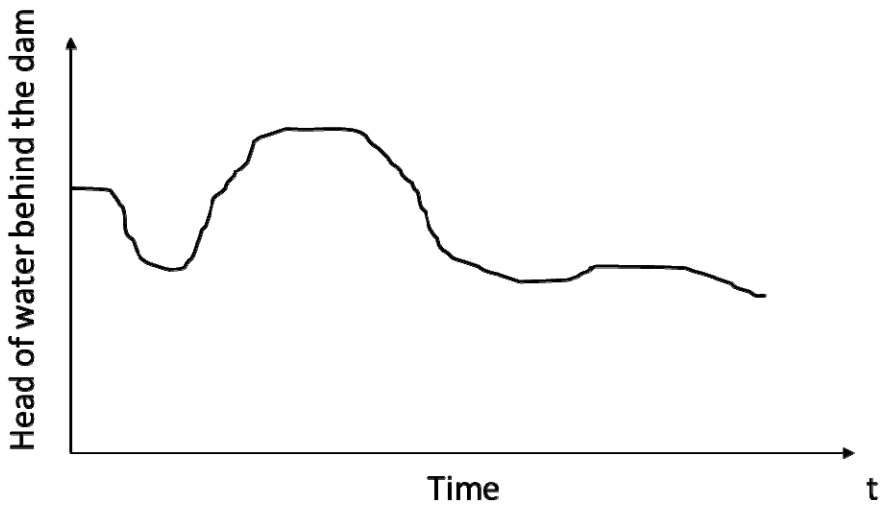


Figure 2.8 Continuous system state variables (Banks et al, 2001)

A number of commercial tools have been developed for building continuous simulation models. They include: ithink (ISEE, 2007); SIMULINK (1994) and Dymola (2005).

2.3.6.2 Discrete event simulation

If it is sufficient to model system changes at only a discrete set points of time, discrete event simulation (DES) can prove most effective (Banks et al, 2001). These points in time are when instants of events occur that change the state of the system. Typical examples of a discrete-event system model are the model of patients arriving at a hospital. Figure 2.9 illustrates that the number of patients arriving over time might typically be random.

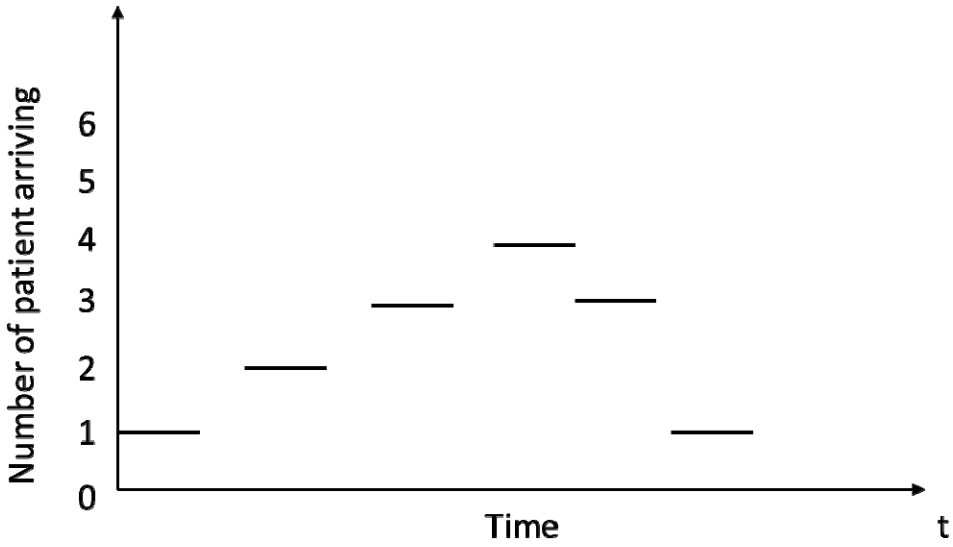


Figure 2.9 Discrete event system state variables (Banks et al, 2001)

As the research field of the author is about modelling manufacturing systems which are essentially discrete-event systems where typically orders arrive and are processed and delivered at discrete points in time, in the rest of this thesis simulation modelling is focussed on discrete-event simulation; and the use of the term simulation will imply DES.

Steps in simulation study:

Much literature on simulation has discussed approaches to implementing simulation modelling and analysis. From this literature it can be observed that a number of issues need to be taken into consideration when modelling a system. For instance system randomness, data collection, project management, validation and statistical analysis are commonly all key concerns (Law 2007). Hence a step-wise approach should be followed when conducting any simulation study (Law 2007, Banks et al 2001); such as:

1. Formulate the problem and plan the study
2. Collect data and define a model
3. Verify assumptions and document them
4. Construct a computer program and verify that it works

5. Make pilot runs
6. Verify the programmed model
7. Undertake an experimental design
8. Make production runs
9. Analyse the results
10. Document and implement the results

It is reported that simulation modelling can support ME design and change in a number of ways including: a) understanding dynamic behaviours within different process phases during product life times; b) identifying possible solutions for ME change; c) visualizing predictions about the future during planning (Rahimifard and Weston 2006).

A number of commercial discrete-event simulation tools have been developed and being used in industries nowadays. A discrete event simulation computer based tool namely 'Simul8' will be utilized in this project, which can support the foregoing modelling purpose within industrial case study environments. In recent decades simulation modelling has became a significant tool that has been adopted for business process re-engineering and continuous improvement to make possible prediction about business activities (Rabelo et al, 2003 and Avni, 1999). A simulation model is a computer executable and dynamic tool that allows the capturing of temporal behaviours of a subject process through time (Banks et al, 1996). Numeric estimated data for certain characteristics of the process can be gathered and fed into computer-based simulations. It has noted in the literature review that simulation is a combination of science and art (Avni, 1999, Mujtaba, 1994 and Law, 2007).

Simul8 deploys windows graphics that is simple and easy to use. Important functional elements of Simul8 are: Work entry point, Work centre, Queue and Work exit point, Work items and Resources. A screen shot illustration of a simple production flow usinf Simu8 is shown in figure 2.10.

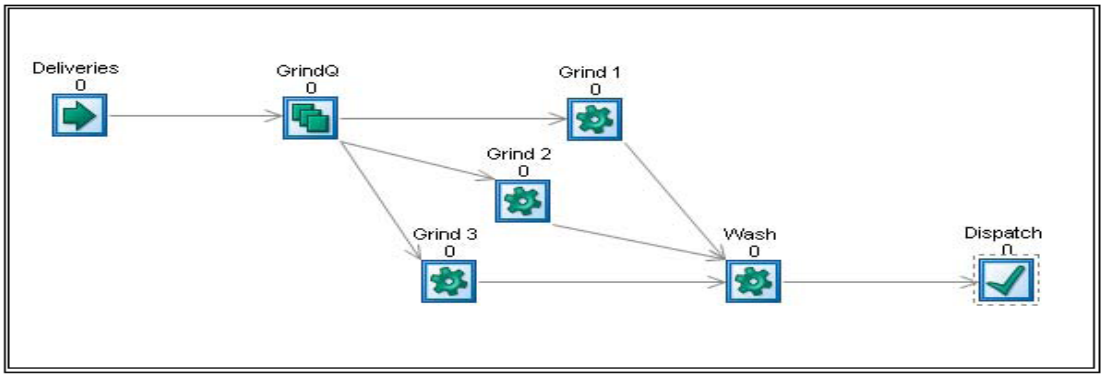


Figure 2.10 Simulation model of simple production flow (source from Simul8 2000)

As shown in figure 2.10, the graphical model is created using objects and elements on the screen, and it allows animation on the screen which has several 'plug-ins' (Simul8, 2000).

Further observation made (Law, 2007, Hlupic and Bosilj-Vuksic , 2004) are that Simulation modelling can be useful for:

- Designing and analysing manufacturing systems
- Designing hardware and software requirements for information systems
- Designing the operation of transport systems as well as service organisations
- Supply chain management

A re-engineered business process can be proposed and refined based on the data which is generated and presented by the modelling. The effect of this is commonly created by some 'what-if' scenario which can 'prototype' a 'To-Be' model. In this way possible improvements to a process can be validated via simulation results and presented and agreed with managers and end-users (Hlupic and Bosilj-Vuksic, 2004).

2.3.7 Relative Strengths & Weaknesses of 'State of the Art' Modelling Technologies

Figure 2.11 contrasts and compares strengths and weaknesses of EM, SM & CLM methods & techniques. It explains that EM's are suited best to describing a 'big (process oriented) picture' of the context of EM's and how that maps into a decomposed set of activity flows (or processes). EMs are models of relatively enduring (hence stable) entities and entity

relationships in ME's, and can usefully cover process, resource, information & organisation views of ME's. Normally EM's are not computer executable.

Enterprise modelling	Causal loop modelling	Simulation modelling
❖ Graphically represents the 'big picture' structure of an ME ❖ Has decomposition & re-integration formalisms ❖ Has extensive set of modelling constructs ❖ Enables multi-perspective model creation at various abstraction levels ❖ Enables 'redesign' of the structure of MEs and help visualise structural aspects of MEs ❖ Supports 'requirements modelling' & 'conceptual design' life phases of ME's ❖ Supports 'generic', 'semi-generic' & 'particular' model building & re-use	❖ Graphically represents causal dependencies between system variables ❖ Can clearly demonstrated causal relationships between departmental units within an ME ❖ Only qualitatively support identification & reasoning about potential control variables & controlled variables ❖ Stereo-typical configurations of positive and negative loop can be identified to categorise system types ❖ causal reasoning can facilitate structural and parameter design of simulation models	❖ Computer executes dynamic models to replicate, analyse & quantitatively predict system behaviours & performances ❖ Process oriented simulation tool to test user's assumptions ❖ Bundles together 'process', 'resource' & 'work flow' aspects of modelled systems, hence models are not naturally scalable ❖ Can only cope with fairly simple models, [i.e. abstract models &/or models of limited scope] ❖ Number of simulation techniques available [e.g. numerical integration & discrete event simulation]

Figure 2.11 Synergistic features of EM, SM & CLM methods & techniques (Rahimifard and Weston 2007)

In this respect SM's complement EM's; because SM's are computer executable. But to computer execute relevant product dynamics SMs are needed so that modelled systems become 'work loaded' and hence build up queues and utilize resources as objects (work units) pass through the process, giving rise to changing states until they reach their end state and pass out of the process. Normally SM's will therefore rapidly become complex, as the scale of any simulated real system grows. It follows that to model ME's in their entirely then many SM's will be required and that they should share a common structural heritage; this is where a parent EM can be used to enable the building of multiple units of 'process-resource system couple' (Weston et al 2009).

CLM's can support both high level (abstract) and low level (detailed) thinking about causal effects as parameters of complex systems (such as MEs) change their values. It follows that CLM's can help reason about the use of potential control parameters (or variables) and potential controlled variables of a system. It follows that CLM's provide a powerful tool which can be used to analyze complex system dynamics. However the support given is qualitative and is not directly computer executable. That said CLM's can support the design

of SM's and experiments using SM's. In fact CLM's can provide a direct front end to numerical integrator simulation tools (Agyapong-Kodua et al 2009).

2.3.8 Simulation modelling in production systems life cycle engineering

DES technology has been widely used in academia and in industry to model manufacturing systems and this had been claimed to have lead to remarkable achievements with respect to the design and analysis of specific production systems (Taha, 1997 and Elizandro and Taha 2009). Indeed a study of the literature has shown that simulation has been used in support of different phases in the life cycle engineering of production systems. Wiendahl (1991) stated that 'during structure planning, rough cut planning and fine planning stages production systems engineering, simulation has been used as an effective tool ; while in the realisation and operation stages, simulation can play an important role for production planning and control and for supervision'. In other words, with different levels of granularity of modelling simulation has played an important role through much of production system the life cycle. Figure 2.12 shows conceptually how simulation models can be used and how much detail is needed to be input into the models during different life phases of manufacturing systems engineering.

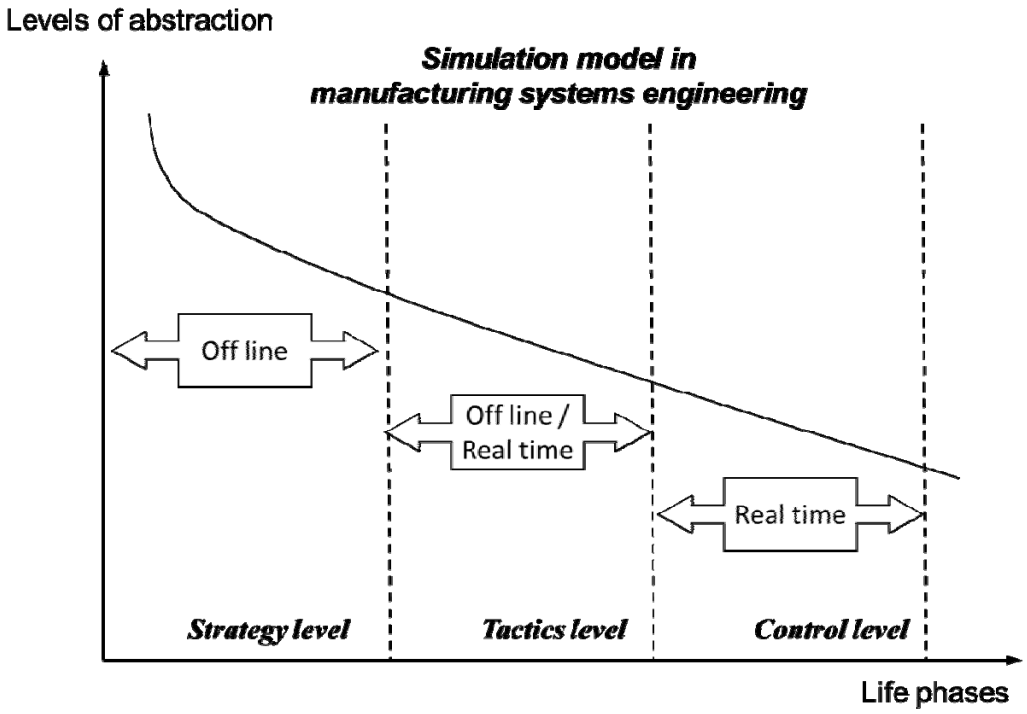


Figure 2.12 Simulation modelling in life cycle systems engineering

Simulation allows us to predicatively observe various performance characteristics of production systems and this provides various types of user with new insights into complex systems behaviours and how variables interact with each other to impact on these behaviours (Elizandro and Taha 2009). McNally and Heavey (2002) described the emerging niche of simulation in manufacturing as providing additional analytical support for: long-term strategic decisions and for real time decision makers.

2.3.9 Production planning and control

Understandings gained about how to smooth (or balance) work flows among workstations comprising an assembly line, and indeed a complete supply chain, can usefully support the planning of production. The hierarchical framework for production planning and scheduling (PPS) shown in figure 2.13 has been widely accepted and used by the manufacturing world. This categorizes planning activities into three levels namely: the ***strategy level*** (long term), the ***tactics level*** (intermediate term) and the ***control level*** (short term) (Hopp and Spearman, 2003). These three levels of PPS can map the work load of a factory onto its capacity with respect to different time scales (Vancza, Kis and Kovacs 2004). This is because top level planning sets the goals associated with resources and temporal constraints for production. Scheduling, which can be at either or both at a middle and low level of planning, is responsible for realising the plans with their related resource assignments and process sequences.

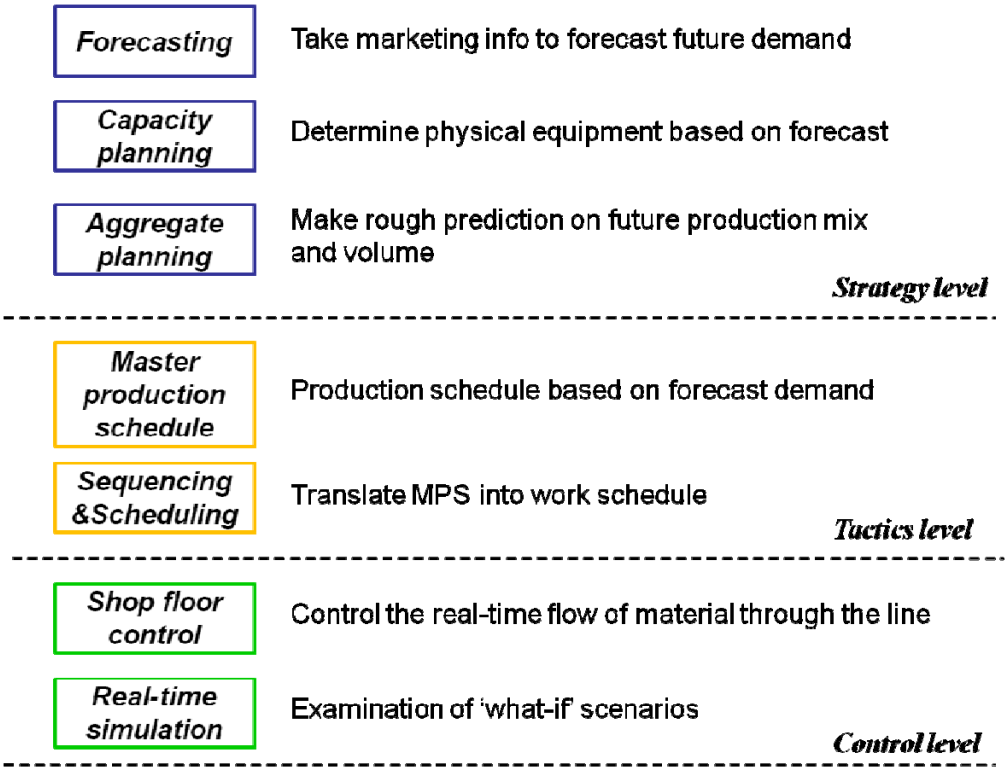


Figure 2.13 hierarchical production planning and control (PPC) framework

With reference to the literature reviewed in this Chapter, the next Chapter considers gaps in the state of the art modelling provision available to support the life cycle engineering of production systems; and more particularly multi-product realising systems.

Chapter 3 Gap analysis and research design

This chapter analyses the literature reviewed in the last chapter and observes a gap in both industrial and academic approaches to the modelling and engineering multi-product manufacturing systems. It then proposes a set of research objectives for this study and in outline designs the remainder of the author's research study.

3.2 Gap analysis

The author's primary research assumption is that in MEs producing multiple product types there is a need to establish an effective balance point between Lean and Agile. RMS provides a means of implementing some aspects of such a balance, while GT facilitates thinking about ways of moving towards such a balance. But neither of these or indeed other currently available paradigms provides a systematic way of specifying, analysing and quantifying 'what that balance point should be'.

Competitive advantage can often be gained if manufacturing systems are designed so that they can continue to fit the changing environment in which they must operate (Wiendahl et al, 2007). It follows that competitive advantage can be gained if Enterprise Engineers (including designers, developers and planners of MEs and their constituent manufacturing systems) can readily deploy suitable large scale systems engineering philosophies, methodologies and implementation technologies so as to support their decision-making and action-taking in timely and effective ways (ElMaraghy, 2007) . However as discussed in this thesis section through literature review and subsequent exploratory research study, the author observed a gap in the current provision of ways deploying models of MEs and their constituent Manufacturing Systems (MSs) in support of a number of aspects of Enterprise Engineering; such that on an ongoing basis Enterprise Engineers can conceptually design MSs that continue to fit their host ME, and the changing environment in which that host ME must operate. Hence this thesis will show how a systematic (step-wise) and synergistic (and coherent) use of a number of state of the art modelling tools can begin to fill the observed gap in current Enterprise engineering provision.

Figure 3.1 classifies some of the key philosophies, strategies and technologies described in the literature which can usefully inform the conceptual design of manufacturing systems;

such that they possess characteristic properties that suitably match the production environment in which they are used.

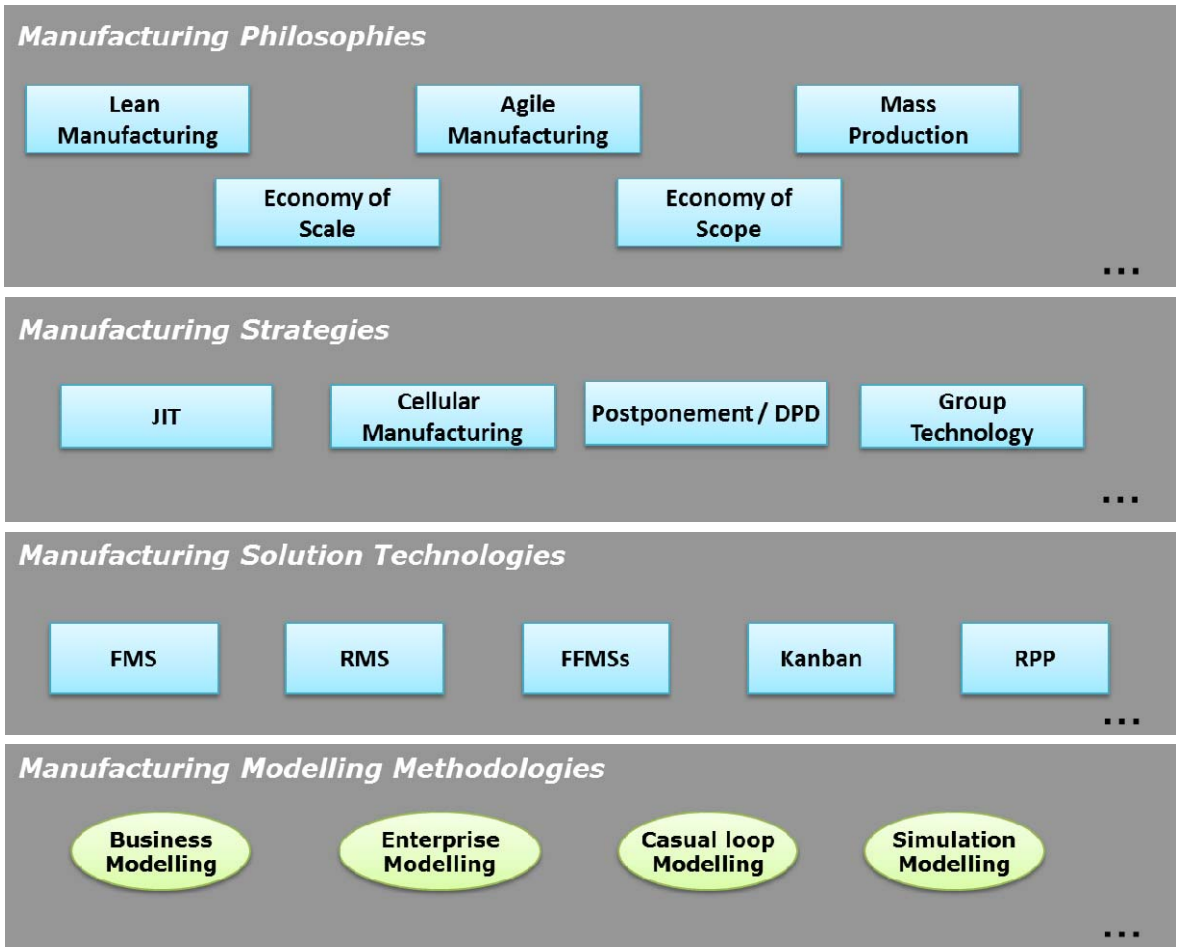


Figure 3.1 Manufacturing philosophies and solution techniques

The literature has shown that by adopting one or other of the manufacturing strategies discussed, many companies have become more successful; meeting changing customer demands without very significantly increasing their inventories (Watkins 1997). Mohanty and Wenkatraman (2003) describe how major benefit has been achieved by realising economies of scale production; in situations where the required product volumes are high. But other authors (including Vernadat 1996; Koren and Ulsoy 2002; Weston et al 2007) have stated that an emerging industry trend is to achieve competitive performance through dealing with increasingly dynamic (possibly uncertain) market demands. When customer demands change over time it may prove possible to deploy the same manufacturing system to realise a broad range of products; thereby achieving economies of scope as well as economies of scale. However to realise combined economies of scope and scale new manufacturing methods need to be devised, which build upon recent concepts like RPP, FFMSs and DPD, and can

innovatively and readily be applied so that: (a) volatile production demands can be met, whilst (b) the manufacturing systems used remain cost effective over sufficiently long lifetimes to pay back investment costs. Additionally many researchers (Keys., 1990, Mintz., 1994, Yan and Zhou., 2003) have considered life cycle engineering issues involved in integrating product and process developments, particularly so that products can be better designed for manufacture. However, in many (possibly most) MEs operating in a variety of industry sectors, impacts of changing volume demands, product variance and mix of products can lead to complex and in-efficient decision making and very significant investment risk taking. As discussed previously a number of manufacturing techniques, like GT (Group Technology); Evolving Parts/Product families; and Reconfiguring Process Plans can be deployed to reduce effects of product dynamics on manufacturing systems operations short and long term. But generally to date these techniques are applied in an ad hoc and piecemeal way without appropriate connection to a bigger picture, and a more formal set of enterprise engineering ideas and tools.

The author has observed that relatively little has been written about the conceptualisation neither (formal nor informal) of economies of scope systems; and particularly where production systems are used to make a variety of products with the same 'process and resource sub-systems'. Also currently available literature on economy of scope production systems does not quantitatively identify constraints on product dynamics that will likely arise from the way multi-product realizing systems are designed, operated and changed. By contrast, with respect to single (or 'cognate') product realizing systems, the piecemeal application of various methods based engineering approaches (including Lean and Agile philosophies and toolsets) is reported fairly widely to deliver business industrial benefit (Vernadat.,1996, Nicholas et al, 2006, Salvendy, 1992 and Mason, 2000). However, the holistic, systematic and model driven industrial application of such methods is the exception rather that the norm (Weston et al., 2007). Literature on 'postponement' (Loe., 1998 and Ian et al., 2001) and 'Leagile' (Mason, 2000) offers useful qualitative guides to linkages between product design and production systems design, but these neither quantify relationships which can inform (short to long term) decision making about how process, resource and work flow systems should be configured to realize required behaviours and performances.

The literature illustrates how significant business benefit can accrue for industry from the piecemeal use of 'state of the art' modelling technologies, such as Enterprise Modelling (EM), Simulation Modelling (SM) and Causal Loop dynamic Modelling (CLM) (Huberman, 1994

and Forrester, 1961). Furthermore far greater benefit can be realized from a suitably integrated use of these modelling technologies, as together they can support systematic and quantitative life cycle engineering of complex production systems, such as multi-product realizing systems (Rahimifard and Weston, 2006, Weston et al 2007, and Harrison, et al. 2001). But much of previous MEs modelling literature have mainly focused on the engineering of single product production systems that have cognate work items that can naturally share similar process and resource systems (Vernadat, 1996 and 1992., Kamath et al, 2002). In such cases, an apparent implicit assumption is that product variance within a product family, and hence propagated changes in production volumes and production mixes, can be accommodated via the use of programmable machines and product type sensing mechanisms, or by deploying people with requisite 'change competencies' and 'operational competencies' needed respectively to set up and process all input item types within a family. In some industrial situations this may be the case, but generally one would presume that significant competitive business advantage could be gained if (i) multi-product realizing systems are near to optimally designed and (ii) that as product realizing requirements change dynamically, required process, resource and work flow configurations of multi-product realizing systems should change accordingly; bearing in mind the cost of engineering such changes. In the current literature, notions about economies of scale have also been qualitatively linked to ideas about: 'extending the useful lifetime of production systems' (Yasuhiro, 1998 and Levinson 2002); 'designing lean and agile production systems' (Ian, 2001); 'mass customization, product modularization and postponement (Loe, 1998). But little analytic or quantitative knowledge has been reported about the nature and likely impacts of fundamental 'linkages' between: ***'the need for multiple-product realization'; 'viable designs of multi-product realizing systems'; 'achievable future behaviours and performances of multi-product realizing systems'; and 'impacts of new product introduction on multi-product realization.*** Neither are there public domain understandings about how knowledge about such linkages can be systematically and quantitatively be re-used, such as by using synergistic modelling technologies to support methods based life-cycle engineering of multi-product realizing system.

3.1 Resume of relevant manufacturing literature

Chapter 2 reviewed a number of manufacturing philosophies, some of which are specifically aimed at achieving improved responsiveness of MEs. Wang argues that there are two main aspects of responsiveness, namely: 1) reducing the manufacturing cycle, to meet changing market demands; 2) shortening the product development cycle to meet market opportunities (Wang et al 1997). Group Technology (GT) can support strategic thinking about both of these aspects of responsiveness; via its approaches to simplification and standardization of similar entities: including parts, assemblies, process plans, tools and instructions. The underlying idea of GT is to take advantage of similarities that exist among items to increase the effectiveness of production and other product realising systems (Angra et al 2008). For example, grouping allows similar, recurring activities to be conducted more efficiently. Cellular Manufacturing (CM) offers a solution technology which can implement GT principles, resulting in the design of manufacturing systems comprising a number of manufacturing cells (Suresh, Kay 1998). In this cited work, a 'Manufacturing Cell' is defined as being a cluster of dissimilar machines (and the processes they realise) that are located in close proximity and are dedicated to the manufacture of a family of parts. A prime aim of CM is to: (a) reduce setup times (by using part-family tooling and scheduling); (b) reduce manufacturing cycle times (by reducing setups, movement times, wait times and using small transfer batches); so that consequently (c) Work-In-Process (WIP) inventory can be lower (Moodie et al 1995).

Koren (1983) stated that a Flexible Manufacturing System (FMS) enables reaction to certain types of predictable and unpredictable change. RMS is a manufacturing strategy centred on being cost-effective and responsive (Koren et al 1999). This is because the machines in any RMS should be designed with an adjustable structure to enable the system to be scalable in response to market demands. In theory there are some outstanding advantages which can benefit industry, namely: 1) the adjustability of RMS machines allows flexibility not only in producing the variance of parts, but also the reconfiguration of the system itself; and 2) the customized flexibility of RMS can lead to faster throughput and higher production rate (Gadan et al 2007; ElMaraghy 2005). Emerging theories on Focused Flexibility Manufacturing Systems (FFMSs) express needs for applying flexibility in specific areas instead of in the whole production system with a view of achieving cost effective (W.Terkaj et al, 2009a and 2009b).

3.3 Research Aim and Objectives

The basic assumption of this research is that:

Generic; semi-generic and specific models of EoSS manufacturing system can be usefully created in support of the following:

1) **Long to medium term design of EoSS manufacturing systems**; such that they fit the requirements of the ME concerned and the product dynamic factors that impact on that ME: and therefore can over timeframes of concern produce all needed product types, in required quantities, with acceptable lead-times and at an acceptable ratio of value/cost.

2) **Medium to short term planning and scheduling of EoSS manufacturing systems**; so that given a planning window and EoSS manufacturing system configuration that the host ME can determine a suitable work dynamic for its EoSS systems which can result in effective ME responses to customer driven product dynamics.

3) **On-going identification of requirements for change to EoSS manufacturing system**; so that they achieve desired KPI's over given time frames.

Bearing in mind the observed gap in current modelling provision for enterprise engineers described in the previous section, this thesis aims to develop and case study test new groundwork thinking about:

1) The life cycle engineering of MEs and their EoSS product realising systems;

2) Big system integration; needed to fit EoSS systems into their host environments;

3) Selecting between and applying latest manufacturing theories; with particulalr emphasis on EoSS applications.

A definitive focus of the author's research is to unify and deploy state-of-the-art modelling technology that lends support to 1) and 2); which can lead naturally to an ongoing and systematic application of 3).

Therefore the author set herself the following research objectives:

Objective 1

Conceive, instrument and case study test a new Modelling Methodology of designing manufacturing systems, which can be used (in theory and in practice) to systemise design decision making about capturing aspects of complexities and dynamics in MEs realizing multiple products. This should cover:

- Quantitative prediction about system behaviours and performances when related process, resource and work subsystems are alternatively configured.
- Development of a coherent modelling method to decompose and re-compose any subject manufacturing system; hence to formalise integration and configuration views of such a system.
- Using the developed modelling method and its derivative models to better understand the operation of real case manufacturing systems used by collaborating MEs.
- Using the developed modelling methods and derivative models to achieve improved integration between different sub-systems within MEs.

Objective 2

Conceptualise key aspects of Economies of Scale and Scope (EoSS) manufacturing systems, so that their concepts can be positioned relative to other manufacturing philosophies, this including:

- Linking the measurements of Economies of scale and Scope with the design of real case manufacturing systems
- Use the levels of scope economies of an enterprise to localise the level of changes needed to a manufacturing system.

Objective 3

Use the developed modelling methodology to explore the operation of E-o-Scope & Scale systems and to quantify key performance measures of such systems; hence to support aspects of complex systems engineering

3.4 Research design

3.4.1 Research methods review and selection

Much literature has have reported various ways in which research can be conducted. In his definition of research, Bennett and Elman (2006) stated that:' Research is a systematic, careful inquiry or examination to discover new information or relationships and to expand/verify knowledge for some specific purpose'. According to Kumar (2005), types of research can be classified from three perspectives:

I. The ***application*** of the research

II. Research ***objectives***

III. The ***inquiry made*** to do the research

In the application of a research point of view, Sekaren (2003) has classified two types of research based on the purpose for which it is undertaken, namely:

1) **Applied research**; in which the research result is applied for specific problem solving in some organisation

2) **Basic research**; where research carried out is for generating a body of knowledge that enhances an understanding of certain problems in an organisation and methods for solving them. This type of research is also known as **pure research** or **fundamental research**.

Both *applied research* and *basic research* are scientific in nature so as to obtain a deep understanding of the problems and to achieve solutions to them.

In the view of classifying research based on their objectives, research endeavour can be classified into various other types (Kumar 2005), which include:

1) **Descriptive research**; It provides systematic description towards a phenomenon, situation, condition of an issues.

2) **Correlational research**; It studies the relationships or interdependence between multiple aspects of a situation.

3) **Exploratory research**; It is often carried out in order to explore an area where little knowledge were known. This is also known as ***pilot study***, it can be carried out to test or refine measurement or methods.

4) **Explanatory research**; It explains why the relationship between two or more objects or phenomenon exist.

If the examination of research study is based on inquiry made employed, two general approaches are classified:

1) **Quantitative research**; It is usually used to determine extent of the problem, issues or phenomenon

2) **Qualitative research**; It is used to explore the nature of an object or phenomenon.

To make the decision on which one to deploy is based on the aim and use of the study. Strauss and Corbin (1990) reported a key form of Qualitative research, which is called grounded study. It generates theories that derived from data, systematically collected and analysed throughout the research process.

3) **Case study**; which is a problem-solving technique that provides in-depth thinking and conceptual analysis of similar situations in any subject organisation.

4) **Action research**; comprises a set of planned activities that start from an identified problem then capture related data and information that can provide problem solution.

Case study research has been proven to be very useful for qualitative analysis and interpretation in certain situations in organisations; hence understanding correctly the dynamics of a situation is critical for problem solving. Action research can be carried out by internal or external consultancies that are able to sense and define the problem correctly and pick up related data correctly, as those are important for the success of the approach (Sekaren 2003).

Bennett and Sekaren have studied common steps taken during research; which can be classified as follows (Bennett 2006, Sekaren 2003):

- Research problem or question
- Literature review / pilot study
- Conceptual or inductive/deductive reasoning
- Identifying hypotheses / research assumption(s)
- Hypothesis testing : testing design; information gathering and analysis
- Testing and evaluating hypothesis: accept/reject hypothesis as tentative answer; identify limitations of the test; suggest further hypothesis
- Report /present a solution
- Apply result(s)

3.4.2 Research plan

The several methodologies discussed in the previous section were considered and selected as needed to achieve the objectives of the present study. Table 3.1 summarises the methodologies selected during the several stages of the research. Overall, it was considered that the present research would be a combination of pure and applied research, involving both exploratory and case study forms of research.

Table 3.1 summary of methodologies selected during the several stages of the research

Research phases	Activities	Objectives
Phase 1	Conduct literature review of key contributing areas to the research: • Manufacturing philosophies, strategies and solution technologies • Enterprise modelling techniques • Simulation modelling techniques	- Obtain knowledge about the state-of-the-art research and practice in the selected areas - Identify the gap in modelling provision
Phase 2	Define the research focus based on the literature gap identified	Set up the research aims and objectives
Phase 3	Learn about selected modelling methods and supporting tools	Form initial research hypotheses and methodology
Phase 4	Apply initial modelling method in exploratory case studies	Research methodology and hypothesis testing
Phase 5	Develop the modelling methodology based on exploratory case study findings	Form an advance modelling method for: 1) problem solving in case study problem domains; 2) generate a new body of knowledge
Phase 6	Apply the extended modelling methodology in specific case real problem solving	Extended modelling methodology testing
Phase 7	Analyse & Report the research results	Evaluation of the fulfilment of the research objectives

Chapter 4 Initial Modelling Methodology Specified

4.1 Research Definitions and Assumptions

4.1.1 Introduction and Definitions

To satisfy the aims and objectives of this thesis a new 'Model Driven Method' is to be designed which systemises and enables the creation and deployment of a coherent and integrated set of conceptual models of manufacturing systems. The purpose of so doing is to enable key aspects of the virtual engineering of manufacturing systems that are, or will in the future be, subject to impacts that may arise from different forms of Product Dynamic. In this way it is proposed that the conceptual design and virtual testing of candidate manufacturing systems, including EoSS systems (that maybe designed to realise benefits of GT, CM, RMS and FMS strategies and solution technologies) will be supported; so as to contrast and compare the relative behaviours of different manufacturing system designs and/or ways of realising effective performances in response to changes in demand. The aim of so doing is to enable rapid and effective design, planning and change decisions that lead to improved manufacturing system performance whilst minimising production costs and investment risks.

The term 'Product Family' has been discussed and defined by a number of authors with reference to alternative manufacturing contexts. According to Fan and Liu (1999) a product family is a group of products based on a specific design concept or a standard product. Laakko and Mantyla (1994) explained that products within a product family share the same core technology and a common manufacturing resource; as they can be processed via similar process routes and manufacturing operations. Products within a family are normally aimed at the same market segment (Meyer and Lopez 1995; Meyer and Utterback 1993). ElMaraghy (2007) proposed a method of 'Evolving Parts/Products Families'. Two distinctive ways in which companies evolve their designs were observed, namely 'chronological' and 'functional'. Also observed was that with many new parts/products emergent, the old design of a process plant is likely to be influenced significantly. Thus an approach to 'Reconfiguring Process Plans' (RPP was introduced to cope with the challenges raised by 'Evolving Parts/Products Families' (Azab and ElMaraghy, 2007a and 2007b).

It follows that products can be classified as belonging to a family in variety of ways. As explained in later sections of this chapter, a new classification is made with respect to the ease with which manufacturing systems can be programmed or configured to realise products belonging to one or more families.

Four types of Product Dynamics were classified by Cui & Weston (2008), namely: ***Product (family, type and feature) Variance***; ***Volume Dynamic***; ***Product Mix Dynamic*** and ***New Product Introduction***.

In this research **Product Variance (PV)** is defined as the change between 'aspects of products' within a 'product family' or within a 'particular group of product families'[3]. Aspects of PV of prime concern to this author are those that will impact upon the process and resource sub-systems (of a subject manufacturing system) such that they (1) *'behave differently'* or (2) need to be '*configured or programmed differently'* to enable them to behave adequately (i.e. be fit for purpose).
Another key aspect of Product Dynamics is **Volume Dynamic (VD)**. VD is the change in production volume of any product type with respect to time. A VD will typically arise from variation over time of customer demand for a particular product type or family. VD might for example take the form of a fairly predictable ramp up or down in some industries while in others it might involve unpredictable variations superimposed over some repeating seasonal variation.

A third aspect of Product Dynamics of concern in this research is **Product Mix Dynamic (PMD).** In manufacturing systems capable of realising a family of products or more than one family of products, PMD will be causally related to both PV and VD. As customer order patterns change, typically the mix of products that must be realised in a given timeframe will change.

The last aspect of Product Dynamics of concern in this research is **New Product Introduction (NPI).** Manufacturing enterprises commonly have to introduce new products to meet emergent customers' needs or to remain competitive. In general NPI activity will generate new products that may differ from existing ones in various ways. Typically this will increase the product variance in the ME so that either new manufacturing systems will be required or the reprogramming and/or reconfiguration of existing manufacturing systems will be necessary. Generally when existing manufacturing systems are used to realise both new and old products then both PV and VD are likely to change. In turn this will likely lead to change in PMD.

[3] Whether it is PV within a product family or across multiple product families depends upon the 'scope of products' input to the manufacturing system being designed.

The literature reports on political, economic, social and technical drivers of change which can lead to increased product dynamics (ElMaraghy H.A., 2009). Figure 4.1 was constructed by the author to illustrate causal effects of some of the key drivers that lead to PV and VD. The figure shows that a number of drivers result in NPI, and that NPI will typically increase the variance and the volumes of multiple products made by a given ME. Although of course if a new product replaces an old one the net effect maybe even be to reduced variance, particularly when new product designs are developed by an ME which seeks to rationalise its product designs with a view to reducing variance. Also shown in figure 4.1 is that ongoing change in customer order patterns will typically impact on the volume of products and the variety of products that need to be made in a given timeframe. But these kinds of patterns of behaviour can vary significantly amongst industry sectors.

The author has assumed that PV and VD are the two prime Product Dynamics factors; although NPI and PMD have causal relationships with these two prime factors. However, three factors (PV, VD and PMD) can directly lead to increased operational complexity in the manufacturing systems used by any ME.

The causal factors described by Figure 4.1 are probably applicable in most industries. Also in many industries such factors are reported to have increasing rates of change. The result has been a trend towards reduced product lifetimes. In other words, the causal effects shown in Figure 4.1 will today typically act more rapidly than a decade ago. This kind of phenomenon is a key motivator of the authors' research. This is because future designers of manufacturing systems need to better understand the implications of Product Dynamics before they can decide upon the conceptual design of new manufacturing system solutions that will function effectively long and short term. In addition, it is important to consider the relative values of 'product redesign', 'manufacturing systems redesign' and / or 'improved planning and control' aimed at attenuating the impacts of Product Dynamics.

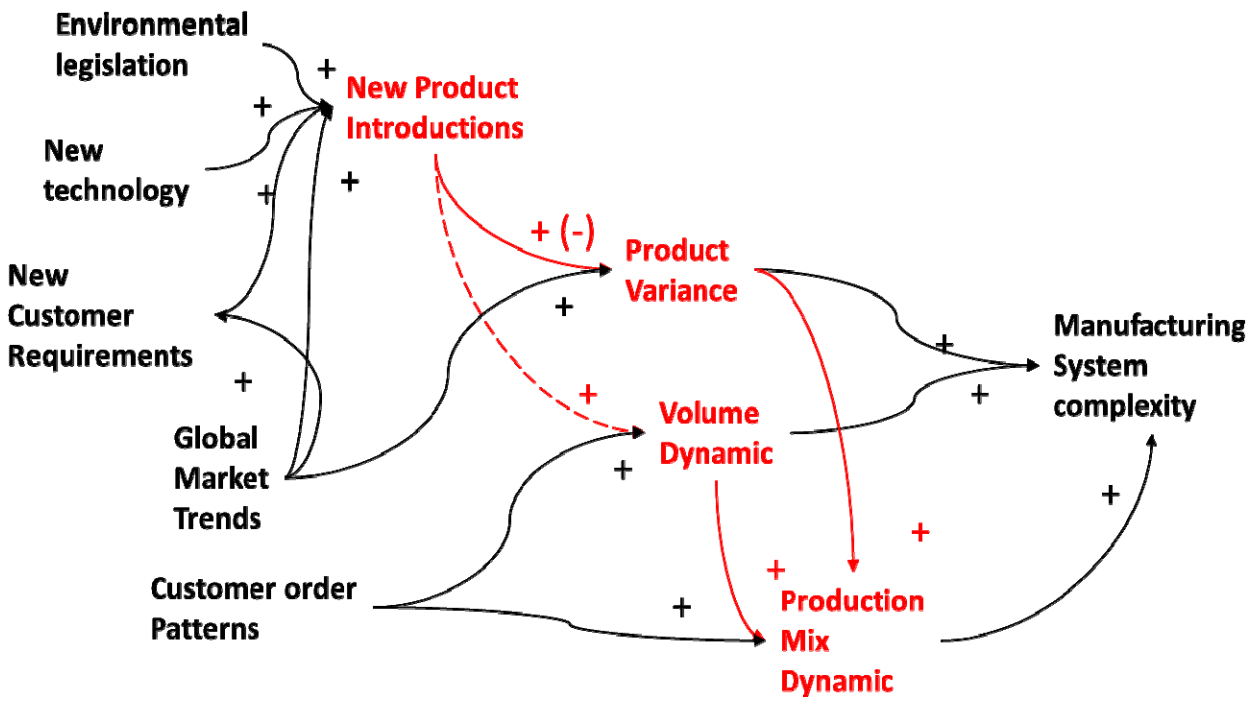


Figure 4.1 causal relationship of reasons and results of aspects of Product Dynamics

4.1.2 Assumptions

Figure 4.2 was constructed to characterize ***EoSS (economy of scope and scale) manufacturing systems***. This illustrates three cases of manufacturing system configuration. Common sense observations about these manufacturing system cases are described in this thesis section. Subsequent sections explain how a Model Driven Method was conceived to test the validity of those assumptions and in so doing to illuminate a new approach to quantifying relative benefits of each case when they are subjected to a given Product Dymamic.

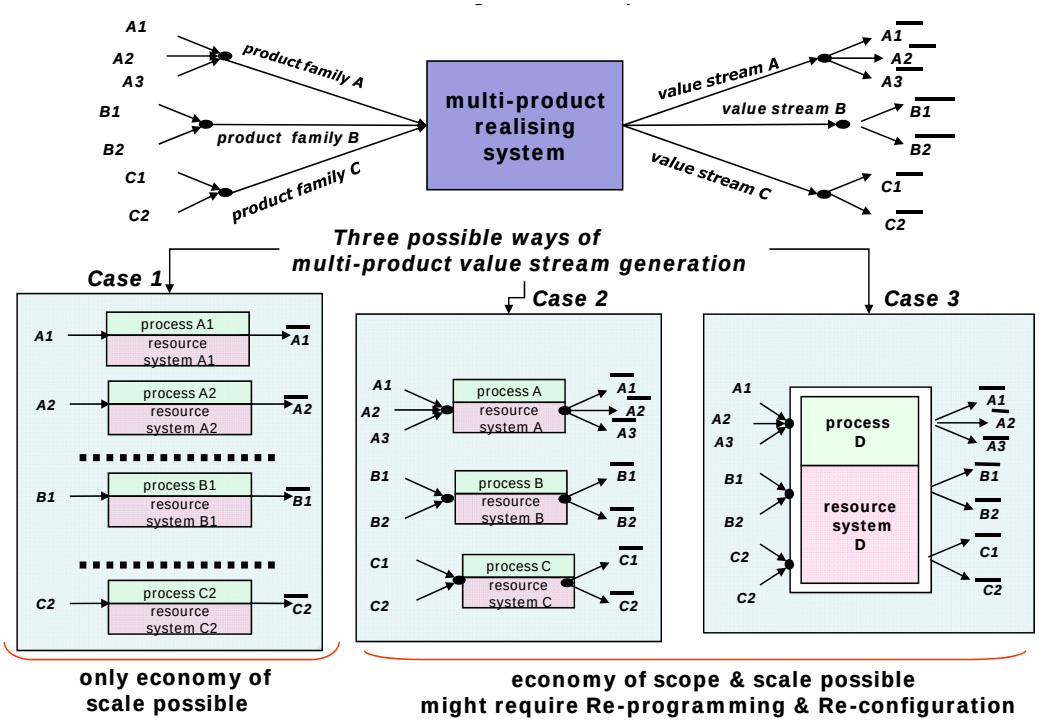


Figure 4.2 Assumption1- possible ways of realising EoSS (Cui, Z and Weston, R.H., 2008)

Case 1 is considered to realise economies of scale but not scope; this is because each value stream is generated by a separate Process and Resource system (namely a separate 'P/R couple'). This means that in Case 1 manufacturing systems each P/R couple can only realise products of one type. A series of such couples might for example be configured in the form of a mass production line; such as found in dedicated transfer lines used to manufacture car engines of a single type. In Case 1 systems it is assumed that VD (i.e. the volume dynamic) is the only form of product dynamic that will significantly influence runtime behaviours (over time). As a consequence the VD variable or parameter is important but essentially the other dynamic factors PV and PMD will be zero and therefore will not influence Case 1 manufacturing system behaviours. In principle if a Case 1 manufacturing system is required to realise products in significant quantities then typically an economy of scale can be realised; such as by making or assembling a specific product with minimal waste via an optimised design of the P/R couple and with production well planned. In general opportunities to improve Case 1 system performance will likely increase as the useful economic life of such a system extends. This will be because (1) relatively the Product Dynamics are really understood, (2) there is a longer timeframe over which to learn from experience and (3) likely greater systems change revenues will be generated (as the lifetime of a manufacturing system extends) to pay for needed changes. Therefore in a given ME, such a Case 1 manufacturing system might well be the subject of a continuous process improvement program to develop

and maintain efficient operation during the life time of the manufacturing system and its constituent P/R couples.

In theory Case 2 systems can realise both economies of scope and scale. This is because they share use of a single P/R couple to add values to products of different types; and when so doing they realise more than one value stream. A manufacturing system making a family of glass bottles with different dimensions is an example of a Class 2 manufacturing system. In such a system the process and resource systems remain essentially unchanged for all bottle types but product differences are realised via process parameter change, tooling changes and change over proceedures that will have previously been defined during production engineering. The capability of a Case 2 manufacturing system to realise a range of product types (rather than only one type as is the situation for Case 1 systems) can lead to significant business advantage, where the demand for products of a specific type is uncertain. By being able to realise multiple product types, the risk of capital and runtime investment made in manufacturing systems can be reduced and the economic lifetime of such systems can be significantly extended. However the extent to which this is true is normally difficult to predict and quantify. It is observed however than in Case 2 manufacturing systems both PV and VD will significantly influence the behaviours of a shared P/R couple. Also as change occurs in instantaneous values of PV and VD a causal impact will be that the shared P/R couple will need to cope with variation in PMD. Consequently a shared P/R couple needs to be sufficiently flexible to cope with the varience between the different product types and with different rates at which products are input to that couple. However a key assumption made by the authors is that in Case 2 manufacturing systems the degree of that flexibility will be limited and this in turn will limit the range of product varience and volume dynamic that can be handled by any shared P/R couple. Alternatively stated this means that in a Case 2 manufacturing system a shared P/R couple will only neccessitate some limited degree of change during its runtime execution. This limited flexibility is assumed to correspond to '***reprogramming***'; where the need for reprogramming is illustrated by figure 3.4. Implicit also in this descrition of Class 2 EoSS (economy of scope and scale) manufacturing systems is the concept that a product family can be defined in terms of its manufacturing system requirements; and that for all members of any product family only reprogramming (of the Class 2 manufacturing system used to realise that family) should be necessary to change from producing one family member to another.

Case 3 EoSS manufacturing systems possess capabilities to realise product types belonging to more than one family of products by sharing one or more common P/R couple; thereby enabling significant economies of scope and scale to be realised. It follows however that Case 3 systems will require greater flexibility than their Case 2 counterparts. A common example of a Case 3 EoSS manufacturing system is a 'machining job shop'; in which semi-generic machines (such as drilling, milling, turning and sanding mchines) are operated by multi-skilled operators, so that a wide range of machined parts can be realised in accordance with new and old part designs. As for their Class 2 counterparts, in Class 3 EoSS systems both PV and VD will significantly influence the behaviours of shared P/R couples. Also as change occurs in instantaneous values of PV and VD, a causal impact will be that shared P/R couples will need to cope with variation in PMD. However relative to Class 2 systems, it is likely that Class 3 EoSS manufacturing systems will be subject to a greater range of instantaneous values of PV, and possibly a greater VD, so that as a consequence the PMD will be greater. Under such conditions, because products belonging to different product families will likely require significant process and resouce change, it is likely that ***'Reconfiguration'***, as well as ***'Reprogramming'***, will be required within Case 3 systems; as illustrated by Figure 4.3.

In figure 4.3, resource 'competencies' are considered to relate to the 'ability' of human and technical resource elements to perform the manufacturing systems activities assigned to them. Hence, manufacturing systems capable of coping with cross family product difference will likely require a greater range of competencies than those coping only with single product family differences.

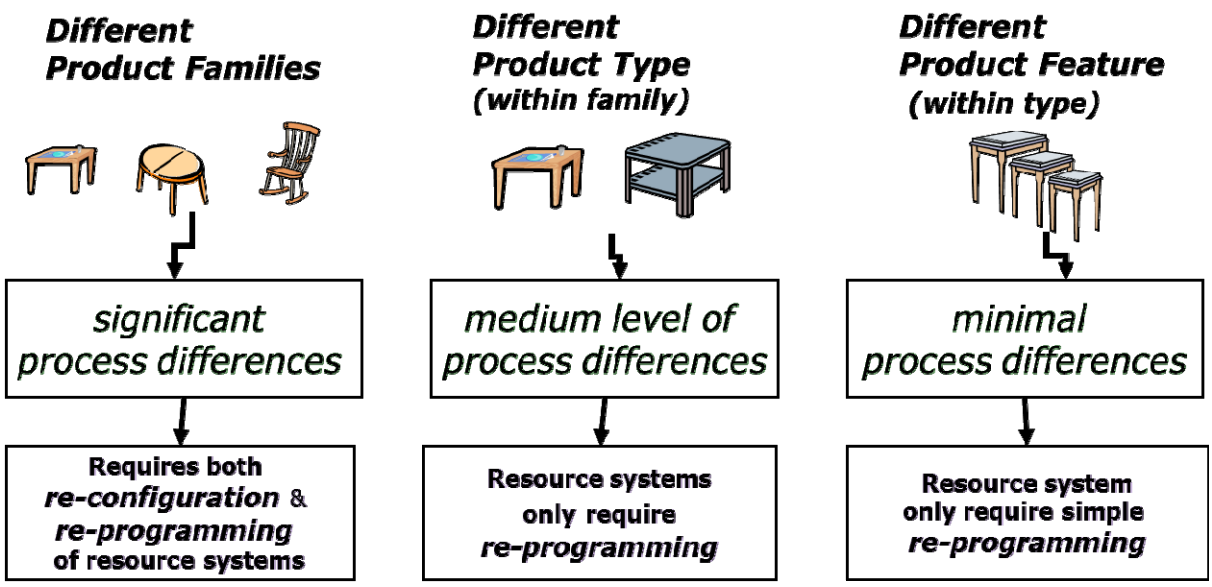


Figure 4.3 Assumption2 - Impact of Product Variance on systems change

The authors also observe that in general the scope of production that can be realised is causally dependent upon the extent to which, and the ease with which, such systems can be (re)programmed and (re)configured. This observation was predicated on the following definitions.

(Re)-programming involves defining one or more trajectories of state transitions; where those states are predefined during system design and engineering and will be contained within an envelope of reachable states. In the case of EoSS manufacturing systems those state changes can relate to either or all of an interrelated set of process, resource and work subsystems. This idea is illustrated by Figure 4.4. This research develops the notion that formally modelled activity flows can explicitly represent manufacturing system requirements and particularly can code up key differences between processing requirements of product variants. This can provide a basis for modelling needed state changes in the process sub-system. Following which required changes in the resource sub-system can be specified as part of a two staged modelling method. In stage 1 competences possessed by viable candidate resource sub-system designs can be matched to the range of processing requirements defined by process sub-system models. While during stage 2, models of viable candidate resource systems are computer exercised so that their performances can be compared when they subjected to a specified Work Dynamic which characterises the work sub-system.

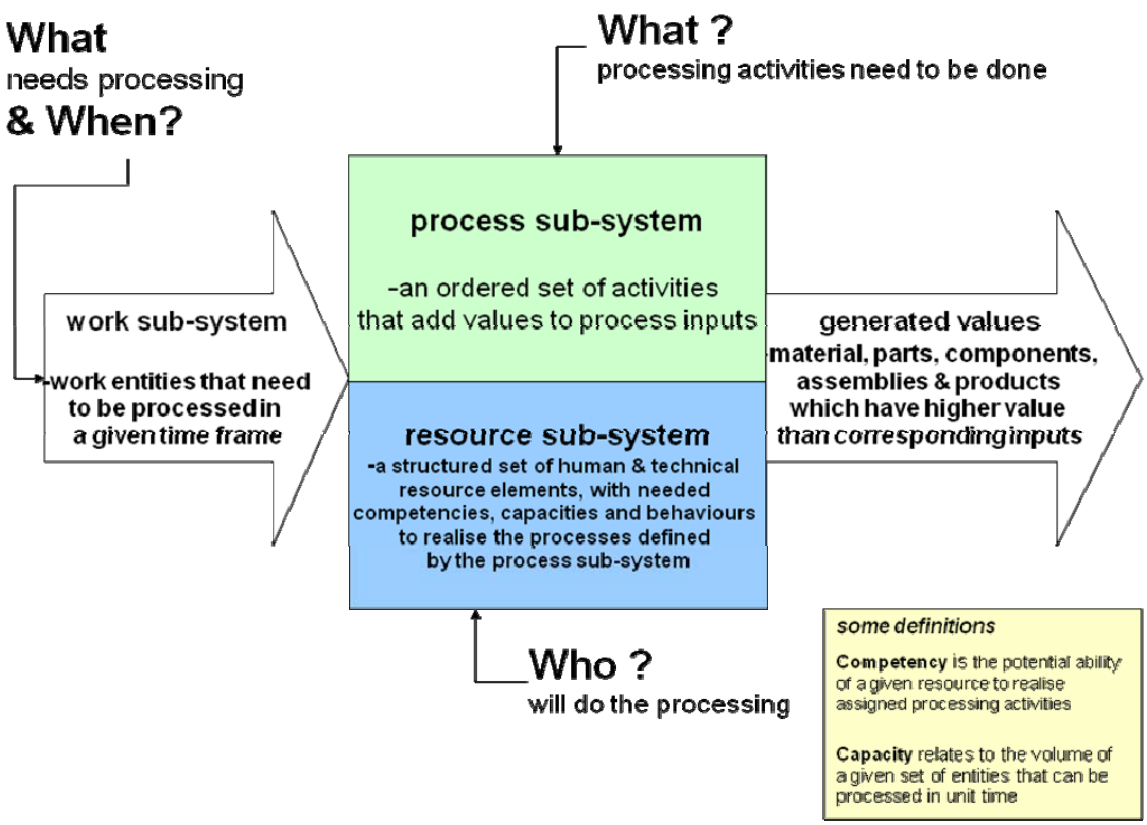


Figure 4.4 Generalised Manufacturing Systems Decomposition

It is presumed however that the number and envelop of the reachable states of any given manufacturing system will be determined primarily by:

- Inherent capabilities, competencies, capacities and behaviours of 'component' elements (that comprise those subsystems) and
- Constraints imposed by various structures used to bind components into subsystems and systems.

Therefore the author assumes that many common requirements to realise a range of product properties, found for example amongst constituent members of a product family, can be anticipated and formally modelled during manufacturing system design and engineering. Such a model can capture the required states of a manufacturing system (as defined by the process sub-system and the work sub-system) and the reachable states of different configurations of resource subsystem components. Further it is assumed that during system design and engineering, suitable runtime (i.e. system execution time) programming methods and mechanisms can be defined and provided.

(Re)-configuration of manufacturing systems involves: (i) change to the (process, resource and/or work) components deployed and/or (ii) change to the way that deployed components are structurally bound to each other. Via such changes new, extended or simply different system competencies, capacities and behaviours can be realised; thereby modifying the states, number of states and envelop of states that can be reached by a manufacturing system. It follows that relative to system programming alone, system reconfiguration can accommodate increased variation in production requirements that is needed to cater for inter-product family differences. Also observed is that in some production situations a set of viable system configurations, capable of satisfying observed inter-product family differences, may be pre-determined during manufacturing system design and engineering; then during system runtime, changes in system configuration may be made. Alternatively as new product families (and family members) need to be realised by a given ME, then new system configurations, and related programmes, can be designed and engineered. Further observed is that the extent to which and the ease with which, system configuration can be achieved will be dependent upon the methods and mechanisms provided to (a) (re)select new components (with properties required) and (b) (re)structure selected components into needed manufacturing system configurations. The new Model Driven Method of conceptually designing EoSS manufacturing systems introduced by this research provides a systematic and analytical foundation for (re)-programming and (re)-configuring such systems.

4.2 Chosen Modelling Technologies

Section 4.1 described some ‘common sense’ observations made by the author as she sought to understand and analyse key properties of EoSS manufacturing systems that are, or could in the future, be used by collaborator manufacturing enterprises. When so doing she observed that the business environments in which the collaborator manufacturing systems operate can in part be usefully characterised by the three product dynamic factors VD (volume dynamic), PV (product variance) and PMD (product mix dynamic).

Having made these observations and assumptions the author chose to develop a new Model Driven Method of conceptually designing EoSS manufacturing systems based upon a unified application of a set of state of the art modelling techniques. When choosing those techniques

figure 2.11 in chapter 2 has fleshed out the pros and cons of Enterprise Modelling (EM), Causal Loop Modelling (CLM) and Simulation Modelling (SM).

Here focus of attention was placed upon the use of discrete event SM, because common characteristic properties of the manufacturing systems being studied at collaborator sites were known to have significant influence on systems behaviours and performances related to discrete parts processing, queues and flows through a finite resource. The analysis outlined by Table 1 clearly indicated that EM, CLM and SM have complementary strengths that can be applied to create models of manufacturing systems and their business environment and then to analyse likely impacts of change (e.g. in configuration and product dynamic characters) both qualitatively and quantitatively.

4.3 Objectives of the Proposed Modelling methodology

With a view to testing and developing the modelling ideas described in section 4.1, the author proposed her research plan which aimed to advance the engineering of EoSS manufacturing systems. This plan is outlined in the following.

EoSS Research Aims: Stage 1

For a given '*product dynamic*' to '*represent*' and '*qualitatively and quantitatively compare*'

(A) *Viable candidate EoSS manufacturing systems configurations* (see figure 4.5), that possess the '*competencies*' to realise products and product volumes that lie within the envelop of that dynamic

(B) *Relative behaviours* of the viable candidate EoSS manufacturing systems, measured in terms of KPI's that emphasise:

- (i) *variation in lead-times, throughput; value generated and cost consumption* within the envelop of that product dynamic
- (ii) *benefits of change capability*, that might be made inherent in possible implementations of the viable candidates, because of the relative ease with which (re)-programming and (re)-configuration of manufacturing system elements could be achieved

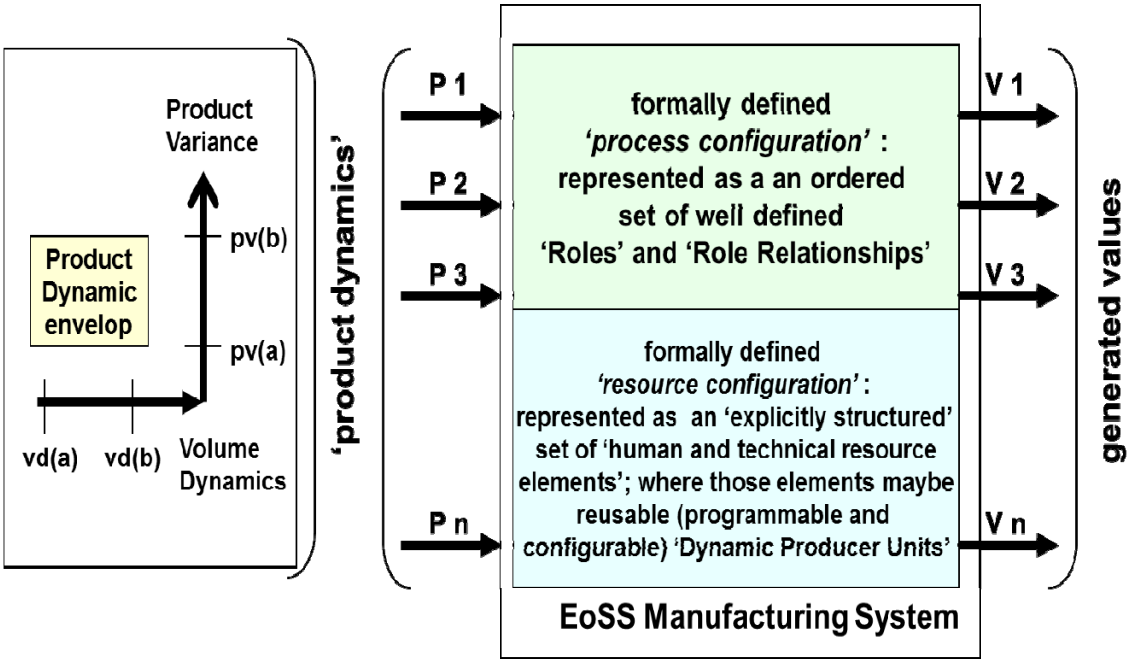


Figure 4.5 Some EoSS terms defined

Prime Objective 1: To develop necessary groundwork thinking about impacts of product dynamic factors on required configurations of EoSS manufacturing systems; such that 'representation' and 'analysis' of those impacts is feasible

Prime Objective 2: To specify, instrument and test a '*Model Driven Method*' of achieving stage1 research aims, such that this method can be re-used on an ongoing basis as product dynamic factors change in support of

(a) 'Conceptually designing' viable candidate EoSS manufacturing systems ,and
(b) Analytically predicting, and contrasting and comparing, likely behaviours of EoSS manufacturing systems during their projected lifetime

Prime Objective 3: To case study evaluate uses of the Model Driven Method in distinctive industry cases, so as to benchmark its use against previous best practice.

Prime Objective 4: To enhance the Model Driven Method in the light of the research findings.

EoSS Research Aims: Stage 2

Given (I) a particular product dynamic and (II) a specific conceptual design of an EoSS manufacturing system configuration to quantitatively predict performance benefits that would arise from attenuating the impacts of that product dynamic, such as via use of (1) a proven

planning and scheduling technique or (2) rationalising the design of the products realised by an enterprise so as to reduce their variance.

Prime Objective 1: reuse the Model Driven Method to test ways of optimising a given manufacturing system (i.e. reducing lead-times, bottlenecks, motion and WIP).

Prime Objective 2: identify impacts of delays and costs caused by Product Dynamics, by using the Model Driven Method to develop and predict benefits of using alternative planning and control techniques to smooth the dynamic effects.

Prime Objective 3 : provide a basis for planning policy suggestions, based on model results analysis, and ultimately to create sufficiently 'usable' and 'realistic' manufacturing system models which can be used on an ongoing basis to decide how best to'(re)-organise', and therefore 'attenuate', a given 'Product Dynamic' into a suitable and equivalent 'Work Dynamic'.

EoSS Research Aims: Stage 3

To consider use of the Model Driven Method developed during research stage 1 to lend quantitative support to the conceptual design of configurations of multiple EoSS manufacturing systems. By so doing to consider and benchmark possible generalised applications of the Model Driven Method in organisations where investment risk is to be reduced associated with the selection of adoption of alternative manufacturing paradigms (such as CM,RMS, Lean, Agile and RMS, DPD, FFMSs and RPP). Here it is anticipated that both specific and semi-generic cases (with associated plant data) would be drawn from industrial case studies investigated during the stage 1 research.

Prime Objective 1: enhance the Model Driven Method by reusing it in different case study companies, so as to anticipate system behaviours given specific 'Product Dynamics' conditions, and to lend support to decision making during system (re)design.

Prime Objective 2: identify potential benefits arising from selecting and deploying alternative manufacturing paradigms, so as to inform decision makers involved in strategy making, and related long term investments.

4.4 Design of the Initial Model Driven Method

It was observed that many simulation based experiments are necessary to computer execute models that predict how Work Dynamic impacts (i.e. attenuated forms of Product Dynamic) can lead to alternative EoSS manufacturing system behaviours. Therefore key aims of the Model Driven Method are to systemise (1) the modelling of configurations of P/R couples (of Case 1, 2 and 3 EoSS manufacturing systems) and (2) the design of simulation experiments that can predict behaviours of developed manufacturing system models in response to Product Dynamics that could likely arise in different types of business environment. With these general modelling requirements in mind the Model Driven Method was conceived to comprise a step wised synergistic use of enterprise, causal loop and simulation modelling technologies.

When using the Model Driven Method to re-engineer existing EoSS manufacturing systems the following modelling steps were proposed. Although it was presumed that the order of these steps may be changed for different manufacturing system cases and forms of manufacturing system analysis.

Step A. Decompose the current 'as is' manufacturing system (such as that deployed by a collaborator ME) into a series of Case 1 Process-Resource Couples; then for each product type within each product family to consider impacts of (empirical and historical) 'Work Dynamics' on resultant 'throughput', 'utilisation', 'bottlenecks', 'Takt time imbalances', etc

The purpose of step A is mainly to systemise the development of sufficiently simple models of 'as is' manufacturing systems, such that they can represent and replicate some of the current behaviours observed in the real system. Such modelling simplifications were observed to be necessary to begin to understand why the real manufacturing system behaves as it does and as a by-product this begins to enable validation of the founding principles and structures of the models generated. Also step A allows comparative analysis to be made between different modelling simplifications where product variance factors require a significant change to the structure or content of models.

Step B. Recompose the P/R Couples into a series of Case2 P/R Couples; for each product family to consider impacts of (empirical and historical) 'Work Dynamics' on resultant 'throughput', 'utilisation', 'bottlenecks', 'takt-time imbalances', etc.

Step B is focussed on using Step A simplified models and understandings to develop new candidate configurations of Case 2 systems that possess some degree of economy of scope capabilities. When so doing there are two main aims, viz: firstly to compare relative performances of viable Case 2 configurations of P/R couples; and secondly to investigate the extent to which product variances and volume dynamics can be satisfied by reprogramming resources, as opposed to reconfiguring them.

Step C. Recompose the P/R Couples into a model of the 'as is' manufacturing system; then for selected mixes of product (family and type) consider impacts of (empirical and historical) 'Work Dynamic'.

Step C is focussed on 'as is' manufacturing system model validation. By using historical data the aim is to convince the modeller and industrial partners/practitioners/potential ME users that the conceptual models behave in a similar way to the real system.

Step D. For various ranges of 'Work Dynamic' compare and contrast the relative behaviours and performance of Case1, Case2 and Case 3 Couples studied under (1), (2) and (3); then develop 'to be' versions of manufacturing systems (with alternative reconfigurations of P/R couple and related work flows).

Having gained confidence in the models and key understandings about realisable behaviours from different model configurations, during Step D new reasoning can be developed about potential advantages and disadvantages of restructuring the models. For example restructuring might be made in conformance with a relevant manufacturing paradigm such as Lean, CM, RMS and DPD.

Whereas when using the Model Driven Method to conceptually design a 'green field' EoSS manufacturing systems it was proposed that an initial conceptual EoSS manufacturing system design would be developed by referencing common manufacturing architectures or by observing similar industrial system solutions. Following which Steps A to D would be completed in an appropriate order.

An overall aim of this study therefore is to systemise aspects of experimental design and related conceptual thinking so that when simulating the operation of EoSS manufacturing systems it becomes possible to cope with the high levels of experimental complexity commonly found when computer executing manufacturing system models. In this way early modelling reported in this research was aimed at initial modelling and understanding of behaviours of manufacturing systems used by collaborating ME's working with the author.

Following which specific and generalise observations will be made about the impacts of different forms of Work Dynamic on the behaviours of alternative EoSS configurations of P/R couples. By so doing specific recommendations for improvement will be made to collaborators and generalised academic contributions will be made.

4.5 Summary

This chapter has described background thinking leading to the definition of an Initial Modelling Methodology (IMM); which was conceived to virtually engineer manufacturing systems subjected to significant product dynamics. The proposed prime application of the IMM was to support qualitative and quantitative reasoning needed to advance understandings about, and best practice deployment of EoSS concepts.

Essentially the IMM specified in this chapter constitutes an advance over and above the integrated use of enterprise, causal loop and simulation modelling technologies previously proposed by researchers at Loughborough; including (Chatha & Weston 2006; Ajeofobi & Weston 2009; Rahimifard & Weston 2009; Ajaefobi 2004; Agyapong Kodua 2009; Rashid 2009; Toh 1997; Monfared 2000). Therefore in principle the IMM can model many different types of manufacturing system which maybe designed to employ different paradigm ideas; including Lean, RMS, Postponement, EoSS, etc. However the advances proposed within the IMM centred on a more definitive systemisation of the selected (enterprise causal loop and simulation) modelling technologies in respect to (a) separated modelling of the work, process and resource sub-systems that comprise any subject manufacturing system and (b) a step-wise proposal as to how to apply newly defined EoSS concepts. Sections 4.3 and 4.4 specified the developments proposed in respect of (a) and (b).

Next it was necessary to apply the IMM in a selected case study company; to begin to evaluate the capabilities and suitability of the IMM. Chapter 5 documents this initial case testing, while Chapter 6 describes a second case study application of the IMM. Following which findings from both case study enabled the author to conceive an enhance form of the IMM which is referred to as the Extended Modelling Methodology. The EMM was then more exhaustively case study tested during this PhD study as described in later thesis chapters.

Chapter 5 Case 1 application on methodology

5.1 Company Overview and Enterprise Model

The first case study company chosen was a UK based privately owned Small to Medium sized Enterprise (SME) called BGF. BGF *Makes-to-Order* household furniture by applying a push synchronisation policy. BGF's production sections include: a 'machine shop', an 'assembly shop'; and a 'spray shop'. Having collated customer orders for up to 4 weeks, BGF creates and releases (twice a week) a production order (termed a 'picking list') to the production shops. At this point in time the assembly shop coordinator requests parts from the machine shop. The machine shop's job list is continually forecast, and prioritised for the purpose of maintaining enough supply to the assembly shop. It follows that 'customer orders' code-up a Product Dynamic (as earlier defined) while 'production orders' (or picking lists) constitute a Work Dynamic (which is an attenuated function of the coded Product Dynamic). BGF manufactures circa 350 different products (Rahimifard and Weston 2007); where the company divides these products into three main categories based on their functional differences, namely 'cabinets', 'tables' and 'chairs'; see Figure 5.1.

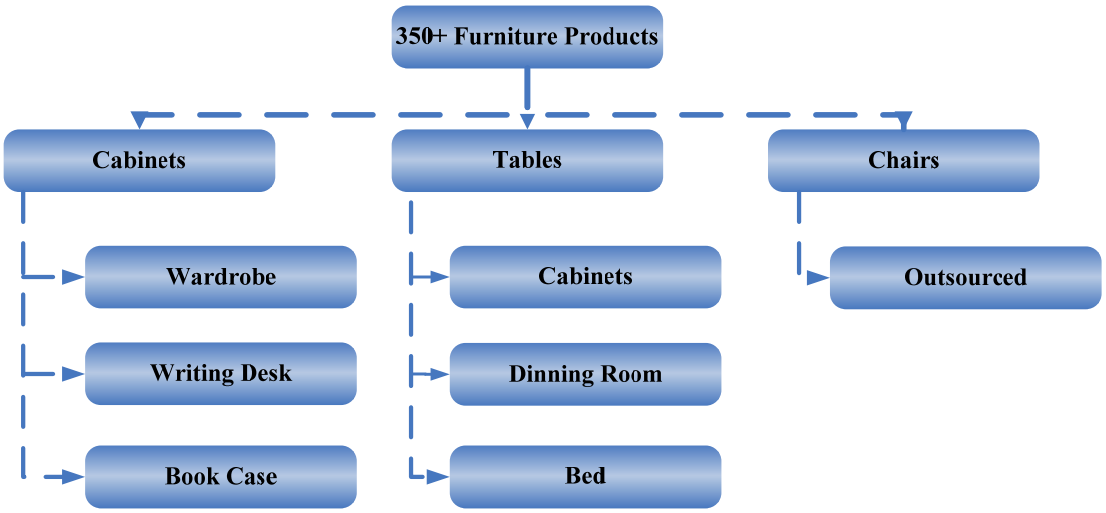


Figure 5.1 Three main Product categories of BGF company

To capture the process network of the case company the author chose to deploy the Computer Integrated Manufacturing Open Systems Architecture (CIMOSA) Enterprise Modelling (EM) approach. CIMOSA was specified and developed in the late 1980's and early 1990's (AMICE 1993). This choice was made because CIMOSA is an ISO Standard and has proven effective in many MEs of different sizes (Vernadat 1993) as a way of creating a process oriented big picture of any given ME which can be formally decomposed into interrelated parts that can be modelled at a level of abstraction that is determined by the modeller

(Weston et al 2003; Chatha et al 2007). CIMOSA provides a consistent architectural framework for helping companies engineer change to their processes and resource systems. This can lead to competitive advantage in terms of price, quality and delivery time (Vernadat 1993, 1996).

The author's research colleagues in the MSI Research Institute visited the case company many times to interview its senior and middle managers. This allowed them to formally capture process oriented knowledge held collectively by those managers, and to organise this into a CIMOSA process-oriented requirements model. The EM produced comprised a number of: Context diagrams; Interaction diagrams; Structure diagrams; and Activity diagrams. These graphical models enabled MSI modellers to obtain sufficient knowledge about how the material and products that passes through BGF processes at runtime. This provided foundation knowledge to begin to create simulation models of the various production shops of BGF, with the purpose of supporting ME prediction and related business, manufacturing and logistical decision and policy making.

Figure 5.2 shows a context diagram of BGF, which was used as the starting point when creating CIMOSA models of the 'make and deliver to (aggregated) order' product realisation processes realised by BGF and its supply chain partners. This figure shows that there are a number of supply chain companies and departmental units (which are defined as being Domains (DMs)) that collectively interoperate to achieve this process network. For these independent units, the modeller can decide whether to model that domain in detail using CIMOSA modelling constructs, or to essentially treat that domain as a black box. In the overall BGF study, prime concentration was on two domains, namely DM6 'Business management' and DM7 'Produce & deliver furniture'. In this chapter focus of attention is almost solely on DM7.

The following is a list of BFG domains:

DM1 'Stockists': These are retailers of home furniture, who purchase products from BGF and other furniture manufacturers and supply them to furniture shops and major stores mainly throughout the UK.

DM2 'Raw Material Suppliers': Suppliers of BGF raw material, mainly pine wood (from Scandinavian countries) but also paint, glue and leather

DM3 'Sub Products (e.g. Chairs) Suppliers': Some sub-products are outsourced by BGF, mainly chairs that are part manufactured so that BGF can carry finishing operations and re-sell them at a higher priceDM4 Miscellaneous Fixture Suppliers: Provide BGF with small items such as screws, hinges and door knobs

DM5 'Technology Vendors': Suppliers of machines, software and other utilities that require support maintenance

DM6 'BGF Business Management': This internal domain of BGF obtains and processes orders, manages interactions with suppliers and customers and carries out business and financial transactions.

DM7 'BGF Produce & Deliver Furniture'; This internal domain of BGF realises the case companies' 'order fulfilment processes'. This domain is the main subject of study in this research.

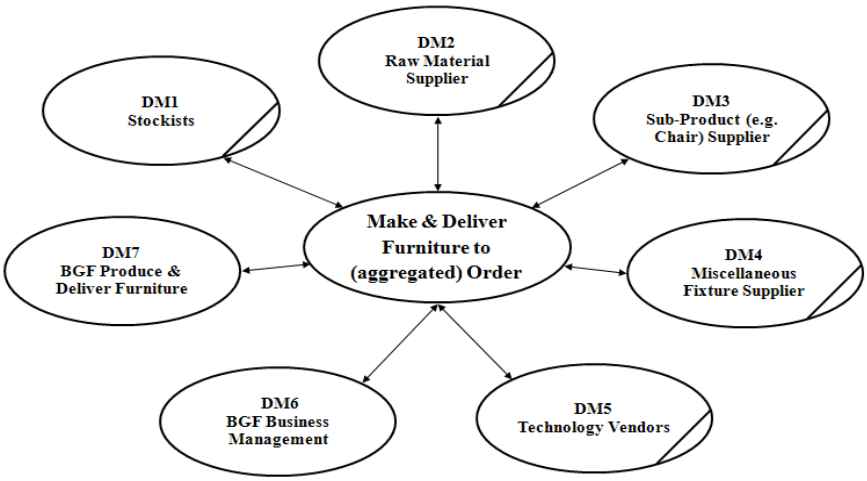


Figure 5.2 Context diagram of BGF

Having created the context diagram shown in Figure 5.2, the subsequent enterprise modelling steps centred on using CIMOSA constructs to capture a significant number of interaction diagrams; structure diagrams and activity diagrams. The purpose of creating these diagrams is to decompose the targeted domain to enable the organised capture of knowledge from key knowledge holders operating at all levels in the domain. By so doing the network of processes owned by that domain are explicitly described at all appropriate level of modelling granularity (or detail). In the case of BGF, DM 7 'Produce & Deliver Furniture' and DM 8 'Business Management' were treated as CIMOSA conformant domains, and as such they were modelled in detail using CIMOSA modelling principles. Figure 5.3 shows the high level structure diagram created to model DM 7. This figure shows that there are 5 sub processes within DP7, namely, business process (BP) 71 'make furniture to order', BP72 'spray and finish furniture production', BP73 'package & deliver furniture', BP74 'support & implement product introduction' and BP5 'manage & maintain production & transport capabilities'. Partly as directed by BGF managers, the research of the author has been focused on the assembly manufacturing system of BGF, the operating requirements of which were described

by BP71. There are sub BPs and enterprise activities (EA)s within BP71. Part of BP 71, namely sub BP 71-2 specifies how BGF assembles carcasses and fits components. This is the specific focus area of concern of this research.

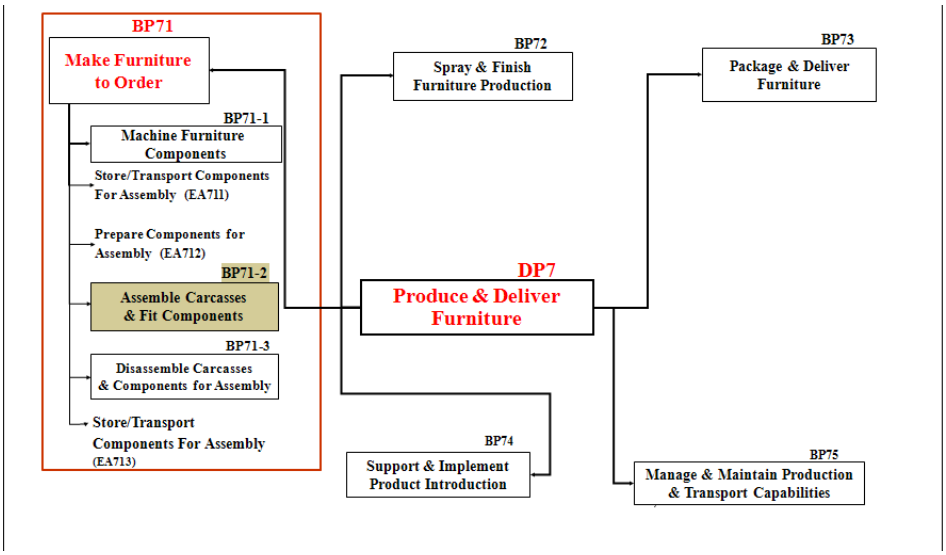


Figure 5.3 Structure diagram of DP7

The ultimate aim of CIMOSA modelling and decomposition is normally to create a network of dependent activity diagrams which are essentially process models that are formally linked together via higher level context, interaction and structure diagrams previously produced and described. Figure 5.4 shows an example decomposition of production process and sequences within BP71-2 'assemble carcass & fit components' that were modelled at various levels of granularity in the form of CIMOSA activity diagrams. The assembly shop of BFG comprises three sections, namely, table, cabinet and bed assembly sections. Essentially it was found that there are two table types that BFG assembles,. They are: 'Drop Leaf' (DL) and 'Farm House' (FH) table. While product sub-groups within the cabinet area consist of Base unit; Solid doors; Drawer; Rothley; Display unit top; Breakfront base. In the area of bed making is the Beau manor bed. Operational processes (and related activity sequences needed to realise these different product types are shown in figure 5.4. In effect figure 5.4 illustrates the decomposition of BP71-2 at the enterprise activity level such that it codes up the processing routes for different products as they are processed by the assembly manufacturing system of BGF. The reader can observe that the 'static process differences' occur because of the PV in the system and that these differences can be clearly shown using CIMOSA modelling technique. However, the impact of other Product Dynamic factors cannot be explicitly described using standard CIMOSA modelling constructs, particularly where dynamic state changes need to be detailed.

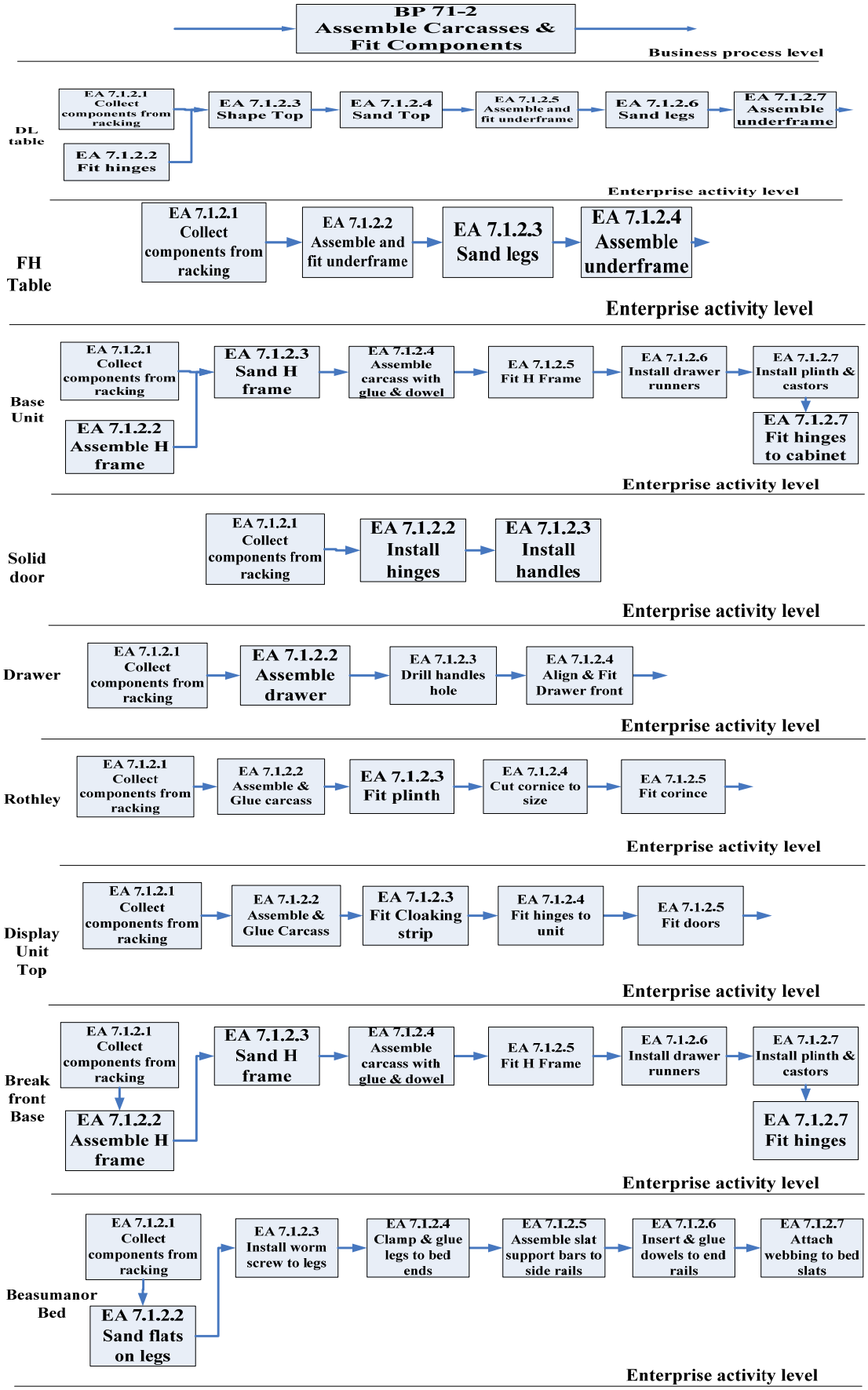


Figure 5.4 Activity diagram of BP71-2

It follows that in the case of BGF, CIMOSA requirements modelling was used to describe relatively enduring (structural) relationships between different elements of the BGF enterprise. However to develop time-based behavioural models of the manufacturing systems used by BGF, so as to enable more effective enterprise engineering, it was necessary to transform the CIMOSA activity diagrams into either discrete event or continuous simulation models that can computer execute, and thereby model states and state transitions of modelled manufacturing systems, as different forms of Product Dynamics are input to these models.

5.2 Simulation model development

Simulation modelling can provide support to ME design and change in a number of ways including: a) understanding required manufacturing system behaviours during the life phases of products; b) identifying possible solutions when ME change is required; c) visualising change in manufacturing system behaviours to facilitate prediction during planning.

These understandings led to the selection of two types of simulation technologies for use in this research, namely 'discrete event simulation' and 'continuous simulation'. In this thesis though, the discussion only describes the use of a specific discrete event simulator, namely 'Simul8' (Simul8 2000). Simul8 was chosen mainly because of its availability and its provision of excellent technical support within the MSI Research Institute. However it was also observed that discrete event simulation technologies are well suited to modelling some of the core variables of concern (particular state changes and queuing) within EoSS systems. Simul8 is not claimed to be the best in class tool for this purpose but it has proven to be flexible and effective. The second simulation technology considered in some detail was a continuous simulation tool called *ithink* (ISEE 2007) which was designed to directly computer executes causal loops of manufacturing systems and their related business environments. *ithink* deploys numerical integration to solve non-linear differential equations and its use is well proven for large scale, complex systems modelling. However its experimental use during this study showed its modelling principles are not well suited to encoding distinction between complicated, time-dependent flows of different and unique product types through manufacturing systems.

A detailed study was made of the assembly operations carried out in the BGF table assembly section to assemble DL (Drop Leaf) and FH (Farm House) table products. Table 5.1 illustrates some of the time study results obtained, which shows average operation times

taken by operators, as (aided by fixtures, tools and general purpose wood-making machines) they produce and assemble different table products. Table 2 also shows that BGF makes 7 different types of FH table and 8 different types of DL table. This shows that the sequence of assembly operations, and average operation times, are very similar for all members of the FH table class. Additionally all DL table types share a common operation sequence, but some operation time differences can be observed within this product class.

Table 5.1 Operation and op-time summary of selected table types of BGF (data source MSI)

	Collect from racking	Fit piano hinges	Shape top	Sand top	Assemble under-frame	Fit under-frame to top	Sand leg	Assemble under-frame
FH1	5 min	*	*	*	20 min	15 min	15 min	15 min
FH2	5 min	*	*	*	20 min	15 min	15 min	15 min
FH3	5 min	*	*	*	20 min	15 min	15 min	15 min
FH4	5 min	*	*	*	20 min	15 min	15 min	15 min
FH5	5 min	*	*	*	20 min	15 min	15 min	15 min
FH6	5 min	*	*	*	20 min	15 min	15 min	15 min
FH7	5 min	*	*	*	20 min	15 min	15 min	15 min
DL1	5 min	15 min	20 min	10 min	10 min	15 min	20 min	10 min
DL2	5 min	15 min	20 min	10 min	10 min	15 min	20 min	10 min
DL3	5 min	15 min	20 min	10 min	10 min	15 min	20 min	10 min
DL4	5 min	15 min	20 min	10 min	10 min	20 min	20 min	10 min
DL5	5 min	15 min	20 min	10 min	20 min	20 min	20 min	10 min
DL6	5 min	15 min	20 min	10 min	20 min	20 min	15 min	10 min
DL7	5 min	15 min	20 min	10 min	20 min	20 min	15 min	10 min
DL8	5 min	15 min	20 min	*	*	*	*	10 min

As explained in section 5.1 and shown in Figures 5.3 and 5.4, prior to the time study of DL and FH assembly sequences, BP 71-2 'Assemble Carcasses & Fit Components' and its constituent Enterprise Activities had been modelled using CIMOSA at a higher level of abstraction. Here BP 71-2 was modelled as part of the BFG 'big picture' process network. Therefore the activity diagrams of Figure 5.4 and the table assembly sequences shown in Table 5.1 flesh out some of the detail of assembly process modelling, which had been hidden within the more abstract 'in context' model of BP 71-2 described by Figure 5.3. But the reader should also be aware that in this case the fleshing out was only partial as many other BFG product types (a total of around 350) have, as required by customers, to flow through the real BFG BP71-2 assembly process segment. Furthermore the reader should understand that BP71-2 is but one of many assembly processes realised in the assembly section of BGF. When building simulation models therefore the model builder needs to cut through this complexity to enable creation and use of models of practical and effective simplicity while still being able to replicate actual behaviours of real ME segments. The complexity of simulation models can grow very quickly also because not only the processing sub-system (and its complexity) needs to be modelled to exhibit system behaviours. In addition the

human and resource system elements, their binding structures, and related work flows through process and resource elements need to be modelled. However the step-wise approach described in sections 5.1 and 5.2 illustrates how simulation model simplification and modelling building can in part be systemised.

In the real BGF Assembly Shop, DL and FH table types are but two of a total of 18 table product types produced. Having considered DL and FH table assembly operations in detail, as described by Figure 5.4 and Table 5.1, it was decided that BP71-2 could realistically be decomposed into 6 EAs. This decomposition was coded in the Simul8 tool by using the work centre, work entry and exit, and queue modelling constructs of this tool; this is illustrated by the screen shot of figure5.5. Each EA was studied in detail to develop groundwork knowledge needed to create this simplified simulation model which will be referred to as SM1. Essentially SM1 was designed to simulate state behaviours of the Drop Leaf table assembly process. Here detailed study centred on: defining processing activities and routes; and on grouping activities into 'roles' that can be assigned to Work Centres (WCs) incorporated into SM1. Following which human and other resources needed to realise each WC were assigned. Thereby SM1 was designed and developed to model the time-based behaviours of : enterprise activities EA 7.1.2.1 and EA 7.1.2.2 that are executed by WC1 Bench 1; EA 7.1.2.3 which is executed by WC2, which in turn involves CNC routing operations; EA 7.1.2.4 which is executed by WC3 to' Sand tops'; EA 7.1.2.5, which is executed by WC4 and Fits under frames; EA 7.1.2.6 which is executed by WC5 and Sands legs; and finally EA7.1.2.7 which is executed by WC6, so as to Assemble under frames.

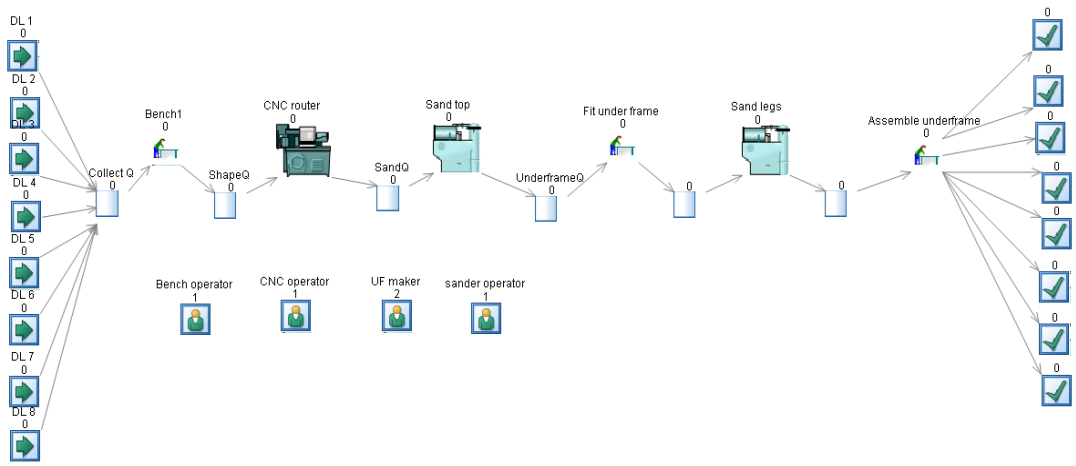


Figure 5.5 Simulation model of Drop Leaf Table assembly process SM1

It was observed that if the assembly process used to realise Drop Leaf tables is considered in isolation this constitutes a Case 2 EoSS system; as previously defined by the author in section

4.2 of this thesis. In other words, SM1 models a Case 2 EoSS manufacturing system. This observation was made as there are 8 types of DL table within the DL family, each of which requires an essentially common manufacturing process such that they can effectively share the same P/R couple. In this example Case 2 EoSS system however only relatively minor processing differences and resource requirements are needed for different DL types. Having studied the product dynamic factors within the isolated DL table assembly system, it was observed that VD, PV and PMD (associated with any DL mix) can all impact on the table assembly system with potentially significant change in instantaneous values; which in turn will significantly influence the behaviours and performance of the assembly shop. However it was later observed that although the 8 types of DL table are physically different in terms of dimension and feature, during assembly this only gives rise to a PMD mix that requires op time (i.e. processing time) differences, which in turn requires relatively minor differences in resource requirements (compared to that found later when DL and FH table types were assembled together). As the BGF factory needs to be able to assemble all DL types in uncertain quantities and mixes, it is however necessary to reprogram the resource systems of the assembly shop (comprising both human and technical resources) every time different mixes of DL are assembled.

However later it was observed that some of the DL tables have the same processing time and resource requirement, while others do not. Hence it was decided that the very similar DL table types could be grouped (into essentially a separate sub-class of table). Within this new group there were still dimensional (shape) differences between group members but this difference had previously been realised via make operations performed in the machine shop. Therefore with respect to operations performed in the assembly shop within this sub group essentially there was zero variance (i.e. PV=0 and PMD=0) across members of that sub-group; which in turn meant that the manufacturing system needed to assembly this sub-grouping of DL table products could reasonably be considered to be a Case 1 (economy of scale) manufacturing system (because only VD impacts as a significant product dynamic factor).

Having made this observation, a new design of the DL table assembly system was proposed and simulated as SM1'. The conceptual design of SM1' is shown in figure 5.6. In the SM1' system model, the input Work Dynamic was in effect reduced by conducting a GT analysis for product groupings (even though the original Product Dynamics caused by production

order variation remained unaltered the Work Dynamic impacting on the modelled assembly system had essentially been attenuated). This meant that for the original Product Dynamics there were 8 different types of DL table giving rise to variance, as individual entries to the system; but this was reduced to 5 by grouping products with the same processing time. As a consequence differentiation between types of DLs was '***postponed'*** to a downstream processing activity (namely assembly of under frames) rather than at original upstream entry points.

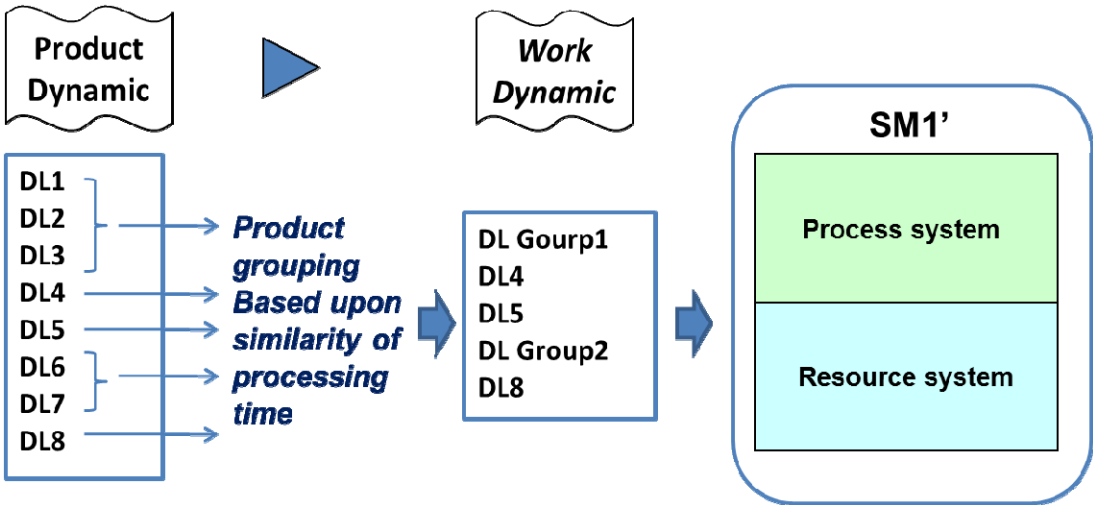


Figure 5.6 Conceptual design of improved simulation model SM1'

This modified SM is illustrated in the Simul8 screen shot of figure 5.7 as SM1'. When compared to SM1, the number of 'Job entry points' is reduced from 8 to 5, because 3 of the DL family members share a Case 1 manufacturing system for which members of the consolidated group enter via a single entry point.

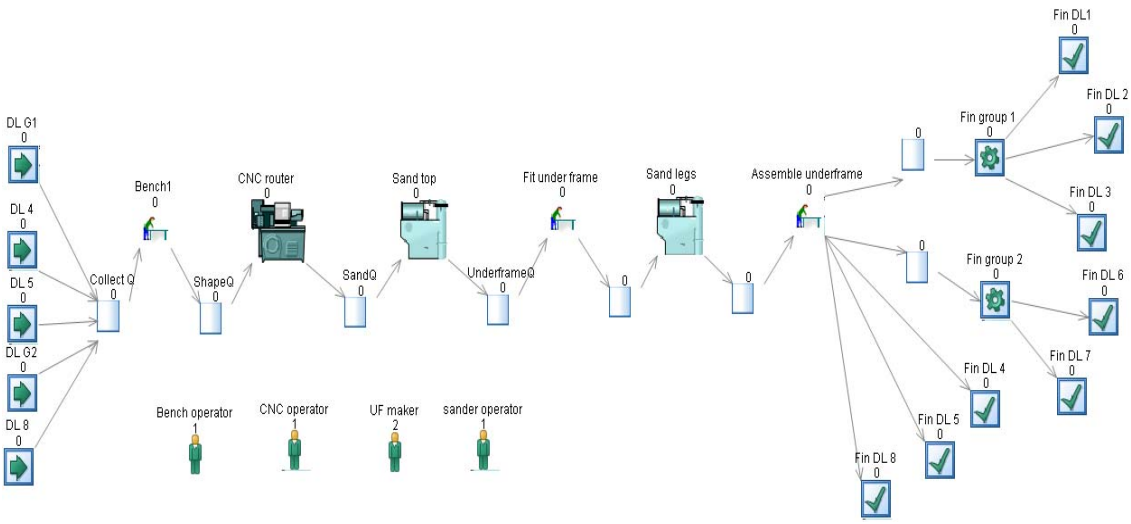


Figure 5.7 Simulation developed model of Drop Leaf Table assembly process SM1'

The reconfiguration of workflows through P/R couples illustrated by figure 5.7 could be highly beneficial in BGF. This is because the original BGF assembly system is overly

flexible because in reality set ups are only required for 5 rather than 8 table types. This example illustrates FFMS requirements simplification (as defined by Terkaj and Tolio 2009) and how a new conceptual system design can satisfy those focussed flexibility requirements. In the developed virtual environment the above assumptions were confirmed when both SM1 and SM1' simulations were run for 1 month, with the same order entry rate. The experiments performed with SM1 and SM1' to test the above assumptions required a choice of model variables that suitably reflect BGF reality and allow a fair comparison to be made about the behaviours of the two model configurations. Having studied historical BGF order patterns, an average inter-arrival time for products was calculated as being every 360 minute. To ensure parity the inter-arrival time for consolidated groups 1 and 2 was also maintained at this value but a batch of 3 and 2 respectively was input for those groups.

Sample results related to this comparison are shown in the 'Lead time' comparison presented in table 5.2. Significant improvement is predicted from the SM1'configuration. Further investigation of the source of this improvement was conducted. Here the source of the reduction in lead time was observed to be due to a significant reduction on queue (Work In Process) time in areas of the SM1' system.

Table 5.2 Lead time consumption comparison of SM1 and SM1'

	DL1	DL2	DL3	DL4	DL5	DL6	DL7	DL8
Lead time in SM1 (days)	27.1	27.2	28.2	27.2	27.6	27.5	27.6	27.4
Lead time in SM1' (days)	7.7	7.7	7.2	7.8	7.6	7.6	7.6	7.5

After-running the model with the aforementioned input conditions, screen shots of SM1 and SM1' are shown in figures 5.8 and figure 5.9. It is evident that the major lead time difference comes from very significant WIPs and Queues in SM1. Figure 5.8, shows these WIPs (or queues) before the 'Bench1' work centre and the 'CNC router' work centre. For the case of SM', figure 5.9 shows a reduced bottle neck in front of the 'Sand top' work centre. To compare the total average queuing time (which can be a measure of WIP queuing time) for both SM1 and SM1' systems, these three significant bottleneck work centres were selected for further analysis. An associated summary of queuing times is illustrated in table 5.3.

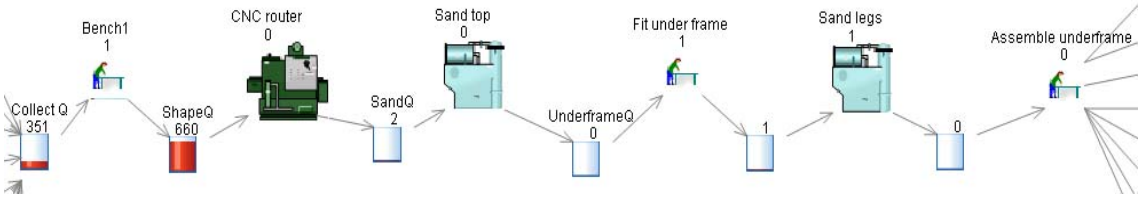


Figure 5.8 After run screen shot of SM1 (bottle neck identification)

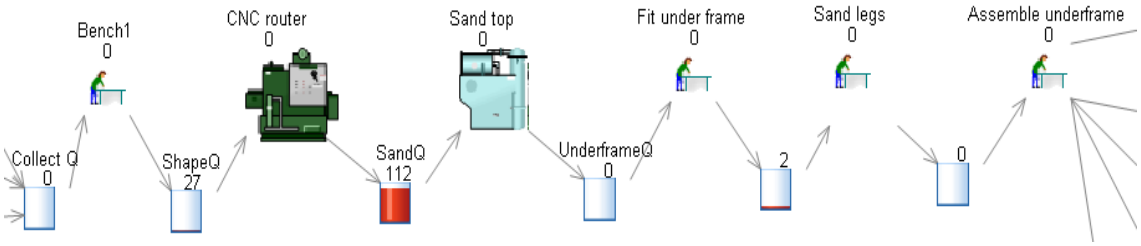


Figure 5.9 After run: screen shot of SM1' (bottle neck identification)

Table 5.3 Queuing time comparison of SM1 and SM1'

Categories	SM1	SM1'	Change in Queuing time
Bench1 Q time (days)	9.7	0.1	Reduced by 9.6 days
CNC router Q time (days)	21.1	2.1	Reduced by 19 days
Sand top Q time (days)	0.4	5.0	Increased by 4.6 days
Sum of delay (days)	31.2	7.2	Reduced by 24 days

The same methodology was used to understand and redesign the BGF assembly systems for FH table types. As explained earlier there are 7 different types of FH table produced by BGF. This led to the creation of a Case 2 EoSS simulation model, namely SM2. SM2 therefore was created with 7 FH table type entry points to provide a simplified model of the BGF FH table class assembly system. Subsequent analysis showed that very minor processing route and time differences are required to assemble the 7 FH table types. Following detailed analysis of their respective processing routes and times, it was decided all 7 FH table types could be reasonably consolidated into one product group. This allowed the creation and simplified use of SM2', a Case 1 system. A SM2' model screen shot is shown in figure 5.10. This product type consolidation and resultant change in assembly system reconfiguration also produced significant lead time spending benefits. The results obtained from SM2 and SM2' experiments have since been published in Cui and Weston (2008). Having created SM1' and SM2' the product consolidation ideas were further developed to consider the design of a Case 3 system capable of using a common system of resources to assemble all DL and FH table types.

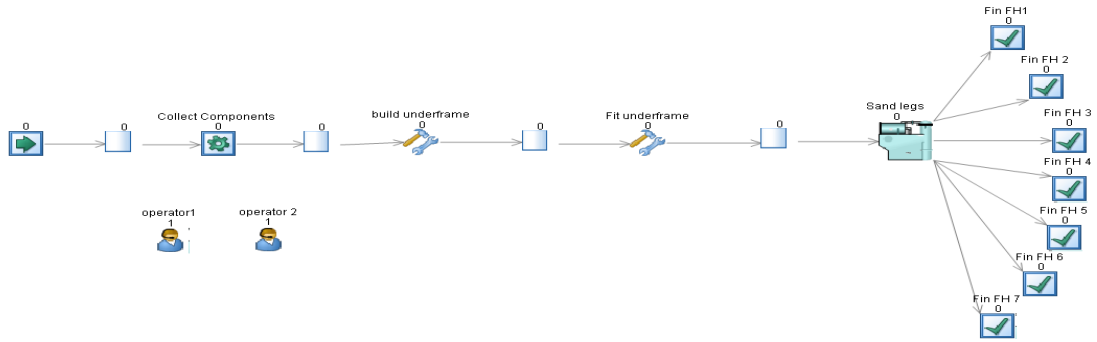


Figure 5.10 Simulation model of Farm House Table assembly process SM2'

5.3 EoSS Model Reconfiguration

After understanding BGF assembly system behaviours in response to different Work Dynamic impacts arising from DL and FH product families, the next stage of modelling carried out was to re-model the manufacturing system in a more realistic 'as is' form. Because in the 'real BGF plant' all table assembly work is carried out in the 'Table Assembly Area', this means that in reality all types of table share the same Process and Resource system. However, that system was understood to comprise an 'as is' configuration of more elemental P/R couples.

Therefore the actual situation was remodelled by creating SM3; such that both DL and FH product families share one assembly process, with the same set of work centres being resourced by a common underlying human and technical system. The screen shot of the developed SM3 is shown in Figure 5.11.

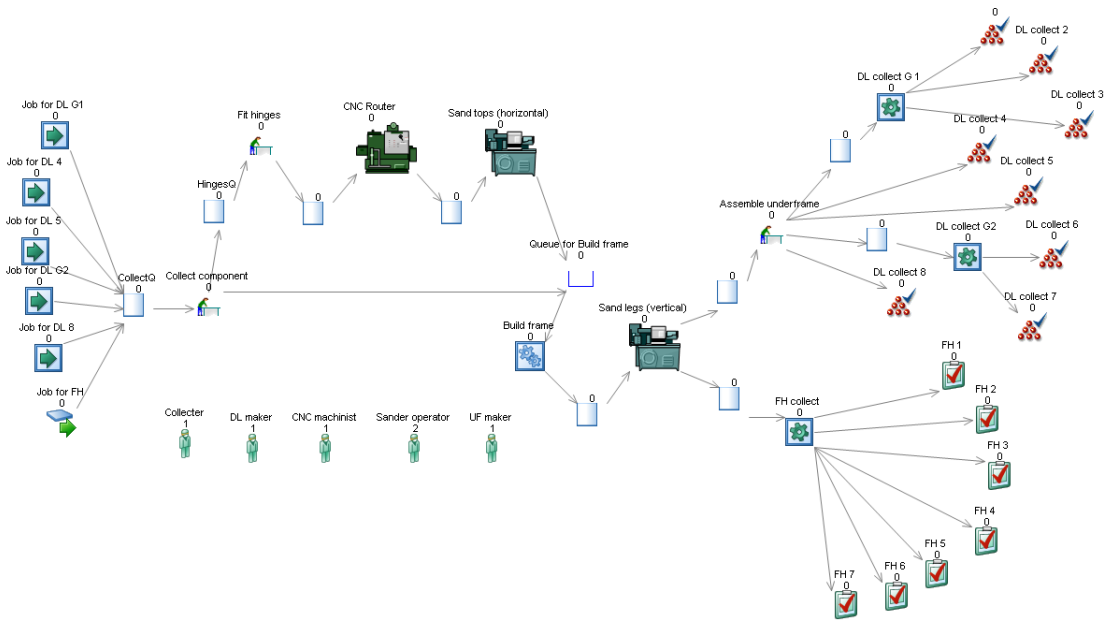


Figure 5.11 'As is' model of table assembly system SM3

The actual manufacturing system, modelled by SM3, realises products that cross product family boundaries. Therefore during model runtime, instantaneous states of VD, PV and PMD all significantly impact on process routings and process timings. Therefore resource requirements will vary as a function of time. This was assumed to mean that reconfiguration of the manufacturing system at runtime is needed to produce all of those different types of table products in order to meet required due dates. As can be seen in the screen shot of SM3 (see Figure 18) there are alternative routings out from the operation 'collect components', leading to different DL and FH table assembly processing. Also as the operation times for DL and FH tables are distinct, in SM3 it was necessary to distinguish the processes of the different product flows by using numeric labels. Therefore when production orders arrive that define a requirement to assemble different types of DL and FH table, this means that a greater scope of PMD is required than was the case for SM1 and SM2; and that essentially a run time reconfiguration of 'P/R couples' is needed. Therefore, the 'as is' manufacturing system is considered to be a Case 3 system; and SM3 which mimics the reality of the 'as is' situation is a Case 3 system model.

The foregoing research and discussion in earlier thesis chapters about manufacturing industry needing more rapidly to respond to changing business environments, explained that Leagile and Postponement strategies (Mason et al 2000; Loe 1998), are becoming widely adopted in different types of ME. In the case of BGF, the management believe that their realisation of EoSS is necessary to achieve cost effectiveness in their business environment where many different products (circa 350 in the real situation) are required in uncertain quantities in any given time frame. Also BGF are heavily constrained as they have a limited human resource with the competencies required to produce such a wide product scope. This initial application of the IMI and its related modelling steps and enterprise and simulation modelling techniques has shown how that a complex manufacturing reality can be decomposed into separate sub-realities associated with different product types, and product families so that behaviours of different product realisations can be much better understood. Following which (also using simulation technologies) those separate realities can be reconstituted back into a whole model (using enterprise and simulation modelling concepts and tools) to mimic (and hence understand and analyse) situations that are closer to the reality. This chapter has discussed alternative designs of BGF's table assembly shop with reference to state of the art manufacturing concepts, as illustrated in figure 5.12.

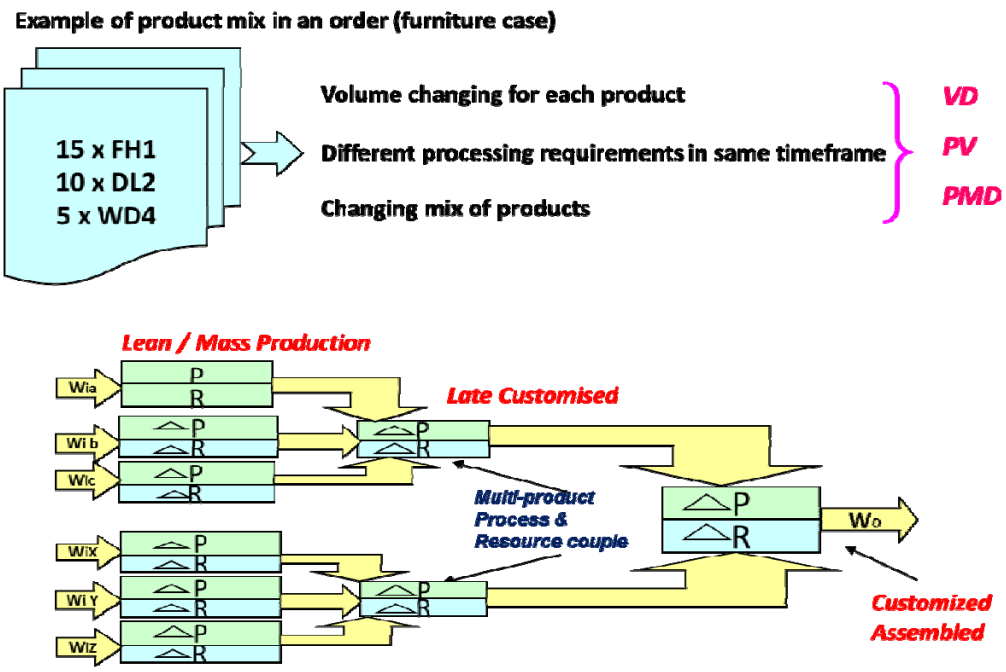


Figure 5.12 Illustration of the use of manufacturing concepts to achieve EoSS

To be able to design an effective manufacturing system that can realise Economies of Scope, it was observed to be necessary to adopt suitable manufacturing technologies so that required productivity and other performance levels can be achieved and maintained. Hence simulation models of possible 'to be' manufacturing system configurations can allow industry to 'try out' their assumptions about implementing different manufacturing paradigms to support medium and long term decision making about the design of manufacturing systems. Mass customisation (Tseng; Jiao 2001) is one of a number of possible manufacturing strategies that can be used to re-design the BGF manufacturing system. When VD; PV and PMD impacts arise with the input of partially uncertain production orders, this can lead to unacceptably long lead-times. The idea of Mass customisation is to realise Mass production for as much of the product realisation process as possible, so as to reduce the set up times of machines and human resources, to minimise queuing times and travelling time of work items, etc. This kind of thinking can be supported by the idea that where possible it would be advisable to postpone customisation to as late as possible (Jiao et al 2004). However this thinking will remain in the realms of qualitative reasoning without the availability of suitable quantitative and predictive technologies. In this chapter however the author has reported on a case study application of the IMM which shows significant promise as the basis of a systematic means of satisfying this observed lack of technology provision in industry. Furthermore, to facilitate such a quantitative redesign (and virtual testing of that design) a 'to be' model SM3' of BGF

assembly processing was created to predict possible outcomes from using a new mass customisation (with late postponement realise) approach to table assembly. A screen shot of the simulation model 'SM3', developed for this purpose is shown in figure 5.13.

From the earlier SM modelling studies in BGF, it was observed that the 'sand leg' operation is needed for both Drop Leaf and Farm House tables. Also observed was that the operations: 'build frame'; 'fit under frame to top' and 'assemble under frame'; are more customized operations. This is because distinctly different operations are required for different groupings of DL and FH tables. So that in SM3', the work centre used to 'Sand legs' was placed in the upstream process rather than in the downstream process.

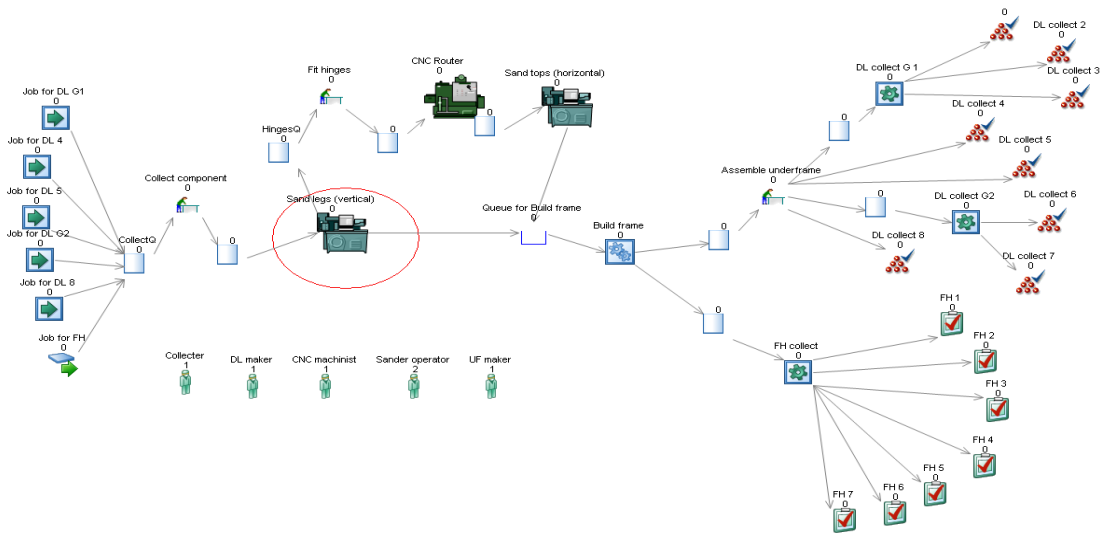


Figure 5.13 'to be' model of table assembly system SM3'

5.4 Related KPI comparison

SM3 and SM3' were both run over a period of one month using the same variations in production order data. Following which their relative behaviours and performances were observed. Here 3 primary KPIs were chosen to systematically differentiate between the manufacturing system designs coded by those SMs. Simulated production behaviours led to runtime calculations related to these KPIs so that simulation model users can compare: 1) Lead time spending in each model; 2) Utilizations of machines and human resources; 3) Throughput.

During experimentation it was observed that lead-time spending was important in terms of benchmarking the pros and cons of different configurations. Illustrative results obtained when comparing SM3 and SM3' are summarised in Table 5.4. The order pattern input to SM3 and

SM3' to generate Table 5.4 was as follows: DL and FH table orders comes everyday with a batch of 3 and 4 respectively.

The total lead-time behaviours of SM3 and SM3' are summarised by table 5.5. This illustrates example rules that can be applied to decide what assembly configuration would be best to adopt for a given a particular group of customer orders or an expected new order pattern. If for example mostly DL 2, 3, 5, 6, 7 or FH 3, 5, 6 product types are required by customers within a specified timeframe, then the SM3' configuration will perform better. But when product types DL 1, 4, 8 or FH 1, 2, 4, 7 are dominant, the SM3 configuration will be a more suitable choice from a lead-time point of view. Clearly however the practically of applying these rules will depend on the ease and extent to which reconfiguration and/or reprogramming is necessary and can be achieved. Also trying to reduce the lead-time may not be the best policy for MEs operating in environments where response times are not at a premium. None the less in general this kind of knowledge about product/work dynamic impacts can assist production planners and production system designers, who might decide to switch configurations regularly or episodically by weighing up performance benefits relative to the cost of such changes.

Table 5.4 Summary of Lead time comparison between SM3 and SM3'

	DL 1	DL 2	DL 3	DL 4	DL 5	DL 6	DL 7	DL 8	FH1	FH2	FH3	FH4	FH5	FH6	FH7
LT in SM3 (days)	15.1	14.8	15.0	12.9	27.3	15.2	15.4	9.5	14.1	12.6	14.8	13.8	13.9	15.1	14.2
LT in SM3' (days)	15.3	14.4	14.6	14.5	17.6	14.1	14.5	14.5	16.1	15.8	14.4	15.8	6.9	14.8	14.7
Improved in LT		√	√		√	√	√				√		√	√	

Table 5.5 total LT behaviours observation in both SM3 and SM3'

	DL2,3,5,6,7	DL1,4,8	FH3,5,6	FH 1,2,4,7
LT in SM3 – LT in SM3' (days)	***12.5***	***-6.8***	***7.6***	***-7.7***

Throughput was also chosen as a KPI to compare the behaviours and performance of different configurations. Here benchmarking was carried out in which throughputs of SM1, SM2, SM3 and SM3' were compared. All models were run with the same four scenario conditions. The four different conditions were:

1) Low order rate and Low batch size. This was characterised as FH table orders come every 4 days with a batch size of 5; while DL table orders come every 3 days with a batch size of 3.

2) Low order rate, High batch size. This was characterised as FH table orders come every 4 days with a batch size of 20; while DL table orders come every 3 days, with a batch size of 15.

3) High order rate, Low batch size. Characterised by FH table orders come every 0.5 days with a batch size of 5; DL table orders come every 1 days with a batch size of 3.

4) High order rate, High batch size. Characterised by FH table orders come every 0.5 days with a batch size of 20; while DL table orders come every 1 days with a batch size of 15.

Figure 5.14 shows that with order pattern 1, namely when both frequency of orders and volume of products is low, SM3 and SM3' configurations generate similar throughputs. But when the order patterns changed the throughput behaviours of SM3 and SM3' systems will react significantly differently.

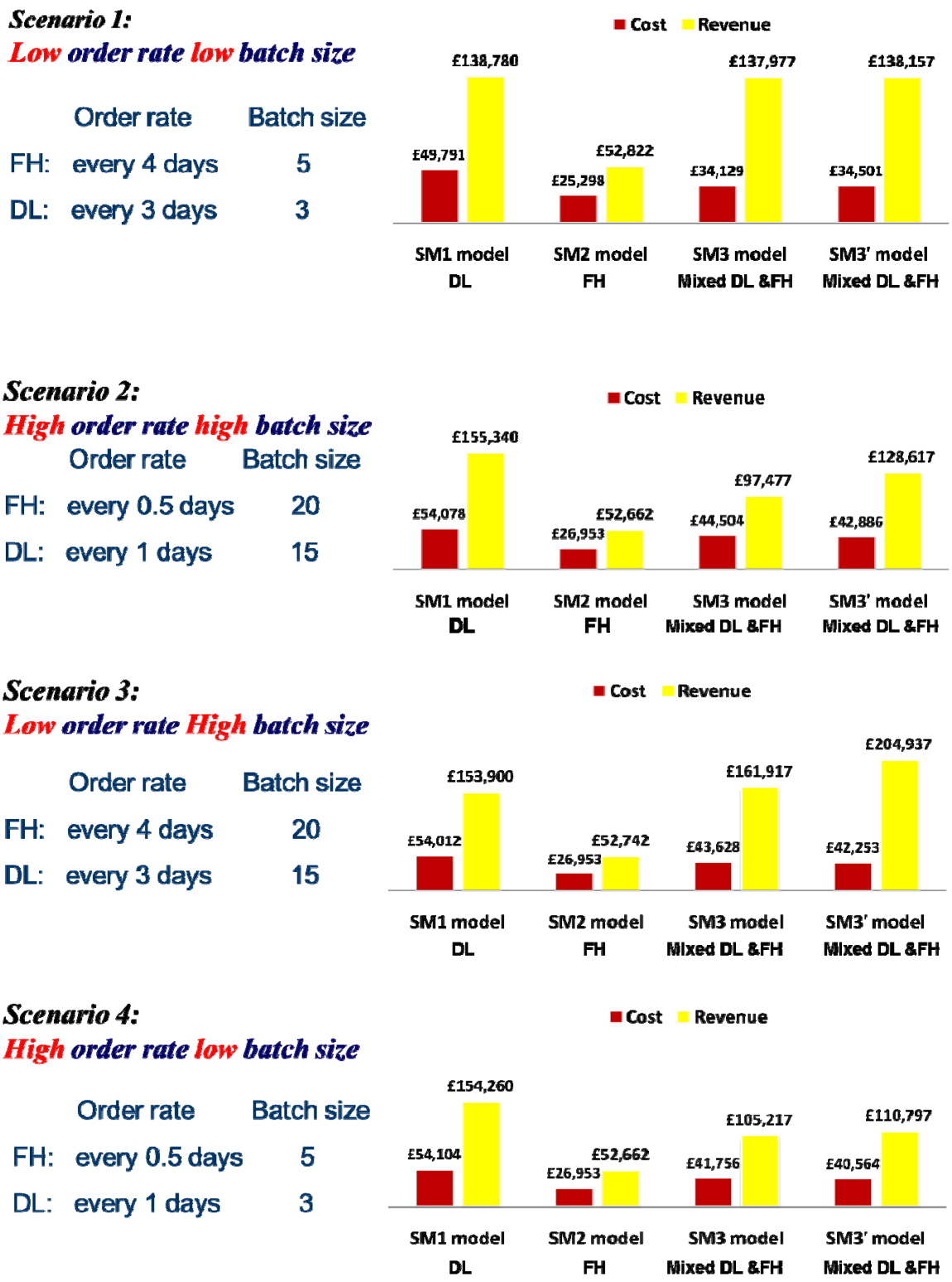


Figure 5.14 throughput comparisons of 4 models

To summarise, models SM1 and SM2 were developed and used to analyse throughput behaviours and performances when BGF is operating as a Case 1 EoSS assembly system; i.e. where only a single product type is made. During SM1 modelling only Drop Leaf table production was studied; while during SM2 modelling focus of attention was on Farm House

table production. The outcomes of modelling experiments using SM1 and SM2 showed that during single product production, DL table type making can realise greater profit for BGF than can FH product types. Subsequently both model SM3 and SM3' were used to simulated feasible operational behaviours and performances during mixed product production when using the then current resource system configuration adopted by BGF. It can be seen that, in a scenario where either orders arrive with a 'high order rate and high batch size' or a 'low order rate and high batch size', the scenarios modelled by SM3' generate a better throughput. Hence it was suggested to BFG management that the proposed Case 3 'to be' assembly system (SM3') configuration can be used with advantage when they need to respond to scenarios 2 and 3 as characterised by figure 5.14.

The cost comparison has been made by including the cost of: human labour and machine depreciation; and materials. But no account has been taken of factory overheads or work in progress costs. This is because all relevant factory data was not available. The assumptions made have not negated the argument but rather this has helped retain clarity of argument. The message of this chapter should be made clear. Namely, by using the IMM proposed, in theory much improved understanding of complex manufacturing realities can be achieved. Potentially this can lead to enhanced manufacturing systems design and engineering decisions; based on quantified performance criteria.

It is important to note that there is no constant best solution, the design or redesign of the manufacturing system is strictly connected to nature of the Product Dynamics in a given ME.

Chapter 6 Exploratory research case 2

During the first and second years of the author's PhD study, as part of a small MSI project team, she carried out a second exploratory case study for a UK commercial furniture manufacturer which trades under the title of the Wood-Team Group. The aims of this study were to obtain: a) further exploratory learning on the industrial application of enterprise and simulation modelling techniques; and b) further experience of working with manufacturing companies. The project activities involved the author in: visiting two factories, which form part of the Wood-Team Group of companies; interviewing high- mid level managers; capturing information and data from knowledge holders within the Wood-Team Group; building models for Wood-Team and validating their structure and content with the potential Wood-Team users; presenting project findings of the project to key Wood-Team personnel.

6.1 enterprise modelling and processes network description

The second exploratory case involved a study of a commercial furniture manufacturer located in the UK, namely Wood-Team (W-T) Group. Their furniture products are used by shops to display their consumer products. For example, W-T realise furniture products like shelves in supermarkets, book shelves for book stores and clothes for demo in cloths stores. Therefore W-T has a wide range of customers, many of whom are shopping chains and large stores.

The first phase of the project work involved creating an enterprise model for W-T. Figure 6.1 is the context diagram of the EM created in respect of W-T.

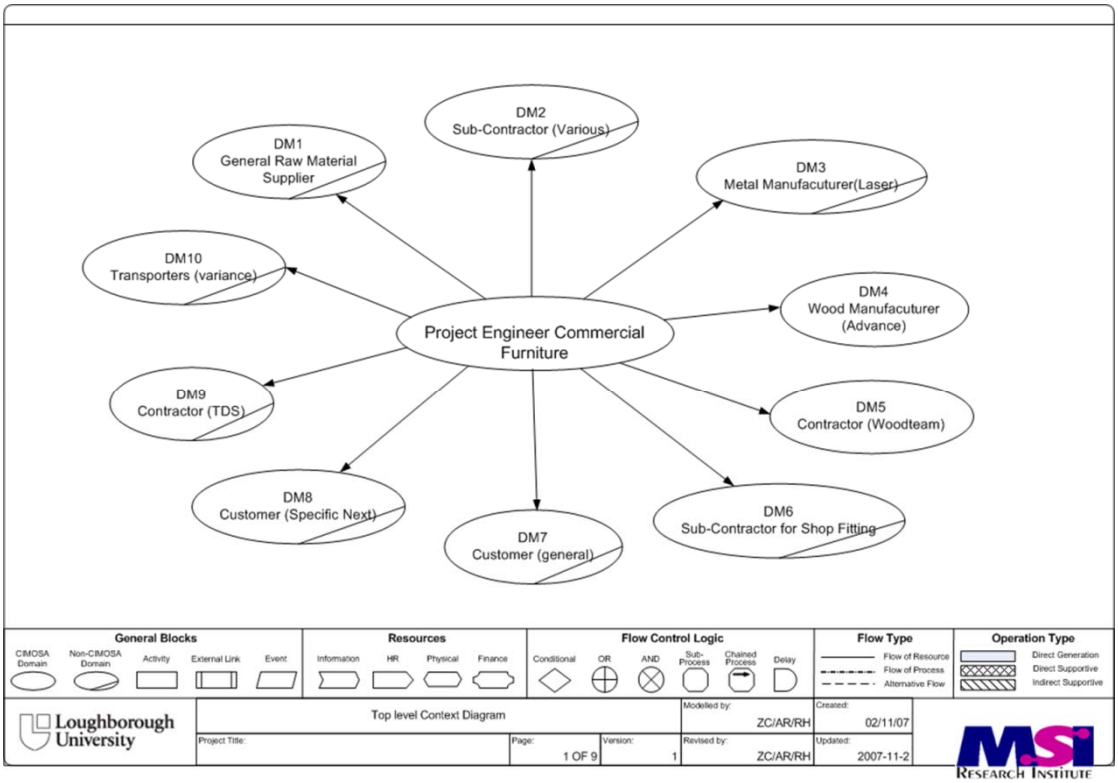


Figure 6.1 context diagram of enterprise model of WT

This figure shows 10 domains (DMs) of the W-T enterprise identified; some of the key details of each DM are listed in table 6.1.

Table 6.1 documentation of EM domains in WT

DM1 General raw material suppliers	Two types of primary (wood based) raw materials are supplied for W-T, namely: 1) pre-finished?? which needs edge banding; 2) raw MDF material
DM2 Sub - contractors	Sub-contractors for the manufacture/supply of miscellaneous parts like glass, etc
DM3 Metal manufacturer	A outsourced supplier for metal components
DM4 Wood manufacturer	Two wood furniture production plants separately located; one primary machining furniture 'components' the other assembling W-T products to meet customer specifications and contractual arrangements
DM5 Contractor (WT)	The commercial wood furniture contract centre
DM6 Sub-contractor for shop-fitting	Specific sub-contractors for the delivery of furniture products/ orders/contracts requiring bespoke fitting at customer sites
DM7 Customer (general)	General customers
DM8 Customer (specific)	A specific customer where have separate order fulfilment process
DM9 Contractor (TDS)	Parts suppliers
DM10 Transporter (variance)	Transportation suppliers

W-T markets itself as an 'Engineer to Order' (ETO) Company. This assertion was confirmed as it was observed that every order (or contract) won is handled by an assigned project manager working in the W-T contract centre.

ETO in the W-T case meant that furniture products built and supplied by W-T so that they meet specific customers' requirement (Bertrand 1993). Therefore in over-view the order fulfilment process is treated as project management process; although this overall process involves managing & synchronising events occurring in more elemental 'purchase', 'make', 'assembly', 'delivery' and possibly 'shop fitting' processes.

The Project Management (PM) team comprises: 5 senior managers and 2 assistants. Each senior manager can head a project (which involves a specific order or contract). In consultation with the owner/general manager of the W-T Group it was decided that focus of the authors study would be on DM4, 'wood manufacture', and DM5, 'Contractor', of W-T; hence these domains were modeled in detail, as indicated in the CIMOSA context domain. The demonstration of modeling this chapter is focused on DM 4 which corresponds to the production system of the company. As mentioned previously there are two parts of the W-T furniture manufacturing system: 1) machining plant and 2) assembly plant; which are located some 5miles apart. Figure 6.2 illustrates the interaction diagram of domain process (DP) 4 'wood manufacturing' of the W-T EM. It can be seen that when W-T obtains orders from customers, the product realization process starts from BP 5.2.3 'Raise purchase order', which is a sub process of DP 5 (the contract center). After receiving an order from BP 4.1 'obtain order', customer information and payments are processed via business process (BP) 4.2, which results in 'order and production planning'; then order information is delivered to the machining plant to start production operations (BP 4.3 'machining'); following which pre-finished furniture components are delivered to the assembly plant where furniture product assembly is carried out (BP 4.4 'assemble'). After assembly, the furniture is delivered to a warehouse (BP 4.5 'warehousing and delivery') where it waits for transportation to customers. Full WT enterprise model is shown in appendix I.

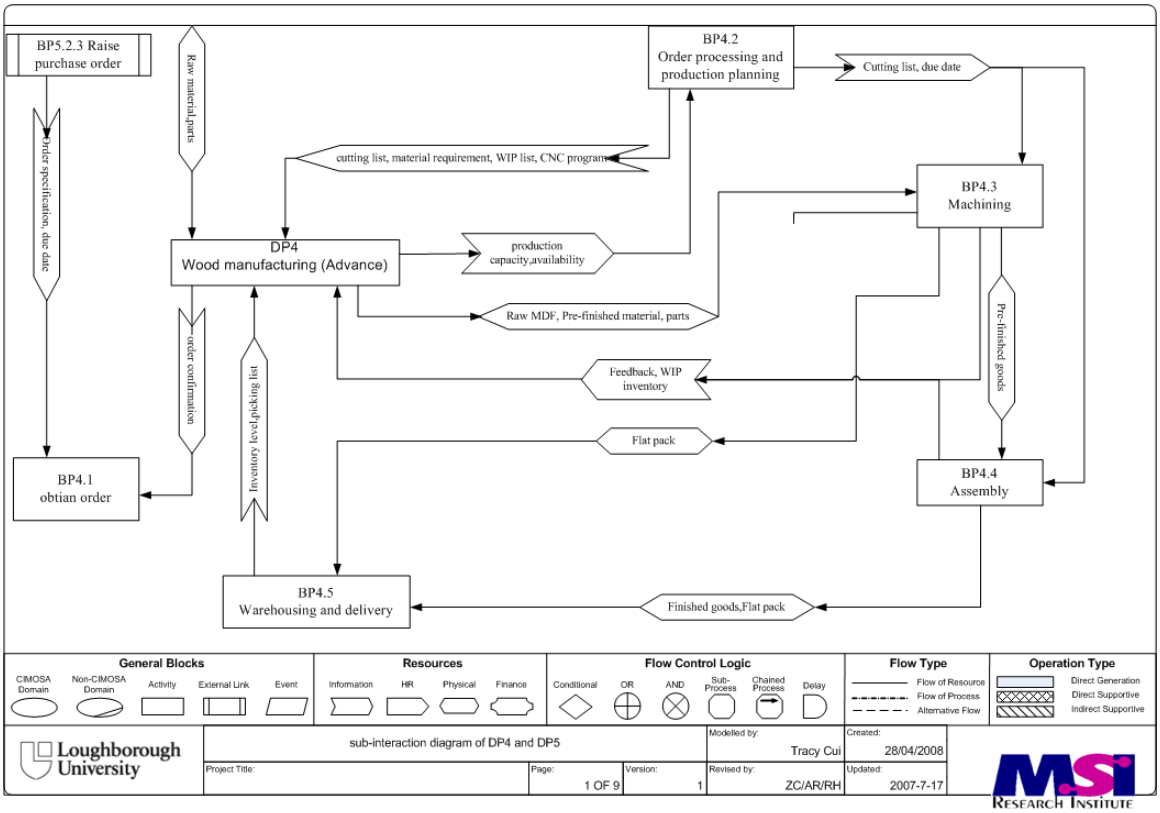


Figure 6.2 Interaction diagram of DP 4 wood manufacturing

Figure 6.3 shows the structure diagram of DP 4, which shows how DP 4 is decomposed into its more elemental BPs and enterprise activities (EAs). As previously discussed, BP 4.3 'machining' and BP 4.4 'assembly' were the main focus of the author's study modelling, hence the author documented a further decomposition of BP4.3 and BP 4.4. The sequence of activities that comprise BP4.3 'machining' and BP 4.4 'assembly' is illustrated in figure 6.4.

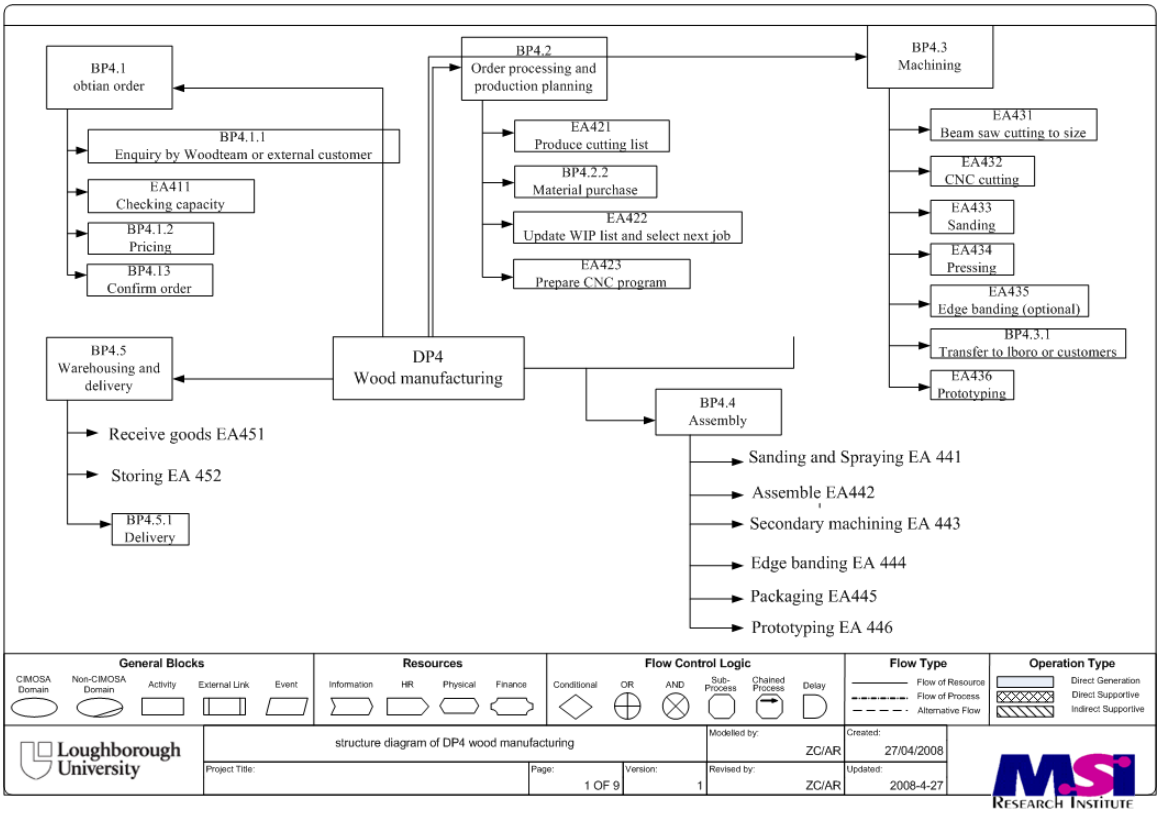


Figure 6.3 Structure diagram of DP 4 wood manufacturing

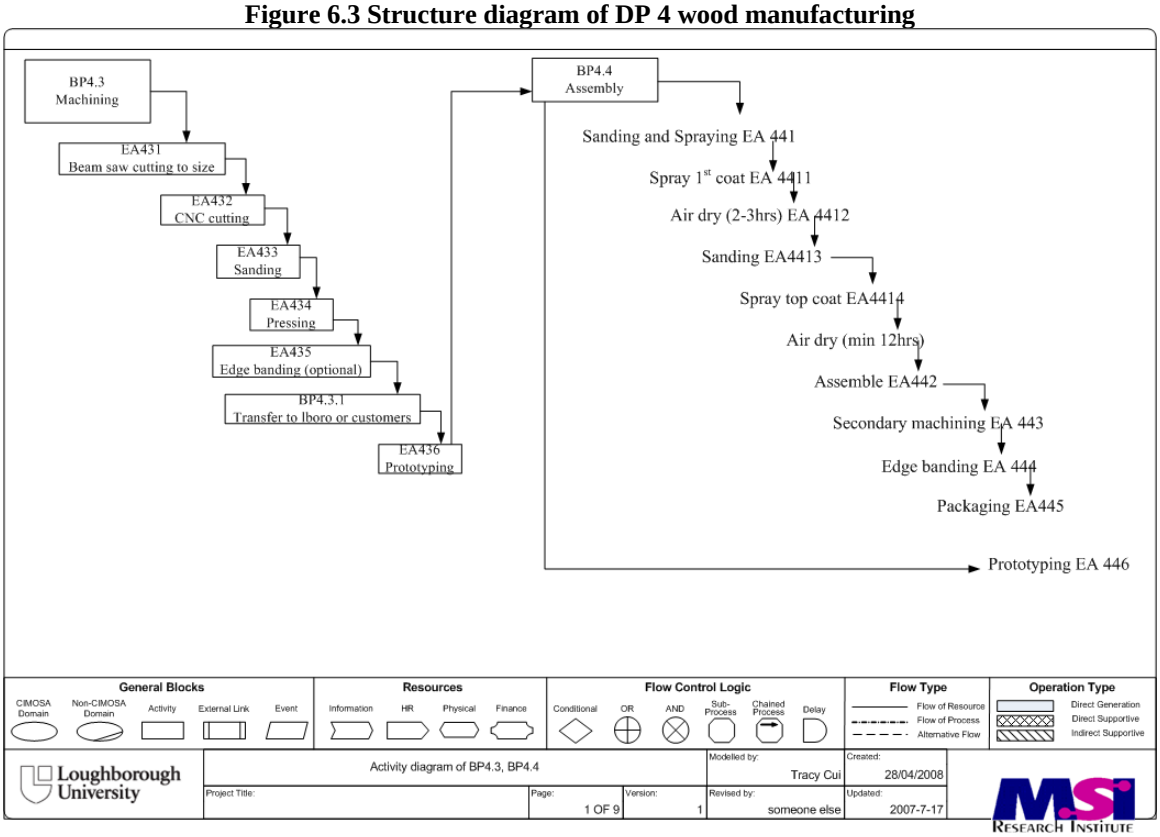


Figure 6.4 activity diagram of machining and assembly process of WT

6.2 product classifications

After creating the W-T EM with its focus on the W-T production system, a common understanding of the process network of the company was formed and shared between the MSI project team and relevant managers in the company. The author and her colleagues then went on to investigate behavioural impacts that product variations have on the W-T's business. Here it was decided that modelling simplifications were needed to:

(a) Adequately and usefully capture real system behaviours with a limited modelling resource, namely in terms of the number of modellers involved (in this case only one person, namely the author) and the maximum available time and effort that could be expended on modelling and on plant knowledge and data collection and

(b) Make the results meaningful and useful to potential users managers in W-T.

Particularly it was seen to be essential to characterise business behaviours and product realisation processes for groups of products. Here it was reasoned that:

(1) From one point of view all W-T products have specific processing needs (and this meant that W-T could claim to 'customise products', such that they meet customer specified functions, dimensions, colours and so forth), however

(2) From another point of view there were many similarities in the materials composition of all W-T products, and in the way that all products are processed using a flexible but constrained set of people and machine resources.

Therefore the author looked for similarity in processing and resourcing with a view to minimising the modelling effort but maximising the benefit gained from use of her W-T models; such that only product families (and possibly types) would need to be modelled, rather than create many specific case models one for each new product specified and processed by W-T. This kind of simplification was seen to be appropriate because:

(A) This was found to be workable with existing company practice; where although specific customisation needs were not normally explicitly understood but in different domains of W-T (such as in the machining and assembly areas) W-T personnel implicitly applied processing rules that are linked to informally specified product families and types.

(B) Because GT theories have for many year tried to group products so as to simplify the management of product realising processes.

(C) Because of the present authors specialist interest in EoSS phenomena, which in some ways she viewed as being akin to GT rationalisation ideas leading to an ability to make many product variants with a common and flexible production resource.

However it was observed that in W-T product classifications are made and treated differently in different sections; as well as at various levels of W-T operation. Therefore it was not anticipated that a single W-T product classification could be determined and used; rather there would likely be a number of product classifications could practically facilitate modelling simplifications.

6.2.1 Product classes from a project management point of view

During the interviewing of senior project managers in WT, It was learned that the company market themselves with their customers as having a core capability to customise commercial furniture products; such that they can meet specialist needs of a wide range of customers. Therefore, because of its ability to highly customise more than one range of commercial furniture products with a constrained set of flexible resources, when viewed as a whole system the W-T group was considered by the author to be a Case 3 EoSS system (as initially defined in chapter 4). IT follows therefore that the W-T manufacturing system has to cope with a very significant product dynamic including variance in product types; volumes and mix (Cui and Weston 2010). However it was presumed, but not directly confirmed by senior managers in W-T, that where practical W-T was adopting management practices (such as via compromise during product engineering and when planning purchases and production) that were implicitly attenuating some of the extreme product dynamic impacts so that the W-T manufacturing system could function in a timely and effective manner.

In W-T it was observed that every order is processed via a ‘project’ team which involves the management and co-ordination of product realising activities which include: design, engineering, machining, assembly and delivery. However, there are essentially repeating product orders; as it was reported that 75% of customers are existing ones with the other 25% being new customers. Therefore in the ‘project management domain’ two distinctive types of product were identified from a project manager’s point of view, which are referred to in the company as;

1. 'Kit supply' products: i.e. furniture that has previously been ordered by a given customer and produced by W-T, which not need to go through any re-designs process. Normally 'kit supply' products are realised for existing customers.

2. 'Shop fitting' products: namely furniture that requires a new design, and typically requires a visit to a customer site/location to access and survey the custom requirements; most often for new customers.

Figure 6.5 differentiates between 'kit supply' and 'shop-fitting' processing requirements from a project management point of view. It can be seen in the figure, both types of product realisation flow are initiated by a 'pre-sales' process which includes: meeting with customers; information providing. Following which for 'kit supply' products, project managers provide a quotation for customers, which might involve a negotiation on the price. After an agreement between the two parties is reached on the price, the- customer raises an order, then W-T starts to process the order. For 'shop-fitting' products, delivery processing requires the project team to visit customers' shops to do specific flooring, electrics, decoration works etc. Shop-fitting quotations are broken down into the different elements that are required.

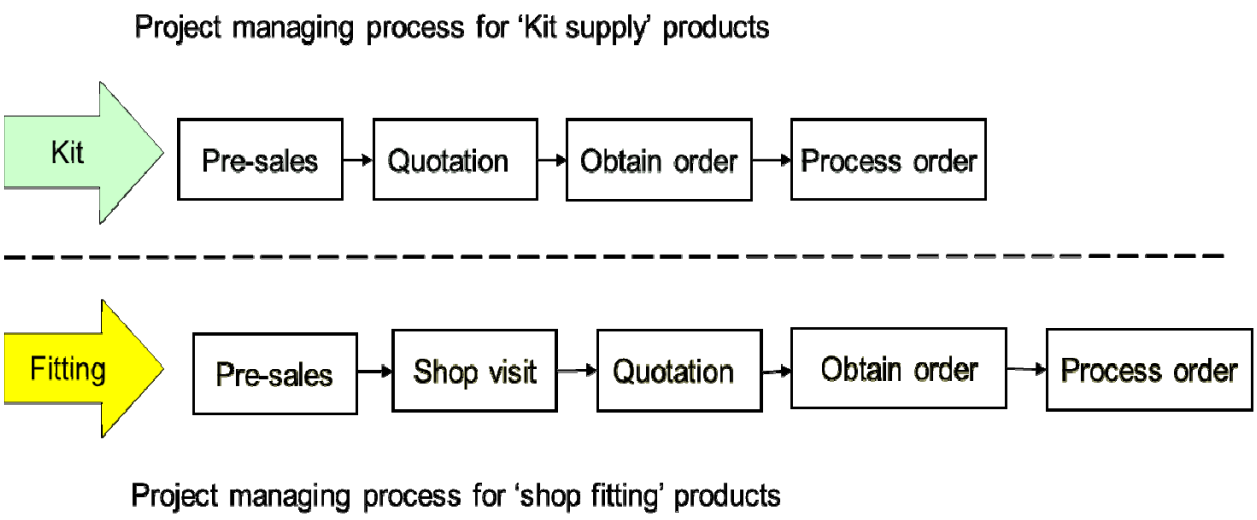


Figure 6.5 process requirement differences between 'kit supply' and 'shop fitting'

6.2.2 Product classes from a machining point of view

When the order fulfilment process starts, machining processes are initiated via receipt of an order (by a separately managed and located machining company within the W-T group) from

either WT or direct from external customers. It was reported that 75% of the current orders in the machining plant are from the W-T contract centre; while 25% are from external customers. The system of machines at the machining plant consists of 1 Beam Saw, 2 CNC's, 1 Press and 1 Edge Band Saw. These machines and their operators are organized in such a way that two distinct material flows are realized as shown in Figure 6.6. This led on to their way of grouping products, which essentially was based on material differences. Hence two types of products have been classified within the machining company of W-T, namely:

1) Flat panel items, made by raw MDF material (MDF)

2) Assembled items or stand-alone parts made from pre-finished raw material (Pre-finished)

The first flow shown in Figure 6.6 characterizes the MDF items that require pressing and follow-up spraying operations; the second flow is of Pre-finished items that require edge banding and possibly follow up assembly operations.

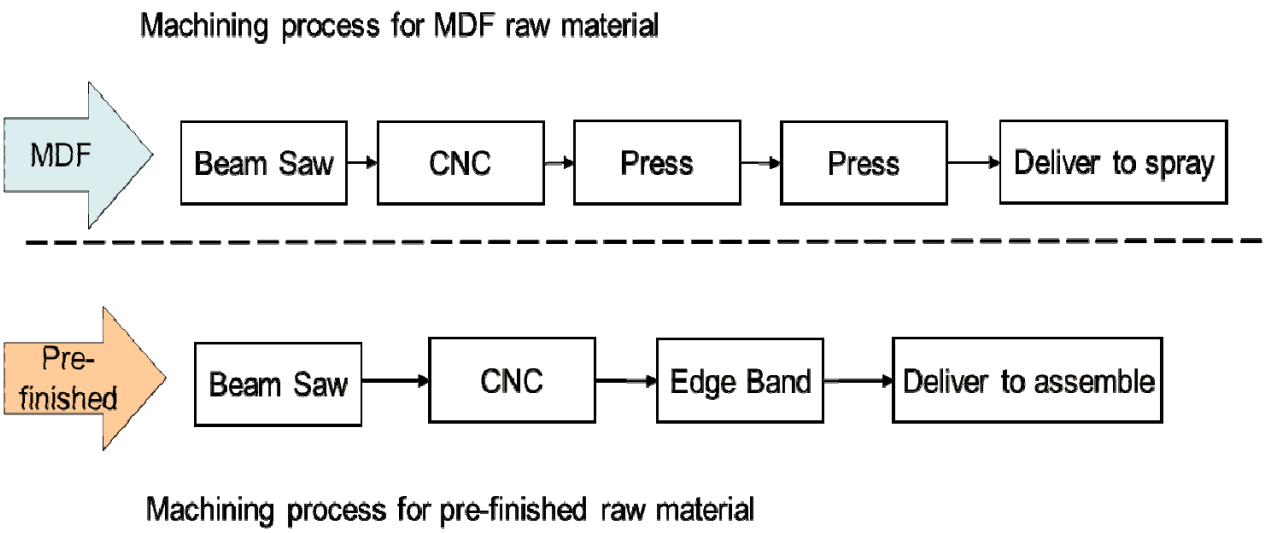


Figure 6.6 process requirement differences between 'MDF' and 'pre-finished'

6.2.3 Product classes from an assembly point of view

Having been machined component parts of products, those parts are delivered to external customers or the W-T assembly plant. Assembly operations are carried out by workers who

possess different levels of assembly skills, with every worker finishing an assigned work item before moving on to next job. In the W-T assembly, plant product differentiation (and hence classification) is made based on an assessment of the complexity of certain product features and how those features complicate assembly requirements. It was observed that the complexity level assigned to any product is primarily influenced by: properties of the material from which it is made; the product shape; and the product size. The complexity of these features impacts directly on the:

- Type of the assembly operations required
- Type of the tool required
- The skill levels required from assembly operatives.

Having assigned a given product into a class, based on its complexity level, the classification is used to inform the decision point at which products are assigned to an assembly operator. From an assembly point of view therefore it was observed that W-T products are classified into 5 assembly complexity groups as described in Figure 6.7.

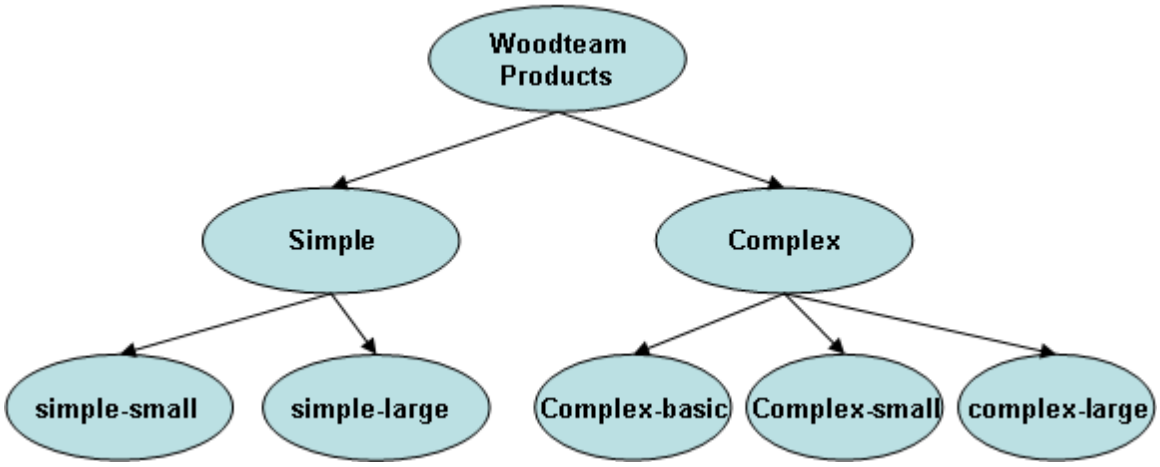


Figure 6.7 Product classification based on assembly complexity

Those 5 product types are used implicitly (rather than explicitly) by the W-T assembly shop supervisor to assign assembly workers to assembly tasks; so that the complexity level of the work it appropriately matched to skills, and skill levels, possessed by operators.

The next section is centred on the discussion on the observed distribution of skill levels amongst W-T assembly human resources at the time that models of W-T were created by the author.

6.3 Assembly realisation resource

At the assembly work assignment decision point, the assembly supervisor considers the following criteria:

- operator's skill types, i.e. can or cannot do
- operator's skill levels, i.e. how long it takes to do it properly
- operator's existing assignments, i.e. when can do

The first two are obtained from operator's competency profiles, the last one from the current shop floor schedule/job list. Assembly shop operators are grouped into 5 competency classes based on the skill types and levels; as described by the Wood team staff. These are:

1. Senior skilled Joiner (1)
2. Skilled joiner (6)
3. Semi-skilled joiner (6)
4. Junior (2)
5. Apprentice (1)

Based on the information obtained from the company about its assembly staff, Table 6.1 summarizes the relationship between competency classes and the assembly complexity product groups. At the time of modeling, it was estimated by the assembly shop supervisor that the frequency of orders for each of these assembly complexity groups is equal at 20% for each work entry point.

Table 6.1: competency classes and job complexity matrix

	No. of people	Simple small	Simple large	Complex basic	Complex small	Complex large	Prototyping
Senior skilled	1			√	√	√	√
Skilled	6			√	√	√	
Semi-skilled	6			√	√		
Junior	2	√	√				
apprentice	1	√	√				

In section 6.1, the author has shown the use of EM modeling ideas to decompose BP 4.4 'assembly operations' into its elemental EAs (as illustrated by figure 6.4), which demonstrates how the W-T process network was modeled at various levels of abstraction. While section 6.2 has explained how decisions made based on the complexity of incoming work (which is specified by works orders) are auctioned so as to distribute workloads to operators with appropriate skill levels. When following this line of thinking the author observed a need to bring three viewpoints together via selected modeling formalisms, namely: the 'process viewpoint' defining the assembly activities that need to be carried out; the work viewpoint defining the types of work that needs to be performed in a given time frame; and the resource viewpoint which concerns the kind of operator needed to perform the said activities on the kind of work currently being performed. Bearing in mind a perceived need to formalize mappings between these three views, so that key aspects of the W-T product distribution system could explicitly be captured the author experimented with the use of CIMOSA FO (Functional Operation) and FE (Functional Entity) concepts.

Here the author constructed a model of FO's and FO sequences needed to achieve the various EAs that comprise BP 4.4. The purpose of this decomposition was to begin to develop and tests an explicit model of W-T assembly resource system competencies and availabilities; which on an going basis, as work types and workloads change could be explicitly mapped onto equivalent models of W-T resource realizing requirements.
To illustrate the modeling principles involved here the author chose EA 446 'Prototyping' as an example activity to be further decomposed into FOs and a possible FO sequence as illustrated in figure 6.8. The reason for this is because 'prototyping' is normally realized by the senior skilled worker in WT assembly plant, who possesses the maximum available assembly skills and skill levels.

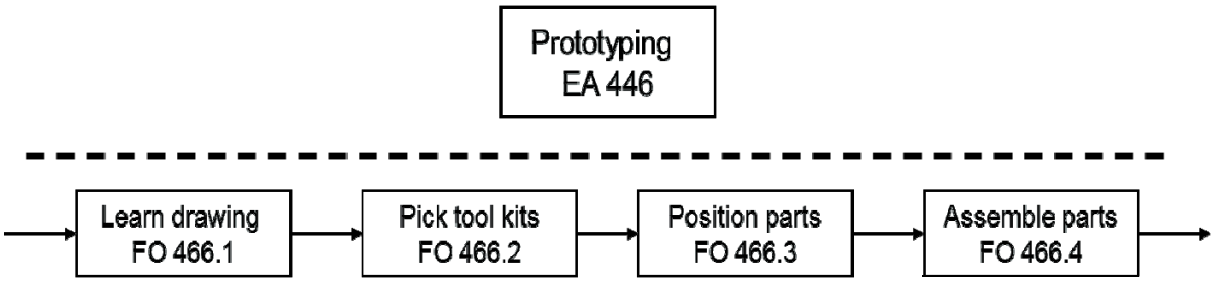


Figure 6.8 FO and FO sequence of EA 446

The purpose behind decomposing BP's into EA's and their associated FO's was to enable a systematic and effective conceptual design of resource systems; such that the competencies

and capabilities that resource systems must possess (to realize groupings of EA requirements) can be explicitly identified, by considering how viable resource system candidates could actually realize those FO's in a timely manner and effective manner. Such subject resources can be characterised by the Functional Entities (FEs) they possess using the CIMOSA resource modelling language (Vernadat 1996). This approach led to the creation of table 6.2 which lists/tabulates FE's needed to enable FO 446.1 to FO 446.

Table 6.2 Function Entities for realising FO 446.1 to FO 446.4

FE1	Ability to learn product drawing
FE2	Ability to select the right tool kits
FE3	Skill of using tools correctly
FE4	Ability to position parts correctly
FE5	Skill of using assemble

The above discussion illustrates how resource system design can be systematically achieved in a top down way. This modelling exercise enhanced the author's thinking about modelling 'work'; 'process' and 'resource' sub-systems separately followed by using a modelling mechanisms to re-unify those three viewpoints.

Also her modelling initiative made it clear that within departmental boundaries, the 'work system' is treated differently; the 'process' network needs to be described at various levels of granularity; and that 'resource system' modelling can be captured by explicitly defining 'roles' (in terms of elemental activities, and their FO and FO sequence requirements) and then by matching this to models of 'role holders' defined in terms of FEs (later this observation led the author to make contributions to the refereed journal publication entitled 'On modelling reusable components of change-capable manufacturing systems.' Weston et al 2009).

6.4 Initial simulation models of the W-T production system

After capturing static (relatively enduring) models of 'work'; 'process' and 'resource' sub-systems within WT, the author sought to transform (and hence re-use) some of those modelled structures within equivalent and more focussed behavioural models in the form of discrete event simulation models of segments of the W-T production system, This was observed to definitively require an integration of the three structural (process, resource and

work)viewpoint together as well as to characterise time-based behaviours within their respective sub-systems. Figure 6.9 was constructed by the author to conceptualisation this integration requirement when creating simulation models of the W-T assembly domain.

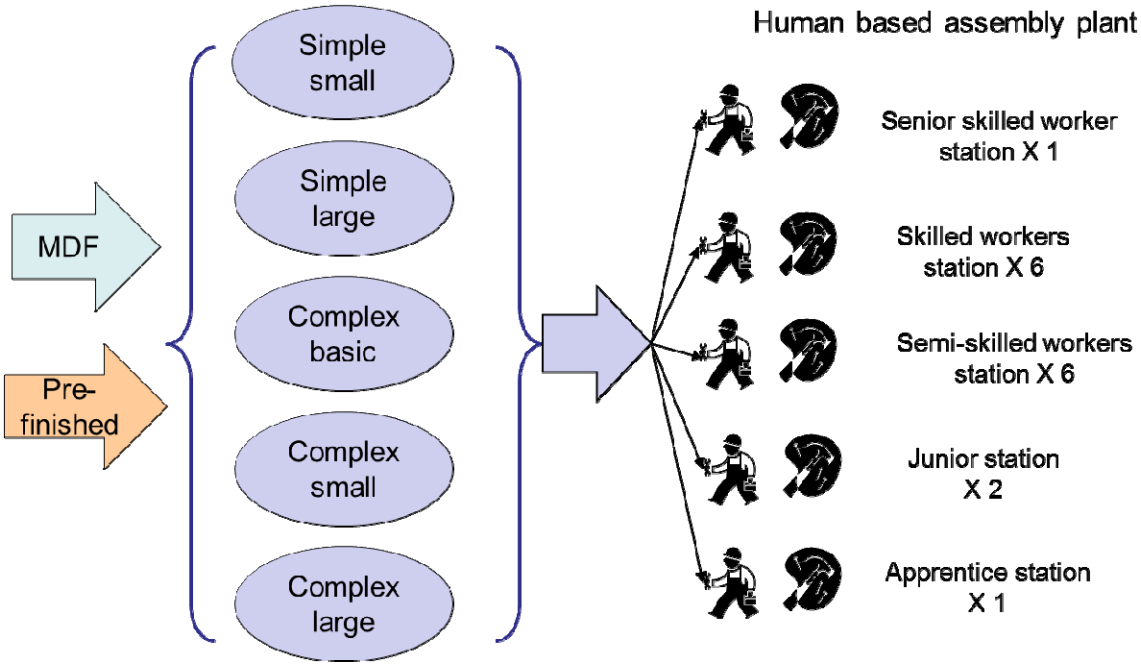


Figure 6.9 conceptualisation of integration of 'work', 'process' and 'resource'

Figure 6.9 illustrates how two types of component parts arrive from the W-T machining plant, namely 'MDF' and 'Pre-finished' building blocks of W-T commercial furniture products. Following which with referenced to a current production orders, and its related furniture product specifications, the assembly supervisor groups the products required into 5 types of furniture based on the complexity of their features. Based on this classification, and with reference to their planned availabilities of the assembly workforce, assembly jobs are assigned to workers with appropriate skill levels. Each of these skilled workers conduct the assemble work assigned to them at one of a number of work stations.

An initial simulation model of WT assembly system was created with reference to structural relationships and data previously encoded by:

* The W-T EM;

* A decomposition of EM activities focused on BP 4.4, into FO sequences and related FE requirements;

* The complexity classification of product types, and how these map into FE's (or skill type and level requirements) and FE levels

* FEs (i.e. skill types and skill levels) possessed by assembly workers

Here the proprietary DES tool Simul8 was selected and used to create the W-T assembly shop model. Figure 6.10 shows a screen shot of that model. The work center modeling concept of Simul8 was used here to represent each primary operational stage involved in the assembly of nearly all W-T commercial furniture products. These primary operation stages are listed in Table 6.3. Conceptually appropriately skilled operators, and their tools and work benches, were assigned to each work center. In this way assigned assemblers were differentiated by differences in average processing times they take to the related primary operation. One such set of operation times which was estimated by the assembly shop supervisor in respect of a 'skilled worker' is included into Table 6.3.

However, due to limited access to the company data, the author was not able to conduct any time studies to capture the real plant operation times, hence many assumptions about operation times needed to be made.

Table 6.3 processing time of each work center of assembly shop in WT

WC	Sand	Spray	Air dry1	Air dry2	Assembly					Pack	delivery
					SS	SL	CB	CS	CL		
Op-time (min)	60	120	180	720	60	90	180	660	1620	30	15

With respect to encoding real system work flow constraints on assembly shop sequences it was observed that via work entry point 'MDF 1', panel items arrive from 'presses' that do not need to be assembled; while via work entry point 'MDF 2' the items arriving from 'presses' do need to be assembled. In addition however Simul8 visual logic capabilities were differentiate assembly processing into the previously defined 5 assembly complexity levels; such that assembled furniture products were modeled as leaving the system via one of 5 exits. Work entering the production system from the work entry point 'Pre finished' are items that are 'edge banded' and they need to be assembled so that they have 5 assembly complexity levels finished items. 4 major labels are used to enable the model to function logically as discussed above. They are:

1. *Product type*

A numeric label called ‘product type’ is used in this model to differentiate four types of products, namely: MDF flat pack items; MDF assembled items; Pre-finished items; prototyped items.

2. *Assembly required*

Another numeric label called ‘Assembly required’ is used to differentiate between work items that need to be assembled (MDF assemble and Pre finished) and work items that don’t need to be assembled (MDF flat pack)

3. *Assembly complexity*

The ‘assembly complexity’ label is used to distinguish between 5 complexity levels of assembly operations; needed in respect of different work items. So that there are 5 distribution points for both types of the assembled items (namely for MDF assembled and Pre-finished). It was assumed that work items grouped into each assembly complexity level come in system in equal frequency and quantity. It follows that a ‘probability profile distribution’ was used.

4. *Spray*

The numeric ‘Spray’ label is used for MDF work items that need a double spray coating. When the work items go through the ‘spray1’ station, their ‘spray’ label value is changed, so that they can go to ‘spray2’ for second coating when required.

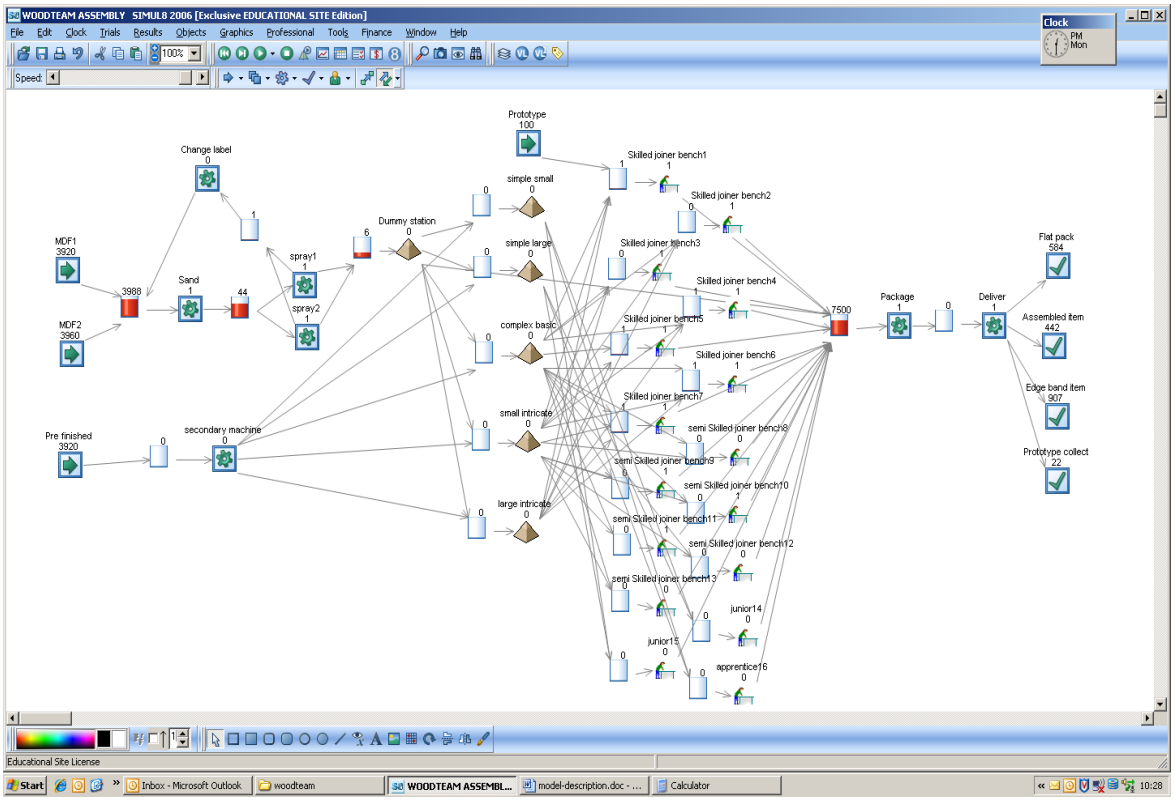


Figure 6.10 screen shot of simulation model of assembly plant in WT

Following a similar set of modelling steps, the author also created structural and behavioural models of the machining system used by the W-T Company. A screen shot of the simulation model is shown in figure 6.11.

Once again the access to real case data was restricted; hence it only proved possible for the author to run rather artificial simulations of both the assembly and machining shops used by W-T. None the less the experience gained by the author when conducting different forms of structure modelling, and when conceptually designing 'in context', dynamic models of ME segments, proved invaluable to the authors' study; also it provided her with much enhanced knowledge about the operation of real MEs, their possible responses to different customer demand scenarios; and how improved modelling methods can be devised, implemented and applied.

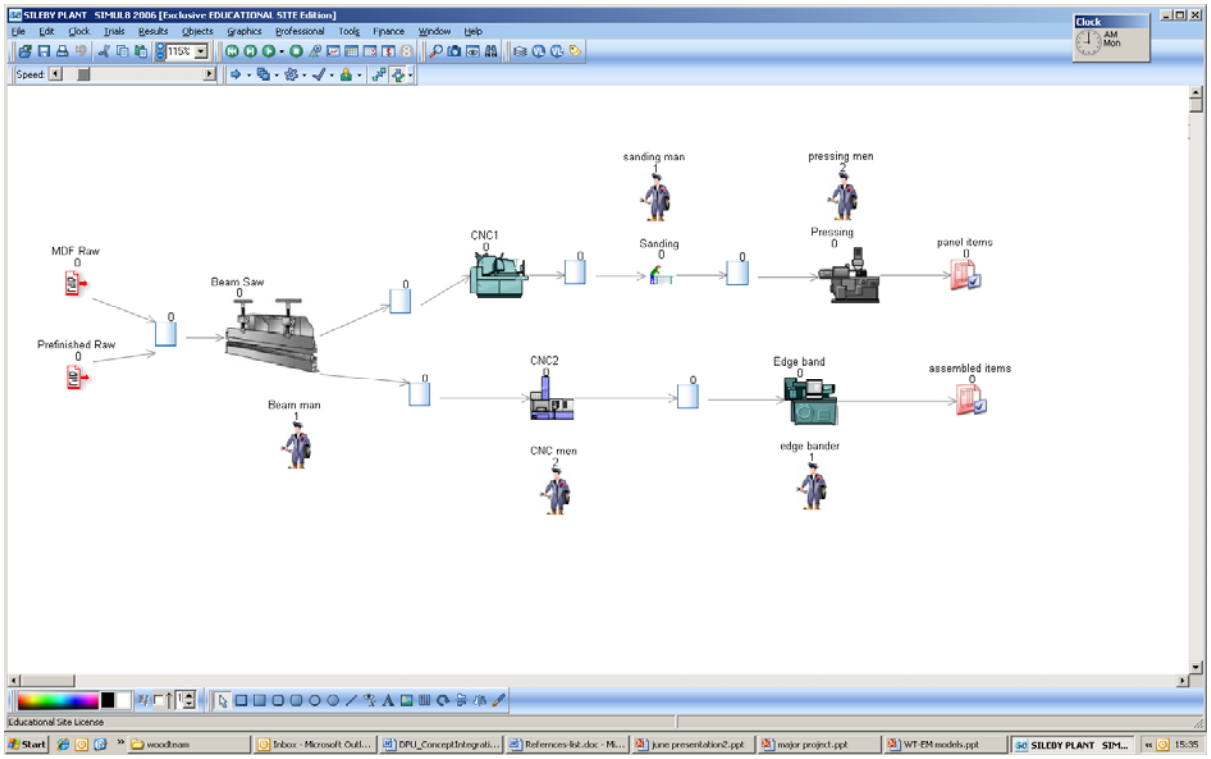


Figure 6.11 screen shot of simulation model of machining plant in WT

6.5 potential outcomes of the modelling

The W-T modelling work carried out by the author has shown that, static models can support qualitative thinking leading to improved ME and related production systems design; while 'in context' simulation modelling has significant potential to forecast ME futures in response to various possible scenario of customer demand.

Hence it was deduced that the authors' research work could in respect of W-T and many other MEs, be developed further to facilitate:

- Dynamic capacity planning
- Dynamic production planning
- Solution delivery, to a variety of concurrency and interoperation issues around 'big systems' involved in product design, capacity planning, production planning, manufacture and assembly

During the W-T project, it was observed that improved project management requires improved integration between its machining and assembly systems, and between those systems and other related business and engineering systems. To help specify requirements for improved integration it was presumed that significant benefit might accrue from creating higher level, more abstract static and dynamic models of the W-T business which would encompass: its sales and customer interaction processes; its production planning processes; and its purchase planning and realisation processes. Those models would need help determine necessary interaction issues between all W-T systems; and where appropriate should facilitate quantitative analysis. This idea, which fundamentally can be viewed as necessitating ME modelling at multiple levels of abstraction, was later tested during a case study described in chapters 8 and 9 of this thesis.

Chapter 7 Extended modelling methodology

7.1 Focused gap analysis

Chapters 5 and 6 report on the exploratory application of the author's initial modelling methodology (IMM), which was specified in chapter 4. This exploratory research created and used enterprise and simulation models of manufacturing systems deployed by two case study MEs. The exploratory studies significantly enhanced the author's knowledge of MEs and potential uses of state of the art modelling techniques to systemise and quantify aspects of ME engineering. Particularly this helped her to develop an improved base of thinking which led onto the conception of a new and Extended Modelling Methodology (EMM). This extended modelling methodology will be referred to in the remainder of this thesis as the EMM. The rationale underpinning EMM conception, specification and development is defined in this chapter. Later thesis chapters describe how the EMM was case tested.

7.1.1 Gaps in modelling methods

Chapter 2 outlined opportunities to use (A) decomposition techniques to break through the complexity of production systems, and the business and engineering environments they operate in, and (B) different modelling technologies in a unified way so as to gain synergy from their collective use. The exploratory research of the author confirmed that CIMOSA EMs can only capture static aspects of an enterprise. Here lessons learnt allowed the author to understand that focussing on structural, and not on behavioural modelling, is an essential constraint to place on this kind of modelling technique if it is to capture practically applicable models of complex system structures; as by not encoding dynamic, time based (state change/ behavioural) aspects the models can remain relatively simple.

The exploratory EM's developed were observed to provide an effective way of decomposing models of various complex business, engineering and production processes used by case study companies. This allowed the explicit capture of a big picture of ME requirements and formally decomposed that picture into more detailed relatively enduring models of the business, engineering and production activities that exploratory case MEs need to perform

within defined time frames. This so called process network of a given ME can be used to capture knowledge about ME requirements from perspectives of high, middle and low level managers (and from plant operators) to provide a source of ME knowledge that can be shared to improve the way that cross business unit decisions are made. In the exploratory case companies, situations were observed where effective decisions were being made with respect to factors that impact within the realms of given ME domains (such as a sales, product design, production planning or purchase planning business unit) but that those same decisions might significantly deteriorate the process-oriented behaviours of the ME when viewed as a whole. CIMOSA EM's were observed particularly to help address this kind of problem, by supporting collective and qualitative reasoning which can naturally traverse departmental boundaries. Connected with this observation it was also observed that process models created in the form of CIMOSA activity diagrams are semantically richer that equivalent stand alone process models. Industry at large is using process models to inform many types of decision-making; but seldom are those models produced with 'explicit reference' to the ME context in which they must operate. By using CIMOSA decomposition ideas, the author observed firsthand how processes can be decomposed and modelled at one or more required levels of abstraction; and when so doing the process models created remain contextually linked to their 'parent' (or indeed 'off-spring') processes because the interdependencies between processes are readily expressed using CIMOSA modelling constructs. CIMOSA was observed therefore to have very significant strengths in cutting through high levels of processing complexity.

In addition CIMOSA was observed to provide fairly comprehensive information modelling concepts which can be graphically linked to process models. This can support the specification and conceptual design of IT systems. However CIMOSA was observed to be far less strong in its provision of concepts for modelling (human and machine) resource systems and related work systems. In these later respects it was found to usefully provide concepts like FOs (Functional Operations) and FE (Functional entities) to enable linkage between process models and resource system models; but these ideas need significant further development to facilitate their industrial use, such as during the engineering of different forms of manufacturing system (including EoSS manufacturing systems).

Modellers should also be particularly aware that weaknesses can result from the ad hoc addition of new model entities into process maps. Firstly any addition of newly modelled

entities will normally lead to increased model complexity; and if any model becomes overly complex (i.e. it encodes things not needed by a given model user in a given application domain) its use will be constrained or it will be overly costly to use, develop and update as the real system being modelled changes over time. A second weakness (pointed out in the discussion about decompositions) is that generally it is better to avoid representing any kind of 'solution entity' directly in process models (or maps). This is because the prime use of any process model should be to represent processing requirements (i.e. aspects of the problem space). Thirdly, would be model users can be confused by an apparent plethora of different modelling conventions that are all termed process maps. Fourthly the eclectic nature of process maps can militate against opportunities to 'standardise processes' and/or to achieve 'standard representations of processes' (Zachman, 1987).

It follows that the author's exploratory research directly confirmed that CIMOSA EMs can provide an effective way of understanding and documenting process-oriented models of complex MEs. Particularly for this researcher it provided a technique for understanding companies from a holistic point of view; following which the EM of a subject ME could be used to facilitate holistic thinking about the ME concerned. Essentially CIMOSA was therefore found to provide a process-oriented architectural framework into which

- actual plant data could be positioned
- process models could be explicitly linked to that framework
- resource and work models could also be positioned within that framework; but this required new modelling concepts to be developed, particularly to facilitate modelling of resource systems and work systems at more than one level of abstraction so that these models can be explicitly linked to related process models
- there was potential to position within that framework, the conceptual design of sets of more focussed simulation models (SMs), so that SMs of different ME segments and/or at different levels of abstraction can be derived from the same architectural model; but this was also observed to require new modelling concepts so that time-based behaviours of different configurations of process, resource and work system models (including EoSS manufacturing system configurations) can be computer

exercised in order to simulate many types of time based behaviours of MEs that will be of concern to ME business, engineering, and management personnel.

The author's exploratory use of simulation models also confirmed the importance of the forgoing discussion. Particularly it emphasised how the universal nature of Discrete Event Simulation modelling has both strengths and weakness. Strengths come as in theory the behaviours of many systems, large and small, can be modelled for many purposes at many levels of detail. But these strengths become weakness if the modeller does not know what to model. In addition because it was observed that many SMs of manufacturing systems need to encode both structural and behavioural aspects of related process, resource and work sub-systems, as the detail of SMs begins to approach the realism of actual manufacturing systems the models and experiments that need to be performed become too complex, impractical and overly costly to produce and use; except where only some piecemeal solution to a small sets of ME problems is needed.

In short the author observed, during her exploratory modelling, that EMs are good at ***big picture structure modelling*** while SMs are good at ***small picture behaviour modelling***. Hence potentially great benefit can be realised if EM and SM modelling approaches can (at require levels of granularity) be flexibly interconnected. Therefore satisfying this requirement, and particularly the need to flexibly connect models of processes, resources and work to each other and to the ME context in which they are used, became a key focus of research attention during this study,

7.1.2 Industrial practice – a requirements view

From an economic/business point of view in many (possibly most modern MEs) there is a necessity to determine one or more competitive strategies then to determine how that strategy can best be operationalized short and long term. As earlier discussed none of the manufacturing philosophies or techniques previously devised and industrially applied can be expected to offer a comprehensive means of achieving competitive performance in a given manufacturing enterprise. But in this research it was presumed that typically in multi-product enterprises the essence of seeking optimum competitive performance is to reach a balance point between achieving economies of scale and economies of scope within a subject

production facility, as illustrated by figure 7.1. Therefore the key will be to decide (short and long term): (1) individually and collectively, how flexible the segments of any given enterprise must be so that all needed types and levels of responsiveness behaviour can be achieved and (2) to what extent wastes and costs can be reduced without compromising the quality of products or the flexibility competencies of the product realisation systems involved. But for reasons previously discussed, such as because MEs involve complex causality between their various parts, and because MEs are invariably in a state of flux, it is by no means a trivial matter to determine what the balance point should be and almost certainly the optimum balance point will continue to change. Hence some organised set of life-cycle engineering activities will in general be required to conceive and develop effective solutions to specific ME problems; through the entire life-time of manufacturing systems (ElMaraghy H.A., 2009).

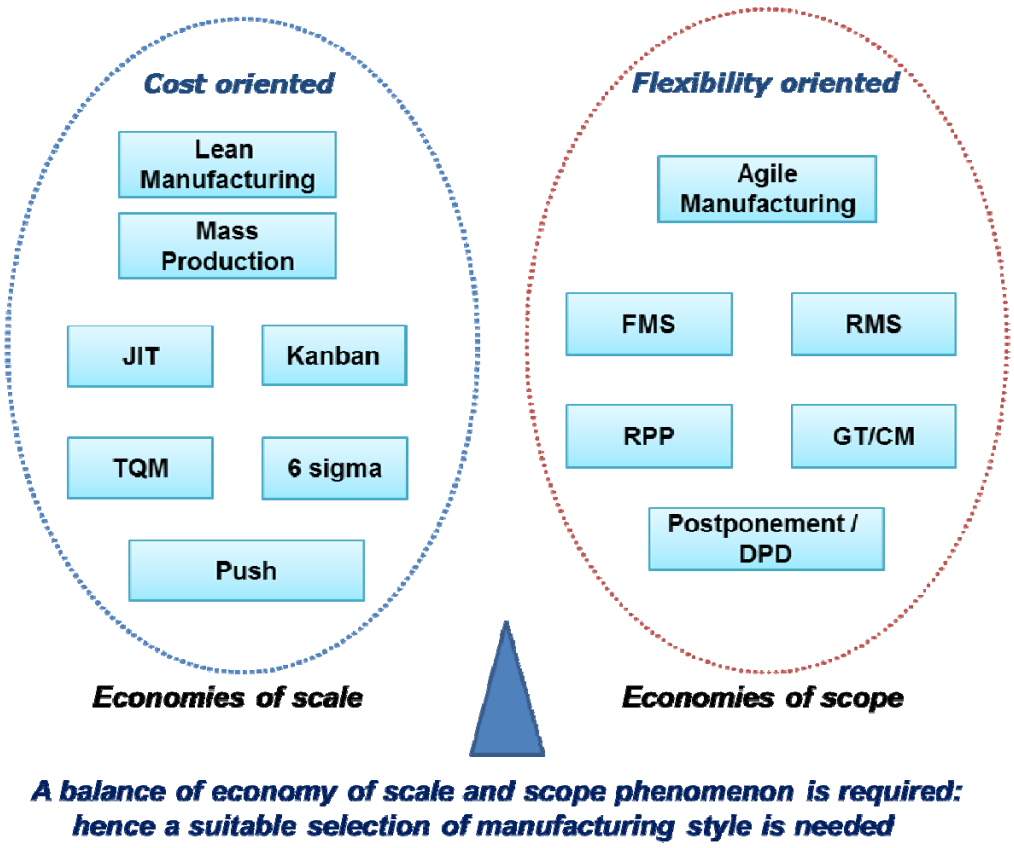


Figure 7.1 enabling techniques for EoSS systems

7.2 Need for holistic approach

With a view to researching a new basis for significantly advancing current best practice industrial use of modelling techniques the author has sought to conceive and case study test a new way of achieving combined structural and behavioural modelling of MEs, at multiple

level of abstraction. Documenting, understanding and developing a holistic view of any subject ME is presumed to be vital to the company's medium and long term business' concerns. Indeed whether any focus is on 'localised optimisation' within a subject manufacturing system or 'holistic optimisation' of the whole ME; long, medium and short term activities need to be involved to ensure that, as requirements change during the useful lifetime of product realising systems, those systems are appropriately designed, implemented, operated and changed.

Therefore as explained in the remainder of this chapter the author conceived and specified the EMM. The following sections 7.2.1 to 7.2.5 describe key aspects of a need for the EMM to encompass general modelling ideas and state of the art approaches to 'model development' and 'model application'. While in section 7.3 the proposed phases, steps, structural and behavioural modelling ideas included into the EMM are specified, as is the recommended use of an EoSS reference model.

7.2.1 Need for decomposition mechanisms and formalisms

Decomposition can allow modellers and their client managers and engineers to break through inherent complexities of a large scale manufacturing business. This in turn can lead to simple but good quality models. In the domain of production systems modelling and engineering, lots of literature have shown that great benefit can be gained from definitive separation (along the life phase/life cycle dimension) of 'complex system requirements' (i.e. the problem) from 'candidate systems design' (i.e. possible solutions, that typically comprise different configurations of human, automated machine and IT systems) (Bernus, P. and Nemes, L., 1996, Panetto, H., Molina, A., 2008 and Cui and Weston, 2009). As a consequence related thinking can better accommodate, and decouple different rates of change in problem and solution spaces. Also this kind of thinking can usefully be linked to decomposition along the view or perspective dimension. For example, figure 7.2 illustrates in overview one set of key decomposition principles which the author successfully applied when conducting the exploratory modelling of manufacturing systems described in chapter 5 and 6. This is an enhanced version of figure 4.4 which was presented in the initial modelling method chapter, where the author made initial assumptions by learning from others within her research group.

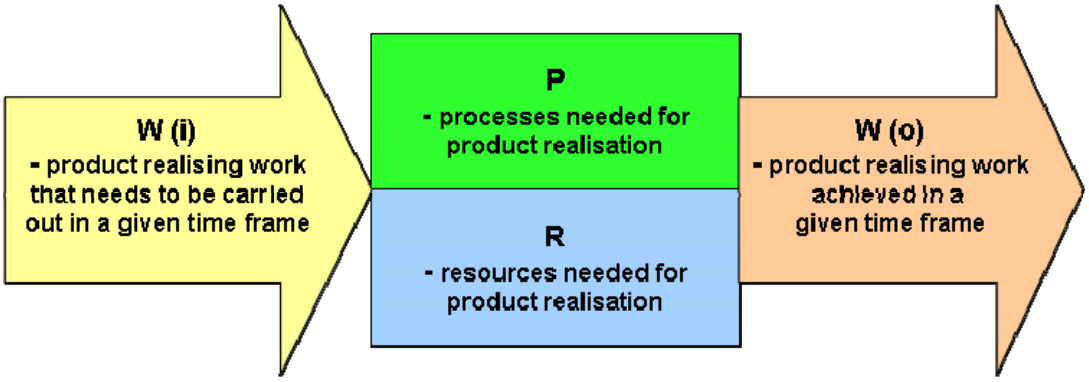


Figure 7.2 Key system decompositions needed to facilitate complex systems engineering

Work: relates to 'how much' of some aspect of product realisation needs to be done. Work demands are typically expressed, as 'customer orders', 'works orders', 're-work requirements' &/or 'products actually realised' in a given planning window;

Processes: are defined to characterise 'what kinds of work' need doing. Processes are typically expressed as ordered sets of activities needed to: 'design', 'engineer', 'plan', 'procure', 'store' 'make', 'assemble', and 'transport' products and/or the elemental building blocks of products.

Resources: are the entities 'who will do the work'. Human, automated machine and/or IT systems will normally be required to: 'design', 'engineer', 'plan', 'procure', 'store', 'make', 'assemble', and 'transport' products and their elemental building blocks.

7.2.2 Need for choosing the right modelling technique

Many authors report that simulation modelling has major strengths and has been widely used in industry; but is limited as it does not naturally enable the creation of scalable system models. Therefore the author has investigated the complementary use of simulation modelling with various other modelling technologies; with the purpose of creating holistic but scalable and re-usable manufacturing system models. Figure 7.3 illustrates some of the modelling technologies that have been used synergistically by the author and her research colleagues, to create holistic models of manufacturing businesses, with their constituent engineering and production processes and underlying (human and technical) resource systems.

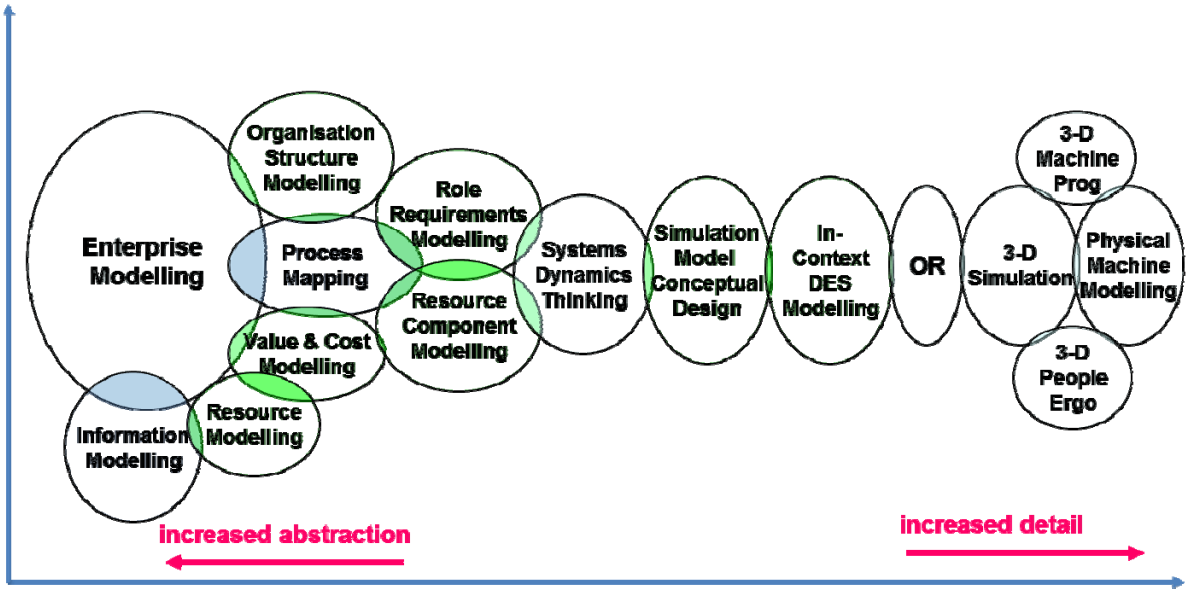


Figure 7.3 Modelling technologies to support manufacturing enterprise engineering

Modelling techniques like Enterprise modelling (using CIMOSA constructs) provide a set of modelling decompositions and related modelling formalisms. This enables the explicit capture of the processing requirements of any subject ME, as a network of business, engineering and product realising processes. It also provides modelling concepts to separately support the conceptual design of resource systems with capabilities to realise defined processes of an enterprise and its supply chain. However as discussed in section 7.1, additional enterprise modelling constructs are need to readily deploy CIMOSA EM as an architectural framework for subsequent structural and behavioural modelling of manufacturing systems.

Therefore to facilitate the conceptual design of SMs, a combination of component-based modelling concepts and structural modelling ideas have been developed by the author and her colleagues; such that they can be used in conjunction with standard CIMOSA modelling concepts to enable the *capture*, *understanding*, *validation*, *experimentation* and *re-use* of simulation models. Key is that the design of multiple simulation models, of appropriate scope and detail, can be matched to specific segments of the ME process network previously defined by the EM. However future options remain with respect to the authors EMM, in its use of different types of enterprise modelling and simulation technology; for example where

manufacturing systems can be modelled more effectively using continuous simulation, OR and/or 3D virtual engineering technologies.

7.2.3 Need for modelling methodology

To deploy modelling ideas in various ways when modelling in a particular domain (such as line balancing, production planning or value and cost modelling) and or when solving a specific manufacturing systems engineering problem (such as designing a particular materials handling system to realise a given movement) it is necessary to decide upon the series of modelling steps that must be taken to realise the objectives of the current modelling exercise. The modelling steps that should (or could be) be taken are referred to as a *Modelling Methodology.* If the steps to be taken are explicitly defined they can be viewed and used to systemise the delivery of the engineering activities involved. Typically in MEs there are very many business, engineering and product realising processes that need to be carried out (sequentially and currently) by a constrain sets of human and technical resources. Arguably modelling methodologies should be designed to support ME resource systems in their achievement of ME processes, therefore it follows that there are very many types of modelling methodology that can be usefully conceived. Those modelling methodologies can be specific and well-focused at one extreme (such as to support the design by simulating the operation of one mechatronic element of a positioning system) or very general and de-focused (such as to provide a predictive capability for a strategic planning team). Essentially therefore the author believes that there is little difference between a process and a methodology, as both are simply a conceptualisation of a sequence of activities. Therefore it is natural to bring together ideas around model engineering and model application (in support of manufacturing systems engineering).

7.2.4 Need for multiple level modelling

During her exploratory research the author has understood that manufacturing enterprises (MEs) are changed, managed and operated at different levels by different kinds of actor. For example, while the senior manager of an ME is mainly focused on the long term strategic development of the entire company, the models he/she uses will need to be at a high level of

abstraction; but when modelling production planning processes, a lower level of abstraction is needed to synchronise various aspects of product realisation; while when modelling a production line, such as to achieve a line balance, a more detailed and focused model is needed.

For academic reasons and to satisfy case study aims, a secondary purpose when conducting qualitative modelling was to reach a later position where multi-level simulation modelling could usefully facilitate quantification and prediction of improved economies (of scope and scale) that can be realised from the various EoSS systems deployed by case companies: such that improved design of these systems and/or better integrated working between these systems could much improve the profitability of the company, despite unpredictable product dynamic impacts. The multi-level simulation models created in this way should naturally inherit a common base of structural elements. To recap these structural decompositions and relations were establish via enterprise modelling, product classification and resource system data capture. Thereby key structural aspects of process, work and resource elements were documented and visually represented as a set of EoSS models of the holistic product realisation system and its various constituent manufacturing systems.

7.2.5 Need for reference models

Many researchers have developed and used 'Manufacturing Reference Models' that support aspects of the life cycle engineering of manufacturing systems. Like Modelling Methodologies, Reference Models can have multiple purposes and take a variety of forms. The main idea when creating a reference model is to abstract away the detail about some aspect of a specific case system or process, to define some essence of specific models that is widely applicable. Typically therefore a reference model might retain the core principles or model structures about some situation to type of application to guide following modellers. With this kind of purpose in mind, the author has formed a EoSS reference model which portrays the essential features of manufacturing systems capable of coping with customer related product dynamics.

Figure 7.4 uses notions about decomposing manufacturing systems into process-resource-work sub-systems to visually represent a generalized, and hence a rather abstract 'Reference Model of EoSS Manufacturing'. This new representation of the EoSS concepts explicitly and

visually represents EoSS ideas described by the author in chapter 4. The EoSS Reference Model conceived shows three alternative ways of 'configuring' 'Work'; 'Process' and 'Resource' sub-systems; where the three alternative configurations differentiate between three so called 'Cases of EoSS Manufacturing'. The author has found this reference model to be very useful when characterising real case manufacturing systems, and considers the simplicity of this reference model to be key in seeking to encourage its wide-spread industrial use.

However as also explained later in this thesis the ideas embedded into figure 7.4 needs to be 'detailed' and 'formally exercised' if benefits and dis-benefits of different Cases of EoSS Manufacturing are to be quantified. As earlier discussed, original notions about qualifying the benefits of Economies of Scope and Scale came from the business community. For example (Willig, 1979 and Teece, 1980) explain that the nature of EoSS phenomenon arise from the production architecture adopted by any given enterprise. But to determine and quantify the impacts of an effective balance point between of economies of scale and scope, systems engineering thinking is needed which can be operationalized via mathematical (as well as by visual) models: to better understand the impacts of essential structures and building blocks of EoSS systems and how chosen essential structures impact on local and global ME behaviours. Figure 7.4 provides such a simple and generic characterisation of structures, selected instances of which can be exercised in both virtual and real environments to model systems that realise products in ways that generate economies of scale and economies of scope.

In Case 1 manufacturing systems each product variant is realised by a distinct 'process-resource system couple'. One key operational impact of which is that only economies of scale can be realised by Case 1 Process-Resource (P-R) couples. This Case of manufacturing system design was assume to suit predictable customer demand patterns; but when such a demand diminishes the economics of this manufacturing system Case come into question. Potentially therefore the useful economic lifetime of Case 1 EoSS manufacturing will be shorter that of Cases 2 and 3. Furthermore it is likely that the useful life-time of any Case 1 system will be closely linked to the life-time of the product type it is used to realise.

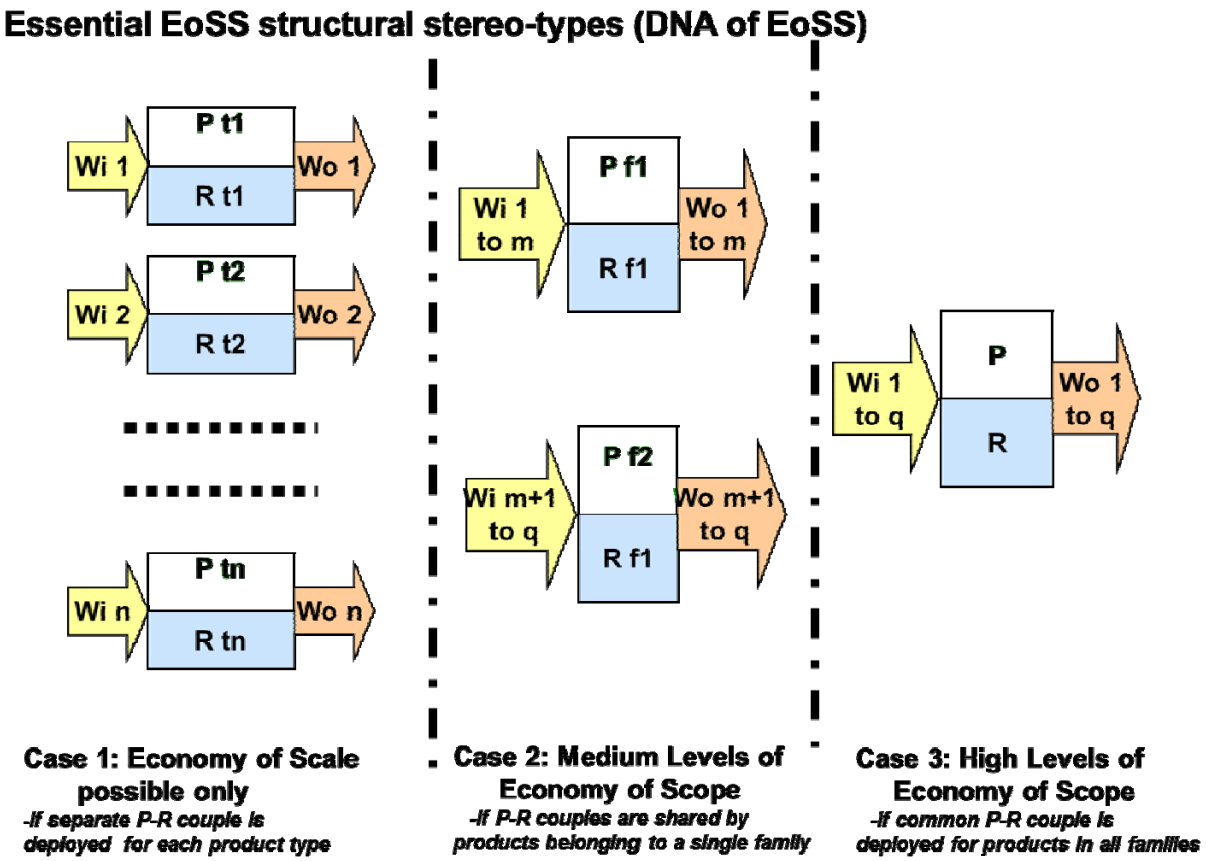


Figure 7.4 generic structures of economies of scale and scope systems

Whereas for Case 2 and 3 manufacturing systems respectively their economic life maybe significantly extended, or stretched, over combined lifetimes of a number of product types and product families. This is because Case 2 and 3 EoSS manufacturing is based on re-use of a common set of 'process- resource system couples'. But this necessitates P-R couples that possess an increased set of functional capabilities as well as a capability to effectively realign their capabilities in a timely manner, so as to switch product realisation between different product types and/or families in conformance with customer demands. Case 2 EoSS manufacturing systems can realise multiple product types within a product family. While Case 3 systems can also realise multiple product families; here it is assumed that product families may have multiple product type members. Therefore by definition it follows that Class 3 EoSS manufacturing systems can realise a greater range of economies of scope than Case 2 EoSS manufacturing systems. But also implicit is a need for Case 3 EoSS systems to possess increased flexibility & engineering responsiveness levels when compared with Case 2 EoSS.

7.3 Enhanced modelling methodology defined

The forgoing set of ideas and assumptions, many of which were an issue of the author's exploratory research, led to the following proposal for a new extended modelling methodology (EMM).

EMM was conceived to encompass two main modelling phases, namely:

- Phase 1 structural modelling and
- Phase 2 behavioural modelling.

An overview description of the two phases follows, while case study work reported in chapters 8 through 10 exemplifies uses of modelling steps that constitute these two phases.

7.3.1 Structure modelling – phase one

There are four main steps within phase 1: during which structural modelling methods are applied. Those modelling steps will be referred to as S1, S2, S3 and S4.

7.3.1.1 -S1 - Process sub system modelling

The need to model processes at multi-level of abstraction necessitates use of some form of process-oriented decomposition technique. As explained in chapter 2 there are a number of techniques available (such as: IDEF; CIMOSA; TOGAF and PERA etc.) that incorporate formal decomposition mechanisms. This study has chosen CIMOSA because as earlier described the author observed that it has:

- Well developed and proven process modelling concepts and modelling decompositions, which can facilitate modelling with reference to both specific and generalised contexts
- It decomposes 'systems requirements' (via use of DP; BP; EA concepts) and 'system solution designs' (via use of FO, FE ideas)
- CIMOSA provides a framework for modelling which can connect process-oriented (requirements) models to (solution) models comprising alternative configurations of candidate resource systems
- CIMOSA has proven effective as a means of eliciting knowledge and data about many case study MEs

Hence during Step 1 the author proposed to capture a CIMOSA EM of the subject ME; so as to provide a specific case process-oriented framework to integrate the outcomes of subsequent stages of her modelling approach.

7.3.1.2 -S2 - Resource sub system modelling

However it was understood that CIMOSA does not specify resource modelling concepts that can directly encode different configurations of EoSS manufacturing systems. Hence this deficiency needed to be overcome.

It was proposed that resource modelling would be focussed on specifying the 'competencies' that need to be possessed by human resources, and/or the 'capabilities' that need to be possessed by automated resources; such that they can perform explicitly identified process-oriented roles. By so doing it was presumed that models of 'work centres' could be explicitly matched to processing requirements identified for each different product type. It was observed that the CIMOSA EM technique, which includes FO and FE modelling concepts, could be enhanced to provide a formal way of expressing respectively 'competency requirements' and 'competency types'. Furthermore a similar approach could be adopted when expressing 'capability requirements' and 'capability types'; such that models of candidate people and machine resources can be expressed in a common way; so that when combinations of human and automated resource systems need to be modelled they can be explicitly characterised in a common manner. It was envisaged therefore that FO and EA concepts could be used as 'intermediate description mechanisms' to flexibly link explicit models of 'Role requirements' (expressed in terms of well-structured sequences of EAs, BPs and/or DP's) to explicit models of human and automated resources that are potential 'Role Holders' (expressed in terms of competencies and capabilities possessed).

7.3.1.3-S3 – Work sub system modelling

As part of the authors modelling methodology, based particularly on experience gained when modelling Wood Team production and project management systems, it was presumed to be important to be able to simplify the modelling of work sub-system aspects. This would be particularly important when manufacturing systems are used to realise many types of product. Hence it was decided that different products types might need to be grouped together

according to some specified principles; so that manufacturing system models could be developed at suitable levels of detail. Importantly products can be assigned to a class or family or type according to other differences, such as functional differences, feature differences, market difference and so on. Other researchers have used these alternative viewpoints for the purposes of product classification. But in this work focus is only on processing differences between families and types. Hence a principle developed and adopted in this research was that products/ parts/ components should be consolidated into product families ***on the basis of similarity in their processing needs***. Hence if two product types have marginal processing differences, such that they can both be realised by the same manufacturing system configuration through programming of the deployed human and/or automated systems, then those two product types would be assumed to belong to the same product family. Also it was presumed that a model of 'the processing' of a product family could usefully characterise all products belonging to that family. While if two product types require major processing differences it was assumed that (a) they belong to different families that will likely require human and/or automated systems reconfiguration to enable the two families to be realised by the same manufacturing system and (b) that distinctive processing models will be needed to distinguish the specifics of product realising differences between the two families. Hence the following definitions were made:

Product types belonging to ***different product families*** will require significant processing differences to facilitate their realisation. Typically these processing differences may be processing route variations or significantly different processing operations and/or operation times; and therefore typically will require significantly different resource system competencies.

Product types belonging to the ***same product family*** will normally require similar processing to facilitate their realisation. Therefore in comparison to product types that belong to different families, typically there will be a need for relatively minor processing differences between product types within a family; which may take the form of relatively minor processing route variations or relatively minor differences in processing operations and/or op times and will likely need relatively minor changes in resource system competencies.

Therefore to reduce impacts of product complexity when modelling multi-product manufacturing systems it was planned to use product type classifications derived from an identification of distinctive processing differences; which might in a specific case be related to a functional or an architectural classification of the same products but this would not in

general be expected to be the case. Essentially by providing a set of rules for grouping product types this provided a mechanism for abstracting detail away from work sub-system models of manufacturing systems.

7.3.1.4 S4 – Integration modelling

Following steps S1, S2 and S3 of Phase 1 of the EMM, the process, resource and work sub-systems of a subject manufacturing system will have been separately decomposed; to enable separated 'in context' and explicit modelling of their relatively enduring (i.e. structural) characteristics at required levels of abstraction. However to realise multiple level representation of actual manufacturing systems, it was necessary (at the same abstraction level) to integrate these three (process, resource and work) views into integrated and explicit representations of ('as is' and/or 'possible to be') structural system configurations. Also it was envisaged that multiple and coherent, 'integrated representations' of structural system configurations would commonly be required to progressive detail the ME business and engineering architectures which form the operating context within which subject manufacturing systems need to operate.

As part of the EMM it was proposed therefore that various 'candidate integrations' of process, resource and work sub-system views could be graphically represented (by using suitable graphical modelling constructs) to: facilitate qualitative reasoning; generate new system understandings; design new system configurations; and facilitate engineering decision making about manufacturing systems, and how they should interact with their related engineering and business systems. Furthermore it was envisaged that integration modelling could be progressively realised in three ways as follows:

1. ***Mapping product families into the process network***

Following S3, individual products/ parts/ components that flow through a subject manufacturing system will have been consolidated during S3 into product families and product types on the basis of similarity of their processing needs. The purpose for so doing was to (A) cut through complexities arising because Case 2 and Case 3 EoSS manufacturing systems use a common resource to make a number of different product types and (B) to characterise impacts of product dynamics (as defined by Cui & Weston, 2010) on a product realization.

Also having explicitly modelled the product realisation processes of a specific ME during S1, it was now possible during S4 of phase 1 of the EMM to map the modelled product families and types onto the model of ME processes. This enables visual maps to be developed to help conceptualise and document (at required abstraction levels) similarities and differences between processing routes, operations and operation times for alternative product families and types. This kind of map can also be used to progressively develop sets of integrated graphical models of a subject ME.

2. ***Forming P R couples*** (which later in thesis, led to new ideas about matching 'process-oriented roles' to 'candidate role holders')

As described in section 7.3.1.2, when deploying the EMM to model configurations of resource systems that match process-oriented requirements, it was proposed that the use of CIMOSA FO and EA concepts could provide 'intermediate description mechanisms' to flexibly link ME (people, machine and IT) resource system actors to ME requirements models. Hence during this stage of EMM integration modelling, it was proposed that this matching principle should be invoked so as to match the *competencies required* to perform ME (business, engineering and manufacturing) activities to *competencies possessed* by candidate resources. Also it was proposed that visual maps, representing configurations of these process-resource couplings, could also facilitate qualitative reasoning; generate new system understandings; and support the design of new system configurations. Additionally it was expected that graphical maps showing configurations of process-resource couples could provide a new means of visually representing architectural structures of MEs; which at multiple abstraction levels can describe process-oriented structural relationships between all ME activities and ME actors assigned to realise those activities. It was envisaged that this could provide much enhanced representation of ME architectures, relative to the conventional use of organisational charts in industry at large.

3. ***Conceptualisation of configurations of EoSS systems***

At this final stage of integration modelling it was proposed that graphical models of work flows of different product types (and families) through candidate configurations of process-resource system couples could be developed and deployed. This would further: facilitate qualitative reasoning; generate new system understandings; and provide support for the design of new system configurations.

Having completed S1, S2, S2 and S4 steps of phase 1 of the EMM, it is expected that, guided by the EoSS Reference model specified under section 7.3.5, ME and manufacturing system decision makers can readily characterise various EoSS system cases that are, or could in the future be, deployed by any subject ME. Chapters 8, 9 and 10 of this thesis illustrate how this assertion was proven to be true, at various levels of abstraction, in a number of case study MEs.

7.3.2 Behavioural modelling –EMM phase two

After conducting structure modelling, it is proposed that behavioural modelling is carried out during the second phase of EMM application. This will involve:

* Selecting the right simulation modelling technology;

* The conceptual design of 'in context' and 'focussed' simulation models, at one or more required abstraction levels;

* Building, testing and validating (sets of) simulation models that realize the conceptual designs developed;

* Conducting simulation experiments based on different scenarios.

In this study DES simulation modelling technology was selected for reasons described in chapters 4 and 5 of this thesis. Therefore simulation technology choice will not be considered further here.

7.3.2.1 B1 – Conceptual design

Step B1 involves the conceptual design of a set of simulation models that match (a) the objective function(s) to (b) user needs as defined during phase 1 of the EMM. This conceptualisation should be at all levels of abstraction needed: such as to consider the holistic operation of an ME, or of selected systems within that ME, such that they perform effectively with respect to the business contexts and product dynamics in which they will be used, or could in the future be used.

By definition, when a Case 1 EoSS system is modelled the work sub-system is usually relatively simple and well defined. While when we model a Case 2 EoSS system, typically time study or informed estimates about work, process & resource sub-system specifics lead to simplifying assumptions (e.g. average Op-times; etc., etc.). When we model a Case 3 system, in general it is expected that further simplifications will be needed with respect to work, process and resource sub-system specifics. Also anticipated was that additional modelling assumptions will be needed when creating simulation models at higher levels of abstraction (for example when ME business models are conceived)

7.3.2.2 B2 – implementation of the design; using a selected simulation tool

This step is typically expected to involve:

1) Building a simple version of a simulation model of the subject system; this is expected to involve the use of a selected proprietary DES tool to implement a simulation model which begins to exercise models of subject system behaviours.

2) Validate and further develop the model. The operation of the models created should be tested with case study data and their operation validated and further developed in consultation with intended model users.

7.3.2.3 B3 – experimental designs

A set of simulation experiments should be designed, based on use of the simulation models created. Here based on ideas embedded into the Reference Model of EoSS, actual plant data should be used to progressively select and adjust model parameters and configurations, so as to understand current and possible future model, and thence real system, 'behaviors' based initially on the use of Case 1 EoSS simplifications of the subject product realization system. After which as required Case 2 and 3 EoSS configurations can be experimentally modeled and studied. The purposes of this step wise approach are:

1. To gain practical but effective understanding about 'as is' system behaviors under different conditions;

2. To enable qualitative and quantities analyses of how changes in the current work sub-system impact on manufacturing system behaviors;

3. To identify the current bottlenecks of an existing system design, this should lead on to the use of the model(s) to support system re-design and change.

4. Using relevant KPIs to measure key attributes of the specific problem.

7.3.2.4 B4 – scenario testing

Normally it is expected that the 'as is' simulation model will be run with various scenarios of input and/or parameter values; so as to systematically conduct sets of experiments that validate the 'as is' model and lead to better understandings about a current EoSS manufacturing system configuration being modelled. Following which it is also expected that further sets of experiments & scenarios will be run with one or more 'to be' model configurations; so that systematic predictions about possible manufacturing systems change can be made. By such means it was expected that model users could:

Systematically quantify impacts arising from adjustments made to the balance between economies of scale and scope product realisation in a subject system; be that for a specific choice of manufacturing, engineering or business system or for a complete ME;

It follows that figure 7.5 summarize the steps of the proposed EMM.

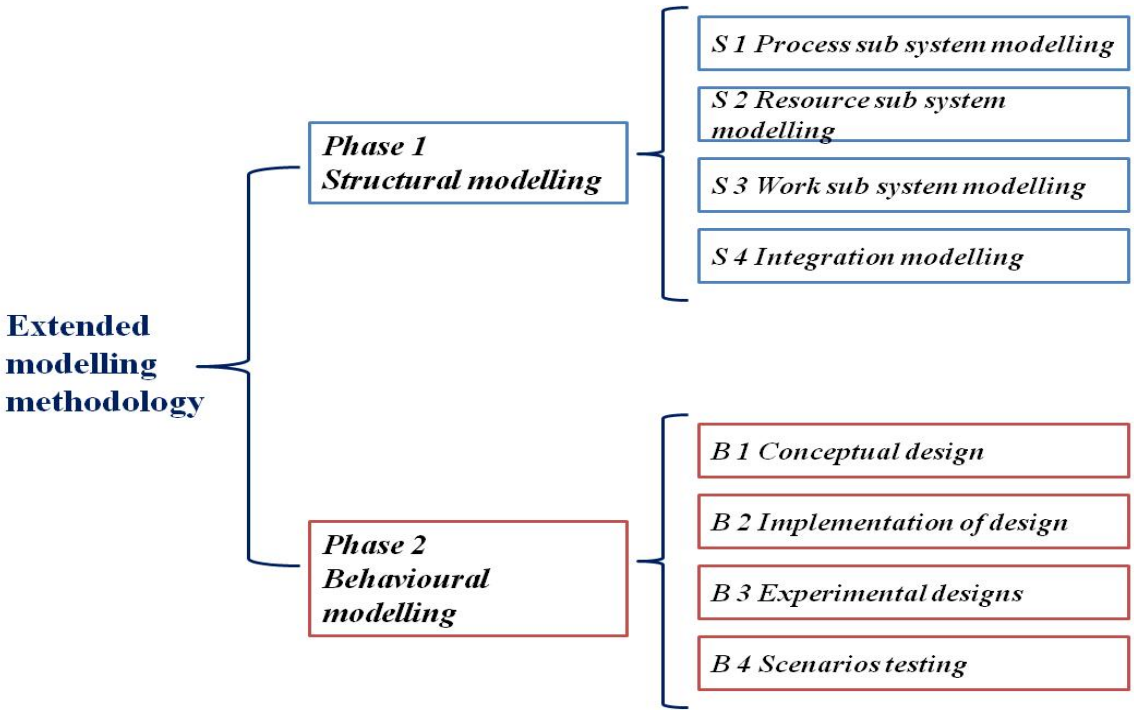


Figure 7.5 Summary of steps in extended modelling methodology

Chapter 8 Implementation and Testing of the Extended Modelling Methodology: Part I

Chapters 8 and 9 describe two parts of a third case study. The first part of this study, reported in this Chapter, describes how the Extended Modelling Methodology was applied with a defined focus on improving one segment of complicated manufacturing system. The second part reported in Chapter 9 concerns a complementary application of the Extended Modelling Methodology at multiple levels of abstraction; with a view to characterising EoSS behaviours of the complete case study enterprise.

8.1 Company Background and Case Study 3 Overview

The third case study company is AirCon International. AirCon is a privately owned Chinese manufacturing company located in Southern China. Since the late 1980's when it was privatised, AirCon has expanded its manufacturing and supply scope and currently specialises in the 'engineering to order' of customised industrialised air conditioners. Its unique expertise is demonstrated in a competence to meet varying customer needs. AirCon employs about 1000 staff, of which 60 persons are main-stream Engineers. AirCon customized products are air conditioners designed and manufactured for use at power stations, air ports and hospitals, and in trains and various special environments. Example products are shown in figure 8.1. These range from chillers, air handling units, humidifiers, humid static equipment and 'standard' air conditioners. AirCon claims it produces 2000 plus unique products with an average lead time of 45 days; although historically, due dates vary from 10 days to 3 months.

Figure 8.1 Examples of Air Conditioner products of Shenling

The author and her research colleagues in the MSI Research Institute first visited the AirCon Company in China in July 2008. The MSI team stayed for one week to interview its senior

and middle level managers as well as to visit the production plant. The visit allowed very valuable information to be captured for the author's research. This enabled: (1) an outline enterprise model (EM) of AirCon to be created during the first visit which was presented to the knowledge holders of the company for initial verification; (2) initial causal loop models to be created to explain how overall company behaviours matched anecdotal problems described by company knowledge holders: (3) the understandings generated by the AirCon EM and causal loops to be re-coded into (a) a relatively simple ithink, continuous simulation model of cash flow behaviours in AirCon and (b) an initial discrete event simulation (DES) model of one segment of the AirCon production system (one shop); and (4) use of predictive and quantitative capabilities of the continuous and DES models to be demonstrated to production shop managers.

Following discussion at the end of the July 2008 visit, AirCon formed an in house team (with a group of 5 people from different company sections) to work in parallel with the MSI team. More detail models were then created by the author after her return to the UK. All information transferred between AirCon and MSI personnel needed to be translated from/to the Chinese language (mainly by the author). This was a rather protracted process involving significant data collection activity in AirCon followed by significant modelling effort in MSI; followed by the creation of documents and presentations to enable detailed verification of research findings by prime knowledge holders in the company.

Therefore a number of EM versions and simulation model developments were created after the first company visit by MSI team, and much of the information gathering was carried out via emails and internet-based interviews between MSI and the company persons.

In April 2009, the MSI team made a second visit to the company to discuss and verify initial project results and to obtain further company steers on problem areas to address. During the investigation and visit discussions, AirCon explained to the MSI team that as a consequence of many interactions between the company and university teams, the company had instigated quite major behavioural improvements in terms of:

(1) Integrated Planning;

(2) Cash Flow management and

(3) The Implementation of 'Lean ideas': a new to the company manufacturing paradigm.

Very encouragingly these three areas were ones the MSI team had recommended as initial project focus areas for AirCon improvement during the first MSI visit.

The then latest modelling results and analysis work carried out by MSI (mainly the author and Dr Kobby Kouda) were presented to the company during the second visit. Also the second visit involved:

- Further data gathering and knowledge finding;
- The provision of a one day course on basic Lean Engineering training to middle AirCon managers (by the MSI team); and
- Detailed discussions were held between the MSI team and key AirCon personnel.

At the end of the visit, suggestions for further action were made with a view to enabling AirCon to maintain continuous improvement in areas (1), (2) and (3.
Additionally, two further issues of company concern were selected as improvement areas for the MSI and AirCon teams to focus on namely:
(4) New premises planning;
(5) Design for Integrated Purchase and Production.
Recommendations of improvement on those five areas were informed and analysed by the MSI team using their developed models of AirCon and their systematic uses of modelling tools.

With reference to the working context described in the forgoing, the remainder of this chapter, and chapter 9, describes research and AirCon modelling work of the author of this thesis.

8.2 Phase 1: 'Structural modelling' to create an Enterprise Model of AirCon

In conformance with the authors Extended Modelling Methodology as defined in Chapter 7, during EMM step 1 standard CIMOSA modelling constructs were used to create the AirCon EM. By deploying CIMOSA's decomposition and graphical modelling constructs, the author was able to capture and deploy a 'process-oriented view' of the network of activities 'then currently' performed by the AirCon enterprise to realise products for customers. Essentially this view of AirCon was populated with understandings elicited from many AirCon personnel. In summary the purpose of this first modelling step was to:

- ***Capture a 'big picture' of the network of processes used by the company to sell and realise Air-conditioning products for its customers;*** this being key as the MSI research team had limited familiarity with the company prior to the visit and needed a structured way of gaining detailed understanding within a few days .

- ***Explicitly decompose and represent processing requirements of the company.*** The EM described in this section was created during the first visit and formally documented the activities that various organisational units (and their related company personnel and supporting computer systems and automated machines) carry out when they sell and realise products. Also the created EM documented key structural inter-dependencies that must be maintained between those activities

- ***Gain general understandings about the various forms of work that flow through AirCon processes and their elemental activities.*** The purpose here was to begin to identify processing differences between product variants as they flow through the case company's process network

Use the EM (or process map) created to begin, as advised by AirCon managers, to identify and characterise areas of concern to the company. Many areas of concern were identified but in this chapter, the prime focus of concern is on using case study models to enable improved and integrated production planning, which it was believed could lead to improved cash flow behaviours in the ME as a whole.

Figure 8.2 illustrates the context diagram of AirCon which was constructed to define the top level operational (day to day) context in which AirCon and its related customer/partner businesses specify and realise air-conditioner products. Essentially this context diagram defined the context in which the remainder of the AirCon Enterprise Model (EM) was situated. The full AirCon EM is included into appendix II.

Figure 8.2 shows that nine 'Domains' were identified by the author and her colleagues which collectively 'Engineer air conditioners to meet customers' orders', namely,
DM1Customers: This domain comprises customers of AirCon who are organisations that will use air-conditioners as they asynchronously operate in different industry sectors.
DM2 Suppliers: This domain comprises suppliers of AirCon raw material. These are suppliers mainly of coiled metal sheets, wood frames; refrigerants; A/C cooling system components; and electronic control components;
DM3 Sellers: In this domain the AirCon sales force operate to obtain customer orders/requests and participate in the transformation of these requests into sales orders for internal AirCon purposes. Also the sellers provide a first level of technical and after-sales support via their interface to customers.

DM4 Marketers: Who develop and establish a new customer base for AirCon.

DM5 Product Designers: Who develop or generate designs, product drawings and BOMs to guide onward production activities.

DM6 A/C Producers: Who produce, assemble, pack and arrange the delivery of air conditioners to meet customer specifications.

DM7 Business Managers: Who manage order fulfilment and support processes.

DM8 Logistics Providers: Who manage logistical operations and transport finished air conditioners to customers.

DM9 Production Supporters: Who realise production control processes.

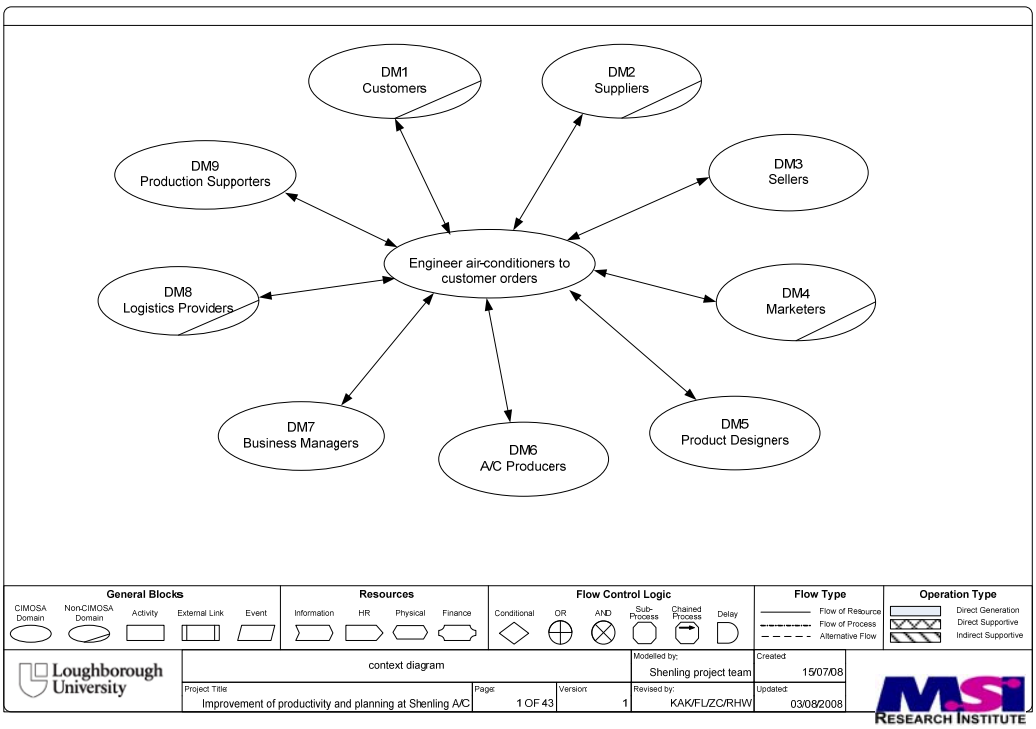


Figure 8.2 Context diagram of AirCon

During the AirCon project, the MSI team had chosen several areas as a research focus. These choices were centred on a more limited set of AirCon enterprise domains and on interactions between those domains. The prime domains of concern were: DM3 Sellers; DM5 Product designers; DM6 A/C producers; DM7 Business managers and DM8 Production supporters. Therefore these domains were modelled as CIMOSA conformant domains. The research foci determined the emphasis of subsequent CIMOSA modelling as the MSI team had limited time and resource to characterise the wider AirCon EM/process network. In respect of research reported in this chapter, the author selected the assembly system of AirCon as the

prime focus of concern; which resides within DM6, A/C producers. While in Chapter 9 a wider, more abstract focus of concern/study was selected

8.3 Detailed Process-Oriented Structure Modelling in the AirCon Assembly Shop

Detailed modelling work was conducted to decompose the production system of AirCon. Figure 8.3 shows the structure diagram of DP6 'produce A/C', which is owned by DM6. DP6 was observed to consist of 6 sub business processes, namely, BP6.1 'fabricate metal sheet', BP6.2 'produce heat exchanger parts', BP6.3 'assemble small sized A/Cs', BP6.4 'assemble large sized A/Cs', BP 6.5 'store materials' and BP6.6 'maintain machines'. It was also observed that physically there are two separately located production units within the assembly system of AirCon; they are assembly shop 1 and 2. Assembly shop 1, which is realised by resourcing BP6.3, mainly makes 'small sized' and 'standardized' A/Cs, while assembly shop 2 is realised by resourcing BP6.4 and mainly produces 'large sized' and 'customised' A/Cs. From historical order data, it was observed that most bottlenecks occur in assembly shop 2; this was presumed to be because it produces A/Cs with the greatest levels of customisation. For this reason the author's detailed dynamic simulation modelling work in AirCon was initiated with a study of assembly shop 2. To begin this simulation modelling work, BP 6.4 'assemble large sized A/Cs' was understood in detail and further decomposed into the activity diagram of BP6.4.

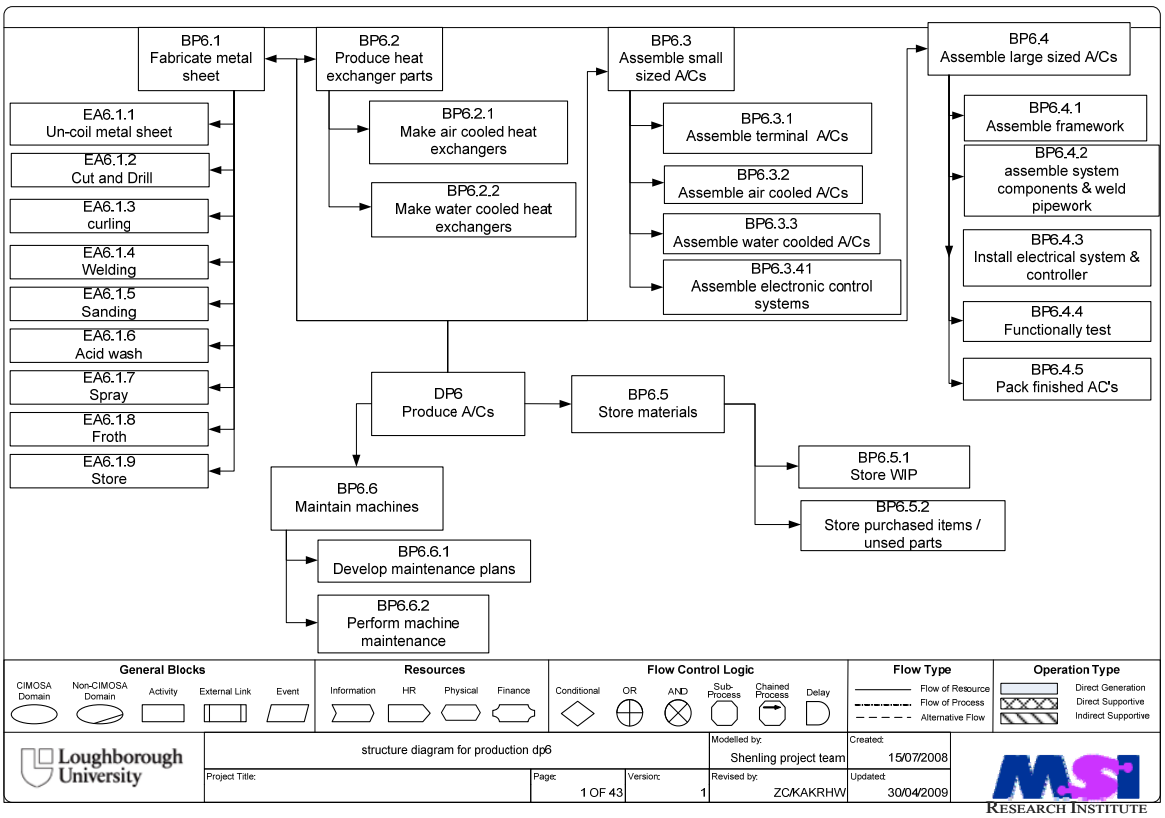


Figure 8.3 Structure diagram of DP6 Produce A/C

From the CIMOSA structure diagram created (see figure 8.3) it was made evident that there are five sub BPs within BP6.4, namely, BP6.4.1 'assemble framework', BP6.4.2 'assemble system components and weld pipe-work', BP6.4.3 'install electrical system and controller', BP6.4.4 'functional test' and BP6.4.5 'pack finished A/Cs'. Figure 8.4 illustrates the activity diagram of BP6.4. This shows that each sub BP within BP6.4 is realised by a 'team based' human resource. At this level of modelling initial explicit understandings about resource system attributions to assembly activities (and 'Roles' - i.e. groupings of activities) was gained. This initiated explicit modelling related to Step 2 of the author's Extended Modelling Methodology.

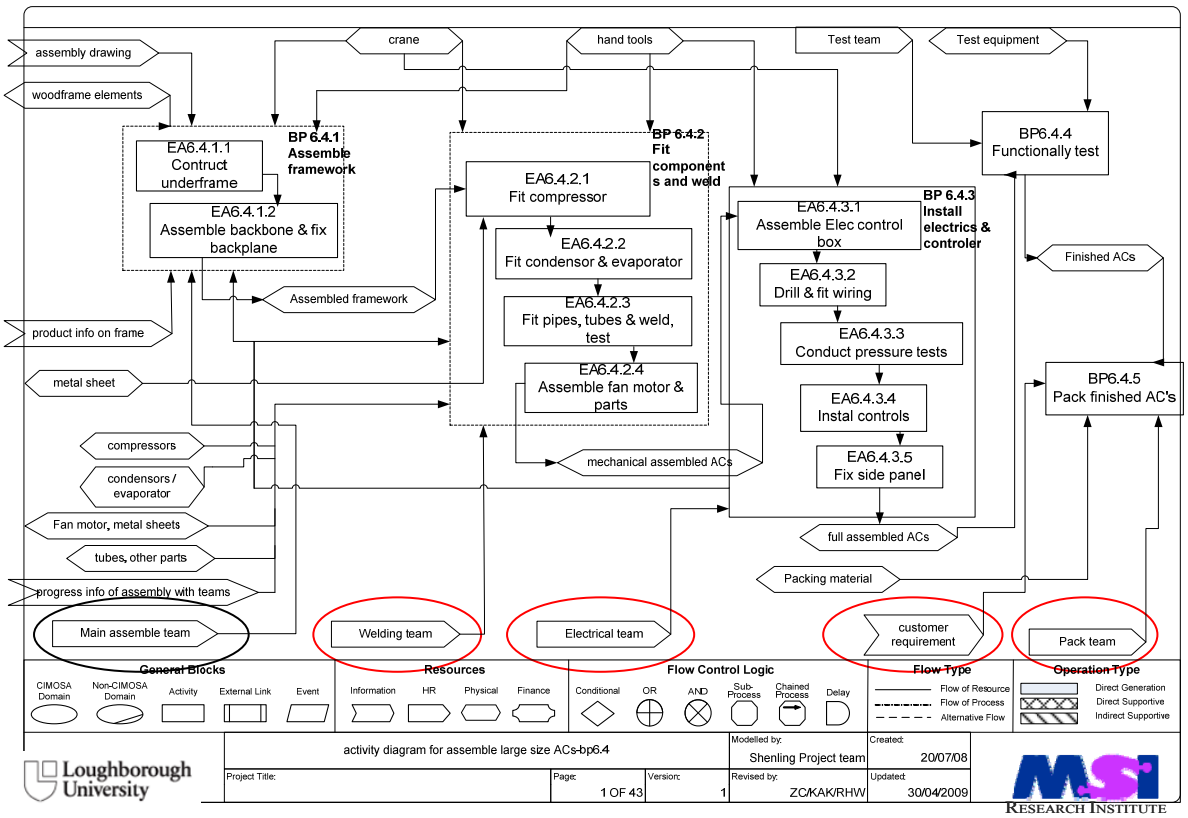


Figure 8.4 Activity diagram of BP6.4 assembly large sized A/Cs

It was observed that the various roles carried out in assembly shop 2 are resourced teams of shop floor personnel, who as assembly system role holders possess different expertise. The 'as is' composition and role of these teams is explicitly defined by Table 8.1. Three of those team types actually comprise sub-team instances of those types who work on different shift patterns; the exception being the Testing team which comprises one team only. For instance, team 1 (the mechanical build team) actually comprises 4 sub-teams who in different time slots complete EA6.4.1.1 'construct under frame' and EA6.4.1.2 'assemble backbone and fix backplane' activities. Team 1 is also the same human resource system used for BP6.4.5 'pack finished A/Cs'. While the role of the sub-teams comprising the welding team 2, is to achieve EA6.4.2.1 'fit compressor', EA6.4.2.2 'fit condenser and evaporator', EA6.4.2.3 'fit pipes, tubes and weld test', and EA6.4.2.4 'assemble fan motor and parts'. Team 3 also comprises 3 sub-teams who realise EA6.4.3.1 'assemble power system', EA6.4.3.2 'drill and weld', EA6.4.3.3 'conduct pressure test', EA6.4.3.4 'install controls' and EA6.4.3.5 'fix side panel'. Team 4 'conducts functional testing' after final assembly of each A/C has been realised via BP6.4.4. Where sub-teams are deployed they are attributed to the roles defined on a scheduled basis by a production planning team, so that the production capacity of the assembly shop can be adjusted up and down as the workloads on this shop change.

Table 8.1 team assignment of A2 shop

Team composition & assignments	
Teams 1 & 5(have 4 sub-teams)	Assembly main framework & Package for dispatch
Team 2 (has 3 sub-teams)	Welding (mainly tubes)
Team 3 (has 3 sub-teams)	Wire Connection (electrical parts)
Team 4	Testing (functional)

8.4 Product classification in the AirCon A2 Assembly Shop –S3 work sub system modelling

Having collated various historical data (from AirCon production system records over a three month period) on 'types' and 'frequencies' of AirCon products, and their respective processing routes, resource requirements and various other production performance information, products were classified with reference to similarity in their processing routes through the A2 shop. The classifications made also referenced specific differences in assembly operations, average assembly operation times and resource competency requirements for different products.

The prime purpose of this process-oriented product classification was to create effective and readily usable models of A2 by cutting through inherently high levels of complexity in A2; as its 'as is' design requires the use a common resource set to assembly a significantly wide product scope (a scope which actually includes nearly all types of A/C realised by AirCon). Also bearing in mind the end target of modelling was to create virtual models (in the form of discrete event simulation models) that can replicate and predict real A2 behaviours sufficiently well, whilst having practical and effective use, it was essential to establish a level of modelling abstraction which could explicitly encode causal and temporal dependencies between A2 process, resource and work sub-system phenomenon in a tractable form. Hence, as explained in Chapter 7, fundamental modelling simplifications made and researched in this study (in respect to EoSS ME and EoSS manufacturing system modelling) were linked to notions about product classification, which in turn is akin to previously published GT ideas (and related practical production systems management techniques) where similar products are 'managed' in similar ways to simplify and facilitate their actual processing. Essentially this meant that a key idea being researched in this third case study was that the conceptual design and runtime time execution of discrete event (virtual) models can be simplified, in a similar

manner to that known to be possible as part of real production system simplifications; such that it becomes possible to replicate complex runtime behaviours such as those that occur in practice in the assembly shop 2 of AirCon.

It followed that the actual A2 assembly shop was observed to be extremely complex, in the sense that is has to assemble many different products in variable quantities and mixes which at least in part are determined by uncertain and time varying customers orders. Also many work, process and resource system variables change over time and it was suspected that dependencies between some of these variables will also change over time. Only some system parameters can be controlled by AirCon whereas other key parameters cannot. Therefore when creating discrete event simulation models of A2, it was necessary to simplify the reality to enable effective simulation model design and thereby to focus and structure the types of experiments that any developed simulation model can be used to perform. However the simplifications made would necessarily determine aspects of the 'fitness for purpose' (or quality) of the models; or alternatively stated the simplifications made should enable investigation of behaviours of key variables of interest, so that the behaviours of subject entities and key relationships between entities of interest to be determined?

Therefore the developed A2 simulation model, and its experimental scenarios, were designed bearing in mind (i) the EoSS principles discuss earlier, (ii) notions about decomposing manufacturing systems into three (work, process and resource sub-systems) with a view to enabling change within these three sub-systems to be investigated independently and (iii) characterising key aspects of customer induced dynamics (in terms of product variance and product volume dynamic factors).

Overall the purpose of developing and using the A2 simulation model was to enable new insights (not previously known to AirCon) to be gained about how current Product Dynamic factors impact on the A2 system. To achieve this purpose it was decided that A2 simulation models should enable:

(1) A wide range of possible behaviours and performances that occur in the actual A2 shop to be animated, studied and quantified;
(2) Replication of actual A2 behaviours and performances; that were known to occur when A2 is subjected to historical assembly requirements and workloads.

When conducting the experiments it was also considered vital to assess the impacts of key product differences on overall ME product cost and due date behaviours.
Consequently the developed A2 simulation model would need to quantify impacts of:

- ***Product variance*** amongst the A/C types input to the simulation model.
- ***Product volume dynamic,*** by changing work item input rates and batch sizes.
- ***Product mix dynamic,*** by changing the mix of multi-product types in the system.

Inherent therefore was the need to determine and deploy a means of classifying AirCon products into types and families, based on their processing similarities, and when so doing to embrace the ideas about Case 1, 2 & 3 embodied into the EoSS Reference Model of Manufacturing Systems.
It was therefore necessary to elicit product and production data from the A2 shop. The original idea pursued when organising that data capture, was to classify the A2 processing of A/Cs into 'complex', 'medium complex' and 'simple' product groupings. Although this idea was not completely abandoned, following initial simulation model creation and experimentation it was felt that a more definitive product classification was necessary to more adequately reflect product differences during assembly processing. Table 2 lists the products most frequently produced in the A2 shop. With current best practice in the real A2 and A1 shops, the boundary between A2 and A1 product types is based essentially on the physical size and power rating of the A/C concerned: rather than the types of assembly processing needed. Indeed, due to the space and facility limitations, the A1 shop has been producing small sized A/Cs, of under HP <= 35000W. This results in an operating policy where each shop can do extra assembly jobs for medium sized A/Cs, when the other shop is overloaded. It was understood by AirCon managers that this could have good and bad effects although the extent of those effects was unknown.

Table 8.2 shows that normally the A2 shop produces five different families of A/Cs, namely, Roof A/Cs, Cold water A/Cs, Purifier A/Cs, Air Cabinets and Modular Air Cabinets. Here it is important to note that the product classes used in table 8.2 are those specified and used by AirCon but there use of this classification is different in the sense that they group products in terms of their purpose and functionality rather than their processing needs. Also there are different functional types of A/Cs within each family; this is also indicated in table 8.2 but the specific functionalities involved are not of concern here.

Table 8.2 Primary products produced in the A2 shop

roof A/Cs	***WLF***	***WLDF***	***WRF***	***WHF***				
Cold water A/Cs	R22 refrigerant				R407 refrigerant			
	LS	***LSF***	***LSQ***	***LSQF***	***LS***	***LSF***	***LSQ***	***LSQF***
Purify A/Cs	Water cooled				Air cooled			
	LJ	***LDJ***	***HJ***		***LFJ***	***LFDJ***	***RFJ***	***HFJ***
Air cabinet	Circulate				Re-fresh			
	GD	***GDB***	***GW***	***GL***	***GXD***	***GXDB***	***GXW***	***GXL***
Modular air cabinet	***ZK***	***ZHX***	***ZKH***	***ZKB***				

Because the author needed to determine an improved (process-oriented) way of classifying products, all departmental and section managers in AirCon were interviewed to elicit their views as to how to specify process-oriented product classifications that could be usefully developed and used. One key, overall product differentiation which seemed to gain universal agreement within the company was that of placing AirCon A/Cs into two groups; namely 'mostly make'(MM) and 'mostly assemble' (MA) products. Figure 8.5 shows the different process routes of MM and MA A/Cs in assembly shop 2; this distinction was visualised by using EMM integration diagrams conceived by this author, corresponding to S 4 of the EMM.

Clearly the different routings have a significant bearing on the overall cost and time delays when processing MM and MA A/Cs. At the time of interviewing this significant difference had not been taken into account when contract negotiations with customers lead to an agreed 'due date' and 'product/project cost'. It was observed therefore that the MM, MA process-oriented product classification was important when considering the behaviours of the overall (4-shop) AirCon production system, and therefore it was hypothesised that this would given rise to distinctive business behaviours which needed to be better understood by AirCon managers so that they could adopt new operating policies aimed at developing good business behaviours and reducing the impacts of bad business behaviours, such as poor cash flows. Therefore (a) A2 shop simulation modelling reported in remainder of this chapter and (b) subsequent higher level simulation modelling of AirCon as a business (reported in Chapter 9) was in part designed to test this hypothesis.

A fairly detailed production flow analysis was considered necessary to distinguish lead-time and cost behaviours of the various product types included into Table 8.2. To help perform this fairly detailed analysis, re-use was made of the decomposition of the BP6.4 activity diagrams, previously included into the AirCon EM: see figure 8.4. Within this EM structural framework a more detailed study of 'as is' assembly processing operations was made to generate detailed static process maps that explicitly describe product specific processing operations in assembly shop 2; where the developed process maps explicitly document required 'specialisations of activity flows' (which essentially can be viewed as being 'standard operating instructions or procedures') for different types of A/C. The analysis made was based on the use of spread sheets to plot activity flows of different products types through A2 and to link these flows to the standard operation sequences to defined processing (operation) times which were collected via time study by AirCon managers. This enabled more detailed process-oriented classification of products in the A2 shop, as an integral, more detailed part of the MM and MA class notions. Some highlight conclusions drawn from this analysis are illustrated by Figure 8.5.

The analysis also provided a process-oriented basis for identifying members of the MM and MA classes. For example it was concluded that:

- MM (mostly make) includes: Air Cabinet; Modular Air Cabinet
- MA (mostly assemble) includes: Roof A/Cs; Cold water A/Cs; Purify A/Cs

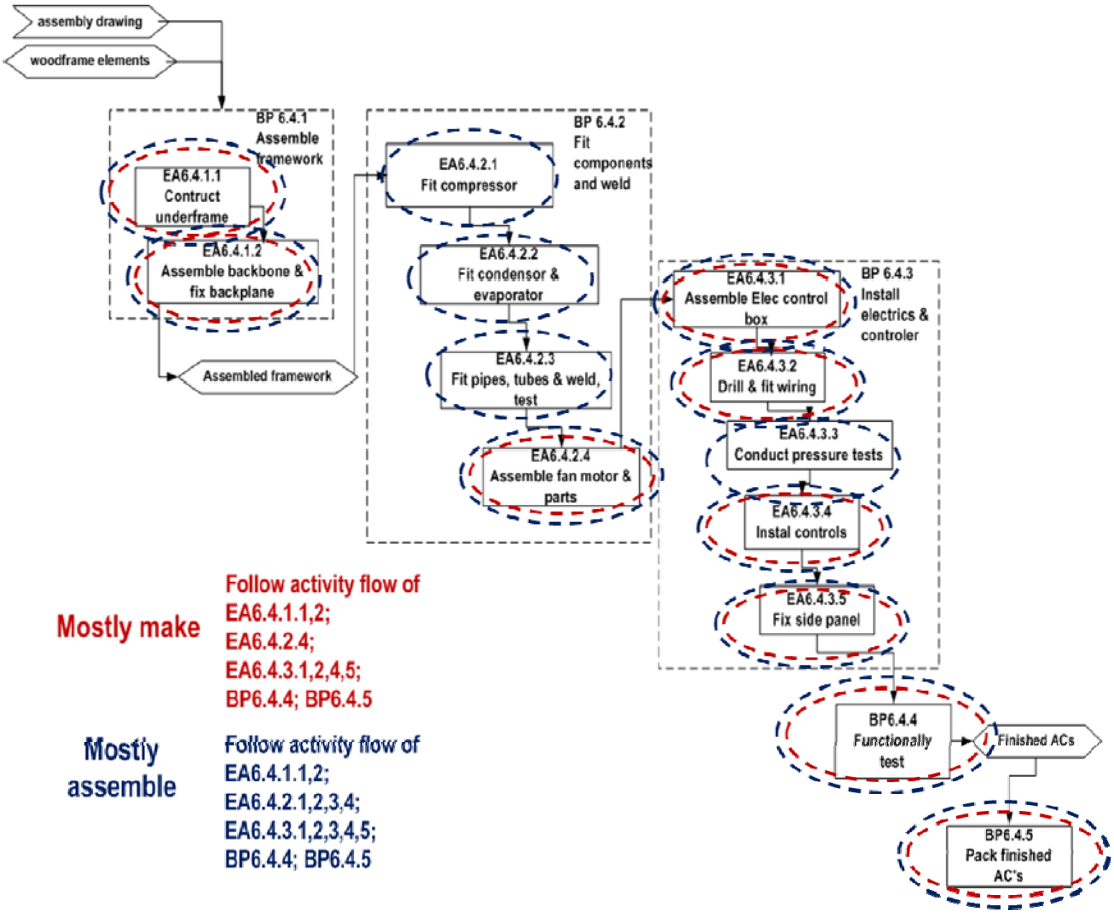


Figure 8.5 process route differences between MM and MA A/Cs

8.4 Further Integration Modelling & Conceptual Design of the A2 Simulation model

8.4.1 EMM integration modelling concepts to conceptually design AirCon A2 SMs: and linking between EMM Phases 1 and 2

It follows that use of CIMOSA EM decomposition concepts allowed the author to document relatively enduring processing requirements of the case company at various levels of abstraction. The EM was not suited however to modelling the states of processing instances as products flow through AirCon processes. However the EM did allow processing operations for different product types to be explicitly specified, but again only structural relationships could be readily encoded this way. Therefore, following steps 3 & 4 of the Extended Modelling Methodology, processing related aspects of product variance had been partially coded up, but to create computer executable models of A2 it was necessary to adopt

the use of an alternative modelling technology. Here the author chose to use Simul8 (Simu8 2000), a commercially available discrete event simulation (DES) modelling tool. Like many other DES tools Simul8 can encode and simulate behaviours of resources as they process time-based product inputs; thereby DES tools can animate time-based interactions between work, process and resource sub-systems. But as earlier discussed, conceptual thinking and additional case study data was needed to transform selected elements of the EM into fit for purpose simulation models which can be used as an experimental tool (Smith, J.S., 2003, April et al 2006).

It follows that the A2 simulation model needed to computer execute relationships that link time-based work, to time based process instants, and to allocated and available resource systems; while realising some well define objective function. In this case the reality of those relationships was very complex; while the objective function of the modelling exercise was to understand impacts on A2 behaviours of historical and possible future product dynamics. Also it was identified that possible model users in AirCon would be 'production planners' (to help them devise improved plans); 'real-time schedulers' (who need to correct in-appropriate production plans); and 'technical staff, advising AirCon sales persons' (by providing them information to support better estimation of cost and lead time differences when they negotiate alternative product options with customers) .

To enable conceptual thinking about the design of the A2 simulation model, and particularly to decide what entities, and structural relationships between entities, should be included into it and what entities and entity relations could be excluded to enable simplification, a conceptualisation of the AirCon four shop production system was developed and is shown in Figure 8.6.

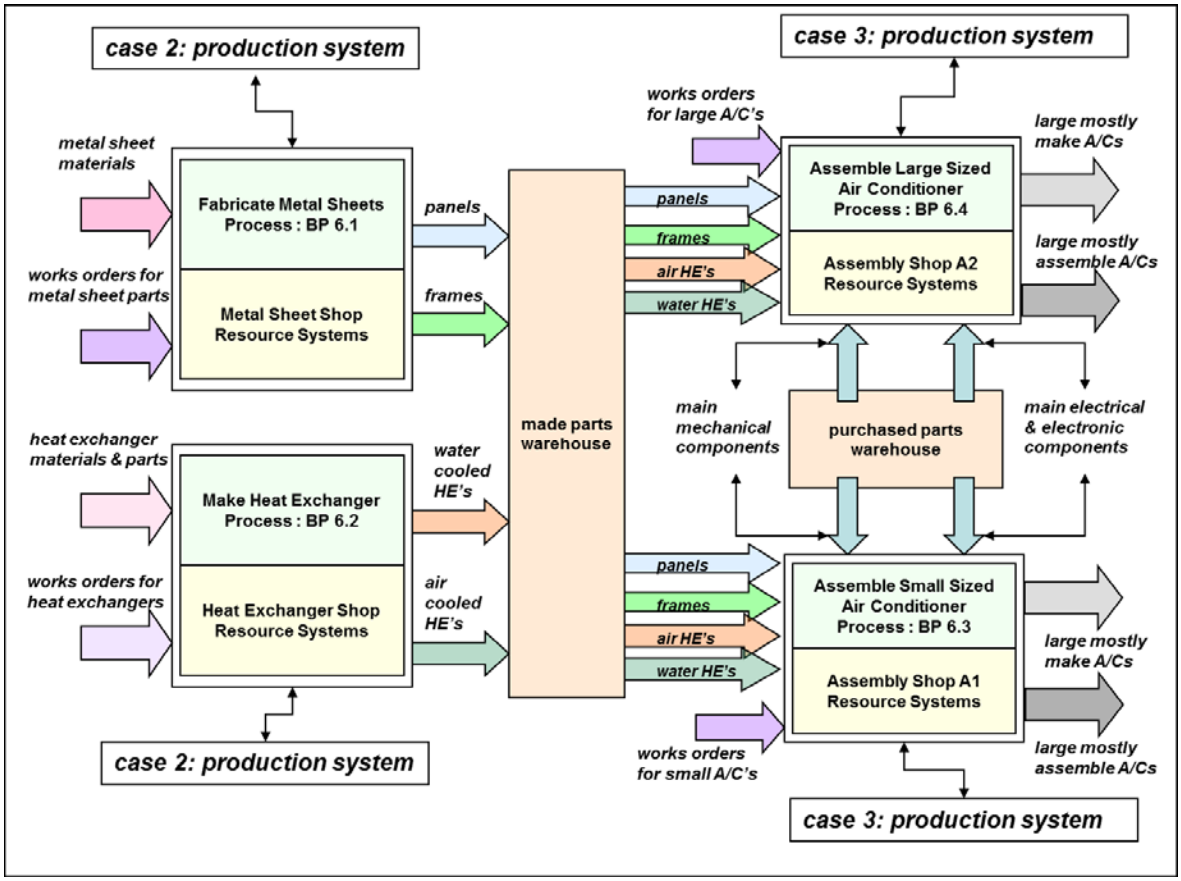


Figure 8.6 Developed conceptualisation of the AirCon Production

Figure 8.6 is a new form of 'Structural Integration Diagram' (or Integration Model) which was devised as part of the authors' PhD study. It shows how the product classifications studied during step 2 can be mapped into explicitly defined configurations of ME systems; in this case mapping is made onto the four production shops in AirCon and shows visually how they, and their constituent sub-systems contribute towards the production of MM and MA air conditioners (leading to product outputs from assembly shop's 1 and 2). Here simple graphically symbols are used to conceptualise and represent, at a high level of abstraction, the way that the 'work' (modelled as product classes), 'process' (modelled as DPs, BPs and EAs) and 'resource' (modelled as resource types) sub-systems comprising higher level 'building block' of business and/or production systems (in this case the complete AirCon production system) contribute towards product realisation. This kind of graphical representation was found to usefully visually represent the 'as is' production system configuration in AirCon, such that ideas about related changes in material and order flows can be communicated between modellers and company personnel. Also, as illustrated later in this chapter, it was observed that this kind of manufacturing system conceptualisation can usefully characterise

order and material flow dynamics within possible 'to be' manufacturing system configurations capable of achieving greater levels of EoSS. In this way it was observed that the conceptual design of current and possible future manufacturing system configurations can be qualitatively compared prior to costly and time-consuming engineering effort involved in their implementation as either a simulated or a real manufacturing system.

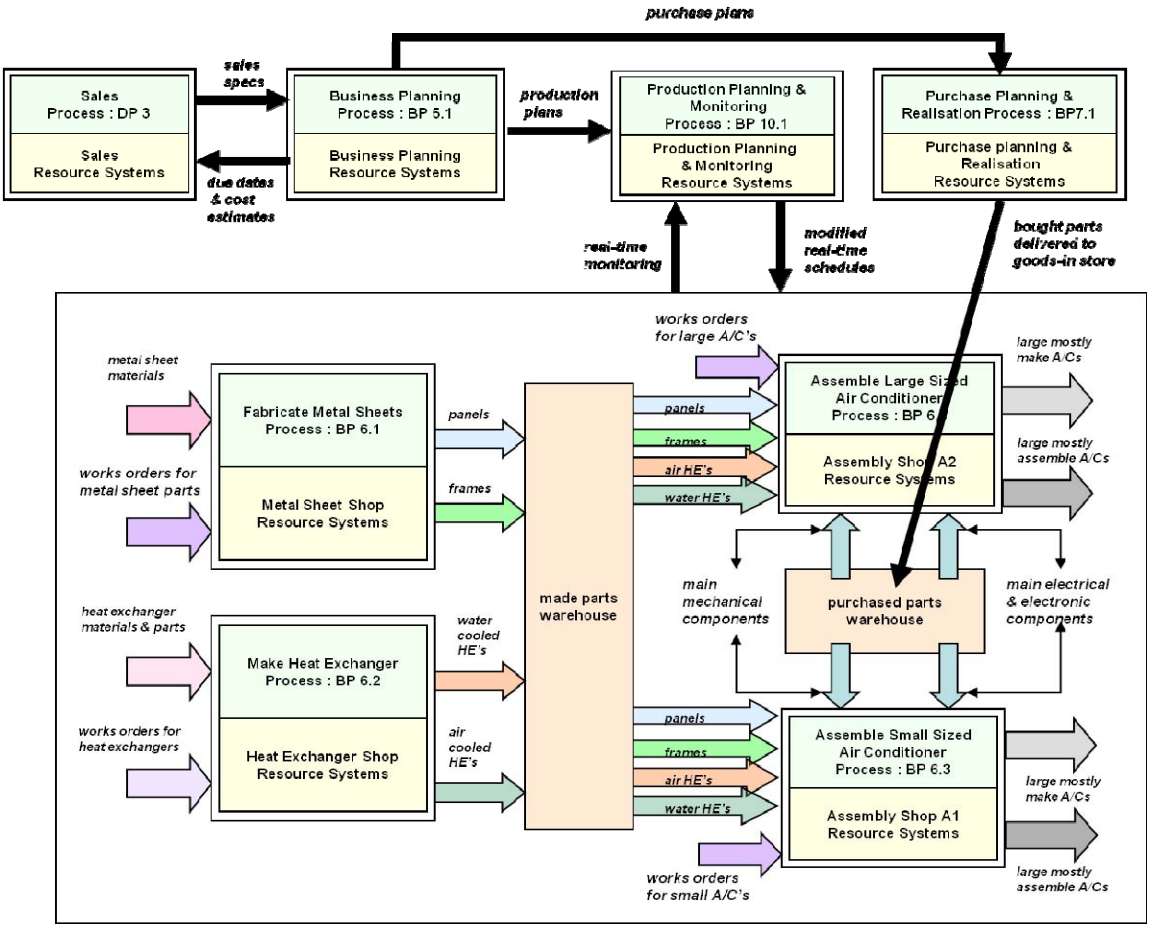


Figure 8.7 Conceptualisation of the 'Context' of the AirCon Production Shops

Additionally in the AirCon case study the EM interaction and activity diagramming concepts had been used at a high level of abstraction to conceptualise links between: AirCon production shop activities; and related sales, business planning, production planning and control and purchasing activities. These relationships were re-represented conceptually, again using the new form of 'Structural Integration Diagram' as shown in Figure 8.7. Later in the authors study this conceptualisation of the 'context' of the AirCon system was used to reason qualitatively about structural and temporal links between low level behaviour modelling and higher level decision taking and policy making. In parallel case study work the ideas encoded

into Figure 8.7 were also used by Kodua (2009), as part of his PhD study, in conjunction with causal loop analysis to inform cash flow thinking.

Furthermore it was observed to be beneficial to use the same conceptual design ideas to drill into the A2 assembly shop in the manner shown in Figure 8.8, to reveal details of the structure of that shop at a lower level of abstraction. Here the EM (created during EMM step 1), as well as specialisations of activity diagrams developed in respect of different product types and families (during EMM step 3) were re-used in a systematic manner to explicitly define interdependencies between the 'work', 'process' and 'resource' sub-systems comprising A2, and in a relatively generic way to show how product variances impact on those dependencies, prior to their more specific implementation and coding using a proprietary Simul8 modelling tool.

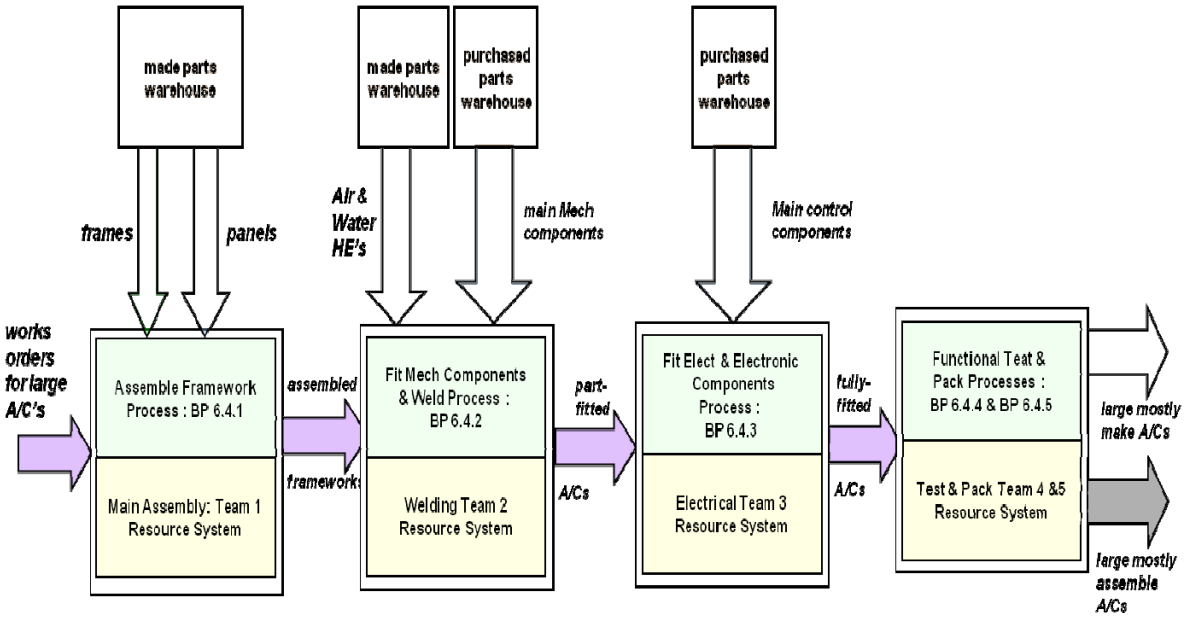


Figure 8.8 Conceptualisation of the A2 Assembly Shop

Hence figure 8.8 was further modelled as an integration of previous 'process', 'resource' and 'work' sub systems to create a visual description of architectural structures that bind assembly operations in AirCon. This is illustrated in figure 8.9, from where it can seen that an implementation of EMM integrating technique can visually map onto the process network various different product families with their associated resources (human resources in the case of AirCon assembly).

Of course it was understood that there will remain limitations on the use of this kind of visual representation of 'architectural structures', or 'system configurations', simply because graphical models can quickly become 'too big' and 'too detailed' for humans to readily understand them. But by following the EMM steps systematically, integration diagrams can be visually represented at multiple levels of abstraction; with models produced at the various abstraction levels remaining explicitly connected by the parent Enterprise Model created during EMM S1, Therefore the author believes that integration diagrams can provide an advance over other public domain Enterprise modelling techniques in respect of the encoding of complex organisational structures, such as those found in MEs. But in sufficient time or resource was available to establish the extent to which such an advance had been made; except in respect of the case study organisations reported in chapters of this thesis.

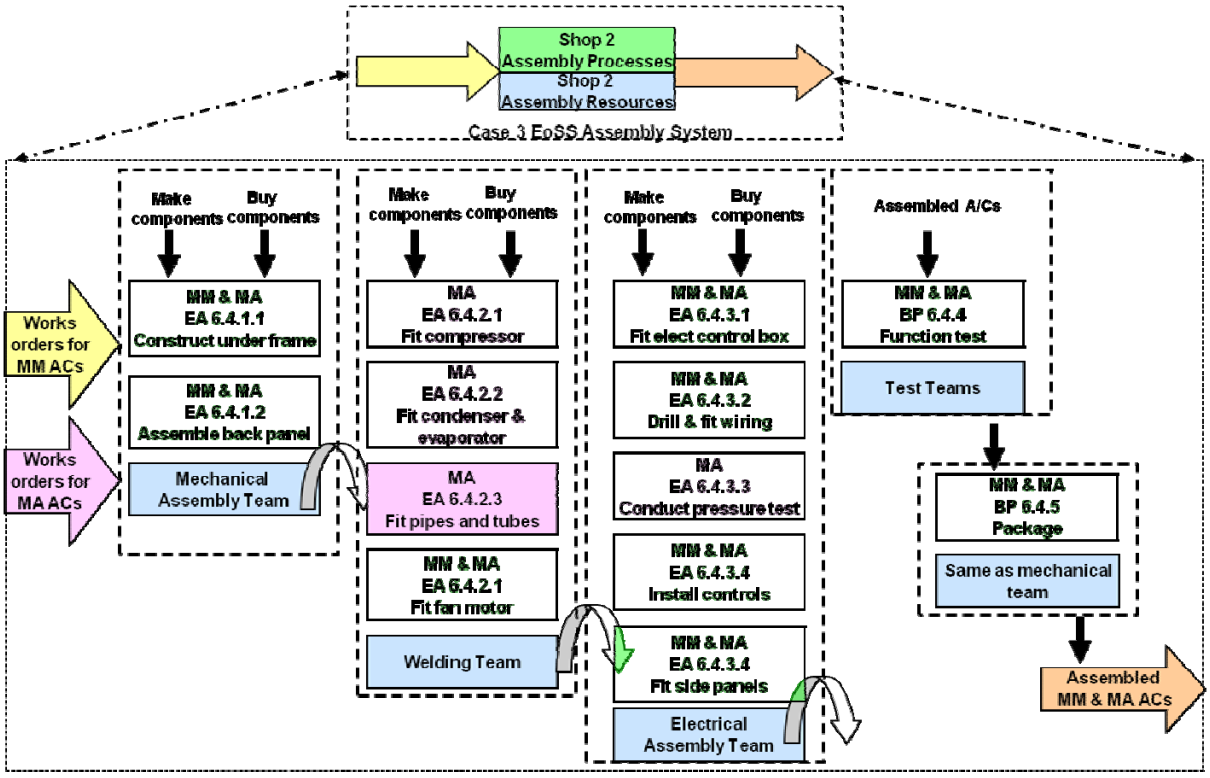


Figure 8.9 Integration modelling of 'process', 'resource' and 'work' sub systems in A2

Figures 8.6, 8.7, 8.8 and 8.9 illustrate how the present author created and used EMM integration diagrams showing of families of work flows (i.e. material and order information) through EoSS P-R (process-resource) couples at needed levels of abstraction. Thereby it was shown to be possible to usefully conceptualise and graphically represent different ('as is' and possible 'to be') EoSS manufacturing system configurations. By referring to such a graphical description, of some subject manufacturing system configuration, it also proved possible to

explicitly define certain modelling simplifications made when designing 'fit for purpose' simulation models (SMs); which in general will populate some part of or some aspect of a parent conceptual model.

Further in the AirCon case the conceptualisation presented in Figure 8.9 help to identify the decision support requirements of 3 sets of potential users of the ***A2 model of product dynamic impacts***, namely: (1) sales and technical staff; (2) production planners and (3) real time schedulers. The enterprise model (EM) developed during EMM S1 had already captured an explicit activity based description of the roles of those potential users, which in turn help to determine the information that needed to be generated by the SMs. Therefore, this author believes that fairly simple conceptual models of manufacturing system configurations, which in effect serve to integrate the three orthogonal and generally important views (and decompositions) of manufacturing systems, can provide an effective platform tool for creating various 'fit for purpose' SMs at any needed level of abstraction. Furthermore as the simple graphical configuration itself 'connects together' a number of more detailed models (e.g. an EM in the case of the process view; a product dynamic model and tabulated routes, op times, order histories, etc in the case of the work view; and tabulated historical resource assignments, competencies, etc in the case of the resource view) a wealth of information can be brought to bear on, and re-used during, SM design, development and experimentation. This was proven in this and later cases reported in this thesis, to facilitate and partially systemise the life-cycle engineering of SMs, including SM re-use as a 'component' of wider scope more complex systems.

8.4.2 Simulation Model Implementation design –B2

To facilitate analysis of different scenarios of product dynamic (or work) and related EoSS assumptions, a significant number of different SM versions of the A2 shop were developed. Those SM versions were conceptually designed and represented using 'Structural Integration Diagrams'; such as those illustrated by Figures 8.6 to 8.8. Mainly because of delays caused to this PhD study while waiting for AirCon company personnel to collect the needed plant data, it was necessary for the data used during simulation model construction and analysis to be collected and input in a piecemeal way over about a three month period. This period followed the first visit by the MSI team to AirCon. Spread sheet feedbacks and internet interview dialogues were used following the visit to facilitate data collection. During A2 simulation

studies, three stages of simulation model building and prototype analysis were specified as being required as follows:

Stage 1: create a basic simulation model of assembly shop 2. At this stage a first stage understanding of the shop was encoded into a relatively simple model, so that initial experiments could be conducted to determine what other information was needed to develop the model to satisfy its purpose.

Stage 2: validate and develop the basic simulation model. As additional required data from the AirCon in-house team was provided, new ways of developing the basic A2 model into different SM versions was determined. The aim of these developments was mainly to seek to replicate behaviours of the actual 'as is' A2 shop. This was based on a staged development of case 1, case 2 and case 3 EoSS 'simulated analogues' that represented work-loaded process-resource couples observed in the real A2 assembly system.

Stage 3: design experiments that enable the development of new understandings about the behaviours of assembly shop 2. After stage 1 & 2, the manufacturing system of A2 was believed to be adequately well modelled; from this point in the study, different experimental scenarios were developed to gain deeper understandings about system behaviours and performances, so as to discuss and develop these new understandings with appropriate knowledge holders in AirCon.

Figure 8.10 visually summarises essential decompositions and an integration of AirCon product realisation, within a common model of AirCon 'hybrid' EoSS systems. This model was captured following an application on steps S1, S2 and S3 if the EMM.

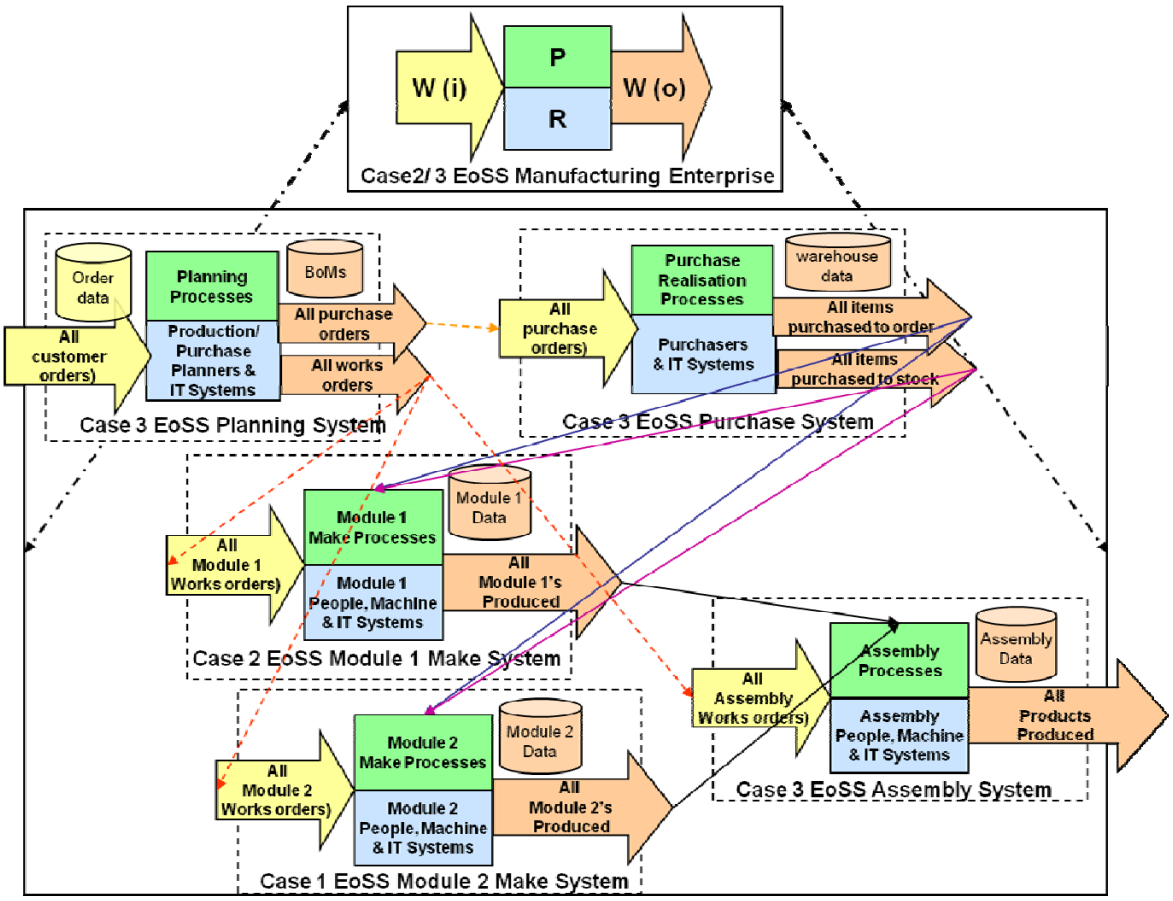


Figure 8.10 decomposition (& integration) of AirCon product realising system using EoSS DNA

By this means it was visually shown that AirCon product realization comprises: 1) a case 3 EoSS planning system (where designated persons do the contract planning), and where process-based differentiation in this sub system is based mainly on route differences between: standard, customized and special A/C products; 2) a case 3 purchase system where purchasing persons need to deal with distinctly differently bought items, that can be classified in terms of items with 'normal purchase lead-times' and 'urgent purchase lead-times'; 3) a case 2, metal sheet shop (production module 1) where significant variation arises because of significant processing differences between 'panels' and 'frames' used to construct the outer metallic casing all types of air conditioners produced by AirCon; 4) two case 1 production lines, comprising a Case2 heat exchanger shop (module 2), where the two lines realize significant processing differences between two families of heat exchanger (namely water-cooled and air-cooled heat exchangers). In AirCon therefore these two families of heat exchanger have an individual 'Process-Resource system', which must cater for minor functional and dimensional change within each family; and 5) a case 3 assembly system, where human resourced assembly processing results in final product realization of very many

A/C types. Hence in the assembly shop there needs to be significant processing differences and fairly late customization. As a consequence the assembly shop is arguably the most complex production system element used by AirCon which can in principle realize the greatest economies of scope. However this means that resource sharing amongst many product variants is necessary in the assembly shop and this was thought to be the major reason why AirCon finds it very difficult to predict the behaviors of this system in comparison to other AirCon EoSS systems used. However in many ways the assembly system is at 'the hub of AirCon successes as a producer of late- customized A/Cs.

8.5 Simulation modelling experiment designs – B3

Based on the assumption that AirCon maintains its current assembly practices, a set of simulation experiments were designed to replicate and analyse A2 assembly shop behaviours and thereby to determine and better understand factors that result in good and poor performance. To achieve this aim it was decided that the A2 simulation models, created in the systematic manner described in section 8.4, would be subjected to inputs corresponding to typical historical patterns of product dynamics. Therefore, three sets of simulation experiments were designed each covering three different types of product flow in the A2 shop, namely:

- Set 1: Mostly make family – where A2 is operating as a case 2 EoSS system (i.e. only the processing of a single product family is simulated)
- Set 2: Mostly assemble family – where A2 is operating as a different case 2 EoSS system
- Set 3: Mix of MM and MA families (two or more) – where A2 is operating as a case 3 EoSS system

8.5.1. Set 1: Mostly make family – Case 2 EoSS system

In conformance with the simulation model design stage (see section 8.4.1), A/Cs from the 'Air Cabinet A/C family' were selected as being representative of the Mostly Make (MM) experimental set 1. As in this stage of experimentation all input/product items would belong to a single product family, therefore essentially the set 1 experiment was designed to computer exercised a specific Case 2 EoSS system. Essentially this meant that a controlled simplification of the actual Case 3 EoSS in daily use in AirCon was realised so that complex system behaviours could be better understood. A Simul8 screen shot from the simulation

model developed for this experiment (with the Air Cabinet A/C family) is shown in figure 8.11.

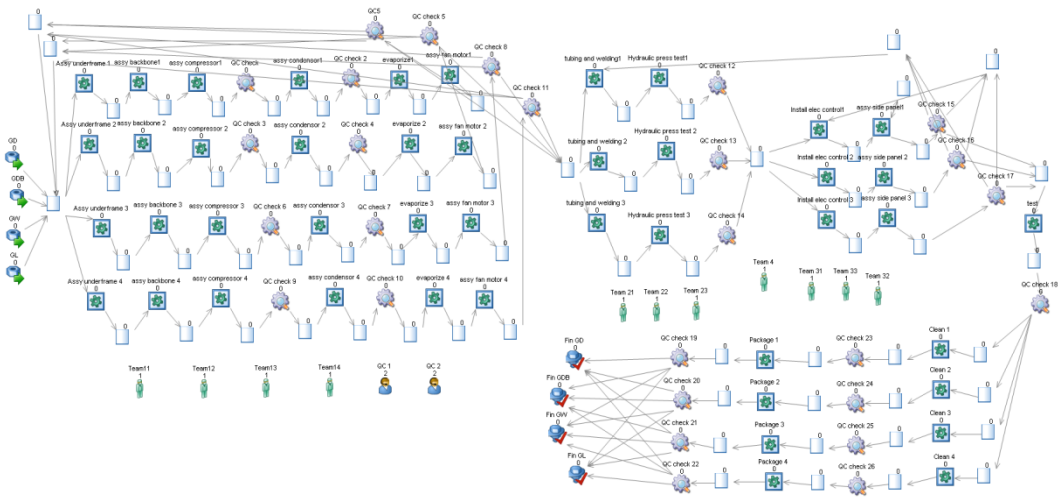


Figure 8.11 screen shot of the Air Cabinet A/C family simulation model

AirCon produces four types of (Circulate) Air cabinets, namely, GD; GDB; GW and GL. All four of these types were included into the modelled MM product grouping. The distinctive operation times for different roof A/Cs were incorporated into the model. This took into account different assembly processing operation requirements of AirCon's four types of MM A/C and their typical processing times (determined via time study by the AirCon internal process improvement team), see table 8.3.

Table 8.3 op-time requirement of Air cabinet Circulate A/Cs family

Team	Activities (needed for Air cabinet Circulate A/C assembly)	Op-time (min)			
		GD	GDB	GW	GL
team1	assemble under-frame	60	60	60	60
team1	assemble backbone	30	30	30	30
team1	assemble compressor	0	0	0	0
team1	assemble condenser	0	0	0	0
team1	Evaporator	40	40	40	40
team1	assemble Fan motor	60	60	60	90
team2	tubing & welding	0	0	0	0
team2	Hydraulic pressure test	0	0	0	0
team3	Install electronic control	30	30	30	40
team3	assemble side panels	90	90	90	90
team4	test	30	30	30	30
team5	package	90	90	90	90

This operation time data was flexibly coded into the simulation model using 'labels' and 'visual logic' functions (simul8 2000). Spreadsheets were also used to store these information entities, and 'labels' were used to differentiate the data pertaining to different product types. Estimated set up times, in terms of 'studying product drawings', 'finding tools' when switching between products, were also included in the simulation model.

During the set 1 experiment, simulation model (parameters related to 'Order Size') were manipulated to realise the assumed scenarios; where the (order) 'Inter-arrival time' was maintained as 17 days throughout the set 1 experiment. This input rate was derived from an analysis of historical data provided by the company. With a view to dealing with randomizing aspects of simulation experimental design, all experiments were conducted with 8 independent replications per trial (Law and Kelton 1991, Chen and Kelton 2003).

Figure 8.12 illustrates how the author input the operation data from table 8.3 into the SM; one example operation is shown, which corresponds to 'assemble side panel'; named as 'assemble side panel time' label. This includes an encoding of the different operation times off three product types. Such that: in column A, as shown in figure 8.12, it represents 1 to 3 product types (with their three different complexity levels); in column B the operation times (in minutes) of those products are shown respectively.

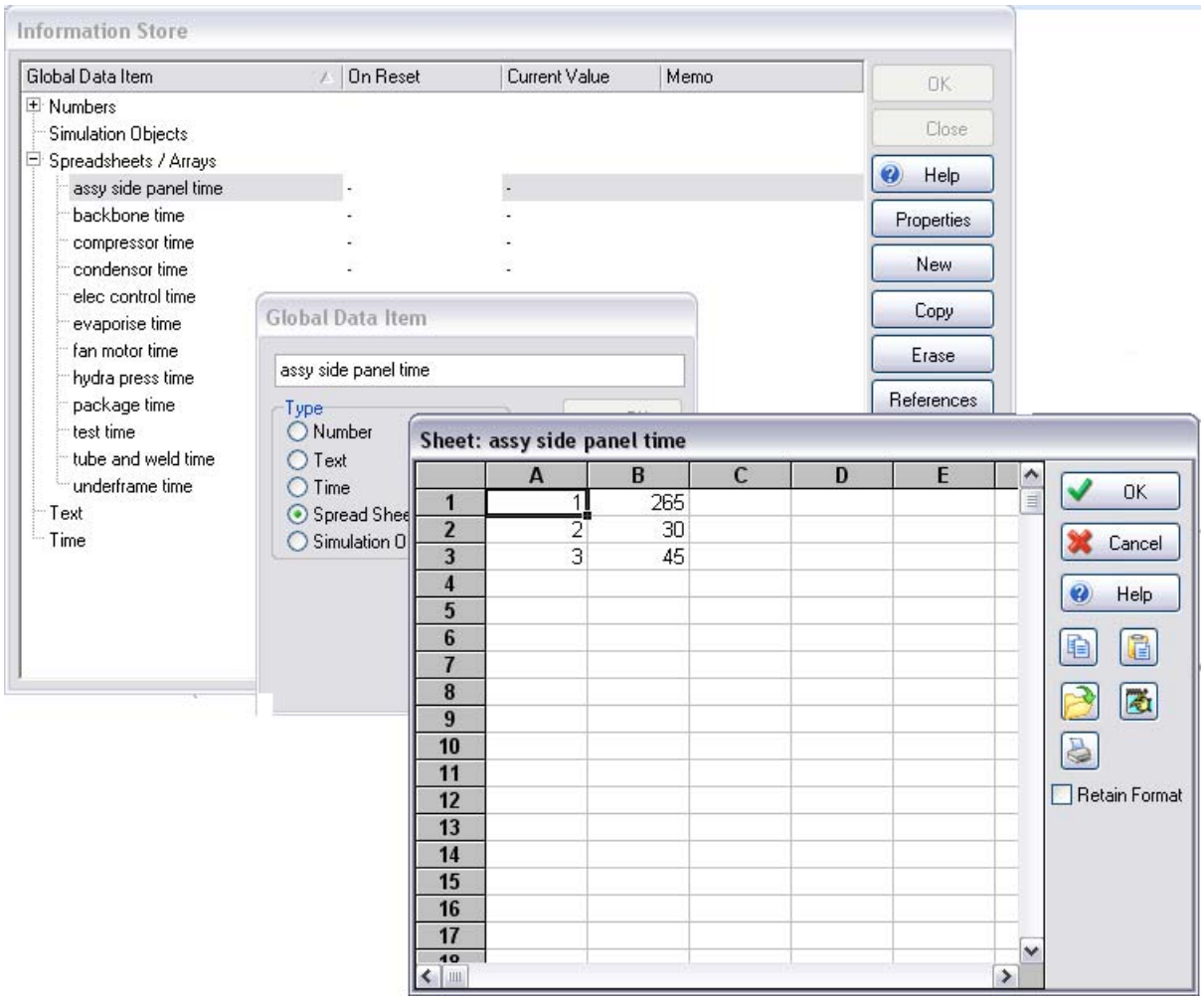


Figure 8.12 example of data input in simulation model

The systematic approach taken during set 1 experimentation enabled the author to observe system behaviours under different product dynamic conditions, namely: in VD (Volume Dynamic); PV (Product Variance); and PMD (Product Mix Dynamic).

There are various KPIs which are commonly used in conjunction with simulation models to quantify performances of modelled manufacturing systems. The KPIs chosen to compare and contrast the simulation results during all three sets of experiments reported in this section were: Lead-Time (LT) spent, when flowing through each model; Average Queuing Time (Ave. QT), while waiting for processing operations; and Queue Size for Assembly (production starting point in Assembly shop) (Q for A). Results from experimental runs with set 1 input entities are summarised in table 8.4: where the 'queue for production' shows quantities of waiting items; 'average queuing time for production' shows how long work items are waiting to be assembled; 'average queuing time for welding', which shows how long the work items have been waiting to be processed at welding operations.

Table 8.4 illustrates the LT results of the four types of Air Cabinet when increasing the Order Size as per trial 1 to 7. For instance during trial run 1, the model was run under conditions of: production orders come every 17 days with product Order sizes of 10, 16, 20, 30, 40, 72 and 120.

Table 8.4 summary of Lead Time performance of circulate Air cabinet model

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7
KPIs in time (Days)	Order size 10	Order size 16	Order size 20	Order size 30	Order size 40	Order size 72	Order size 120
LT of GD	3.6	4.1	5.1	7.4	99.3	151.9	249.2
LT of GDB	3.6	4.2	5.3	7.4	100.7	151.2	247.4
LT of GL	3.5	4.2	5.3	7.5	97.8	151.6	251.0
LT of GW	3.5	4.2	5.3	7.3	100.5	150.6	251.0
QT for assemble	*0.0*	*0.0*	*0.1*	*0.5*	*41.0*	*74.6*	*171.5*

QT (Queuing Time) while waiting for production and welding were observed to be the two most significant time unit contributors to the total Queuing Time. Figure 8.13 summarises the observed trend in Lead time behaviours during the set 1 experiment. It was observed that for this 'pure MM (mostly make)' environment, where the factory only has to produce Air Circulate product types (which can happen in practice according to the company) there arises a significant bottleneck in terms of queuing before the start of assembly operations. As the order size is further increased eventually the current capacity of A2 is exceeded, with a growing queue for 'assembly' operations.

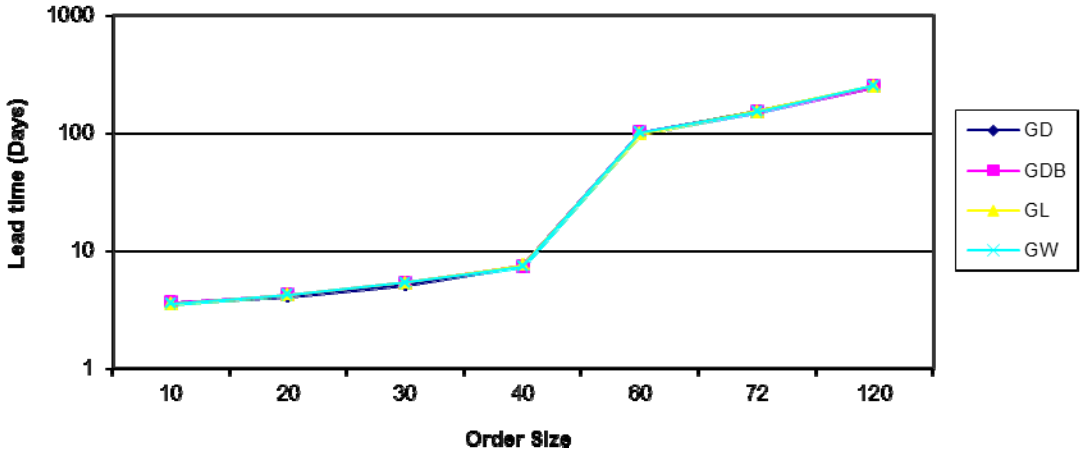


Figure 8.13 Lead time trend of set 1 experiment (MM)

This Case 2 EoSS simplification of the A2 system was observed to behave well, with minimal queues up to an approximate input rate of 24 Air Circulate (Mostly Make) A/Cs every 17 days. Therefore 1.4 MM A/Cs per day was therefore assumed to be the capacity of the A2 shop. Also observed was that as long as that capacity is not exceeded all Air Circulate products take around 5 days to assemble, with relatively minor differences in lead-time within this product grouping. But if the input rate is doubled, the lead-time of MM products grows at a significantly greater rate.

Set 1 experiments served to illustrate and quantify how A2 behaves with respect to key KPIs, under different 'work load' conditions. This experimental set provided an example of using the Extended Modelling Methodology to (1) systematically represent and begin to understand a complex, multi-product manufacturing system; and (2) illustrate how a given Work Dynamic will impact with respect to a chosen group of products.

8.5.2 Set 2: Mostly assemble family– Case 2 EoSS system

The Roof A/C family was chosen as being representative of AirCon's Mostly Assemble (MA) products. As explain previously this family comprises four types of A/C, namely: WLF, WLDF, WRF and WHF A/Cs and was used as product set2 for experimental analysis of another Case2 EoSS controlled simplification of the actual A2 Case 3 EoSS system. Figure 8.14 illustrates a screen shot of the simulation model developed for set 2 experiments. Needed processing operations and operation times elicited from the in-house company team for roof A/C types are shown in table 8.5. These data were coded into the model in a similar way to set 1.

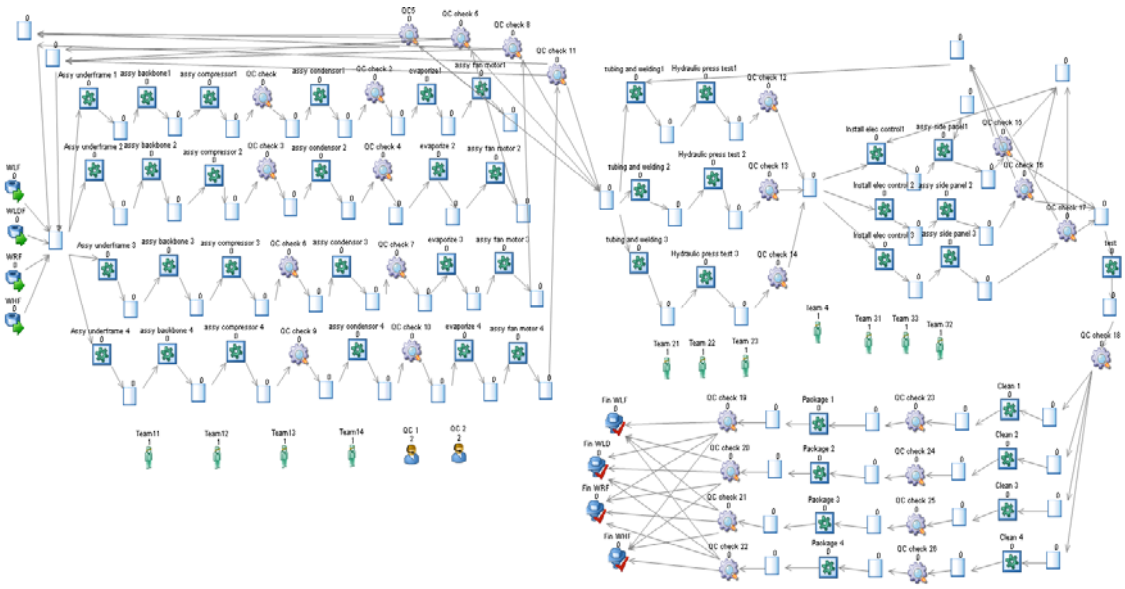


Figure 8.14 Screen shot of Roof A/Cs family simulation model

Table 8.5 op-time requirement of Roof A/Cs family

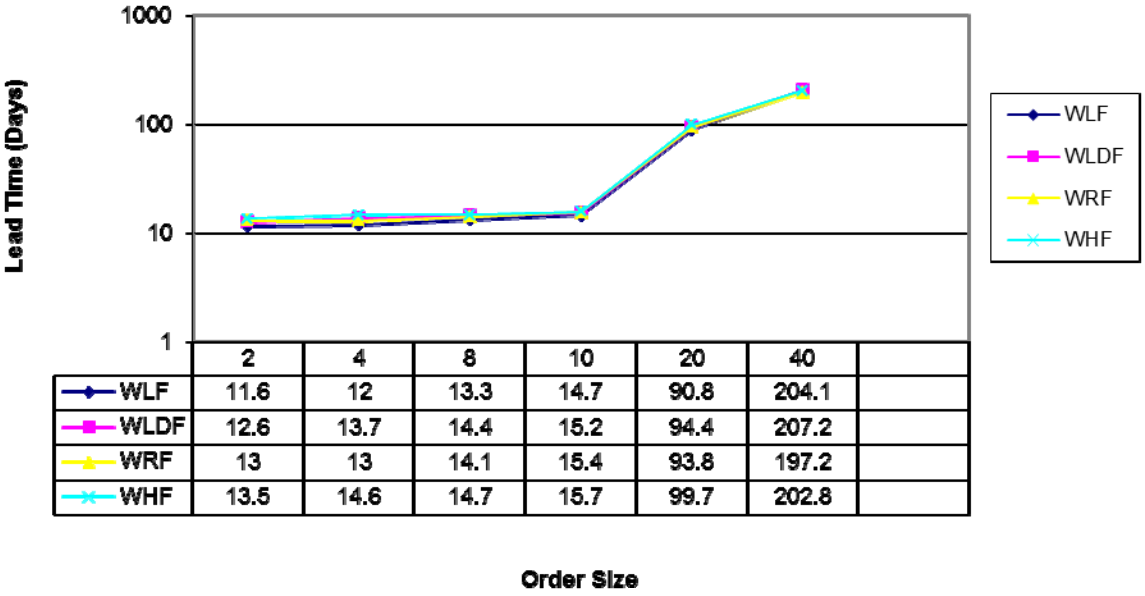
team	Activities Op-time (min)	Roof ACs			
		WLF	WLDF	WRF	WHF
team1	assemble under-frame	30	30	30	30
team1	assemble backbone	30	30	30	30
team1	assemble compressor	60	60	60	60
team1	assemble condenser	200	200	200	200
team1	evaporator	120	120	120	120
team1	assemble Fan motor	180	180	180	180
team2	tubing & welding	600	600	800	600
team2	Hydraulic pressure test	120	120	120	120
team3	Install electronic control	300	360	300	360
team3	assemble side panels	500	560	500	560
team4	test	200	230	300	260
team5	package	180	180	180	180

Table 8.6 shows lead time results for set 2, from 6 trial runs for each roof A/C type. Results for the two significant queuing time elements are also tabled.

Table 8.6 summary of Lead Time performance of roof A/Cs model

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
KPIs in time (Days)	Order size 2	Order size 4	Order size 8	Order size 10	Order size 20	Order size 40
LT of WLF	11.6	12.0	13.3	14.7	90.8	204.1
LT of WLDF	12.6	13.7	14.4	15.2	94.4	207.2
LT of WRF	13.0	13.0	14.1	15.4	93.8	197.2
LT of WHF	13.5	14.0	14.7	15.7	99.7	202.8
QT for assemble	*0.0*	*0.0*	*0.0*	*0.0*	*23.5*	*157.7*

The A2 system behaved well, with minimal queues, with input rates up to 8 MA A/Cs in 17days: see table 6 and figure 8.15. Hence the capacity of the A2 shop was assumed to be 0.45 MA A/Cs per day. Also observed was that the average lead time of MA products is about 15 days, unless A2 capacity is exceeded when the lead times grow rapidly.



	2	4	8	10	20	40
WLF	11.6	12	13.3	14.7	90.8	204.1
WLDF	12.6	13.7	14.4	15.2	94.4	207.2
WRF	13	13	14.1	15.4	93.8	197.2
WHF	13.5	14.6	14.7	15.7	99.7	202.8

Figure 8.15 Lead time trend of set 2 experiments (MA)

8.5.3 Set 3: Mix of MM and MA families- Case 3 EoSS system

Having carried out set 1 and 2 experiments, a mix of MM (mostly make) and MA (mostly assemble) A/Cs was modelled as experiment set 3. Essentially this enabled a controlled re-composition of two Case 2 EoSS models of A2 into a more complex Case 3 EoSS model of the same reality. This allowed testing of a complex product mix which was considered to

represent a 'fit for purpose' discrete event simulation of actual A2 behaviours which commonly occur in day to day practice. A Simul8 shot of the combined Mostly Make (MM) and Mostly Assemble (MA) model is illustrated in figure 8.16.

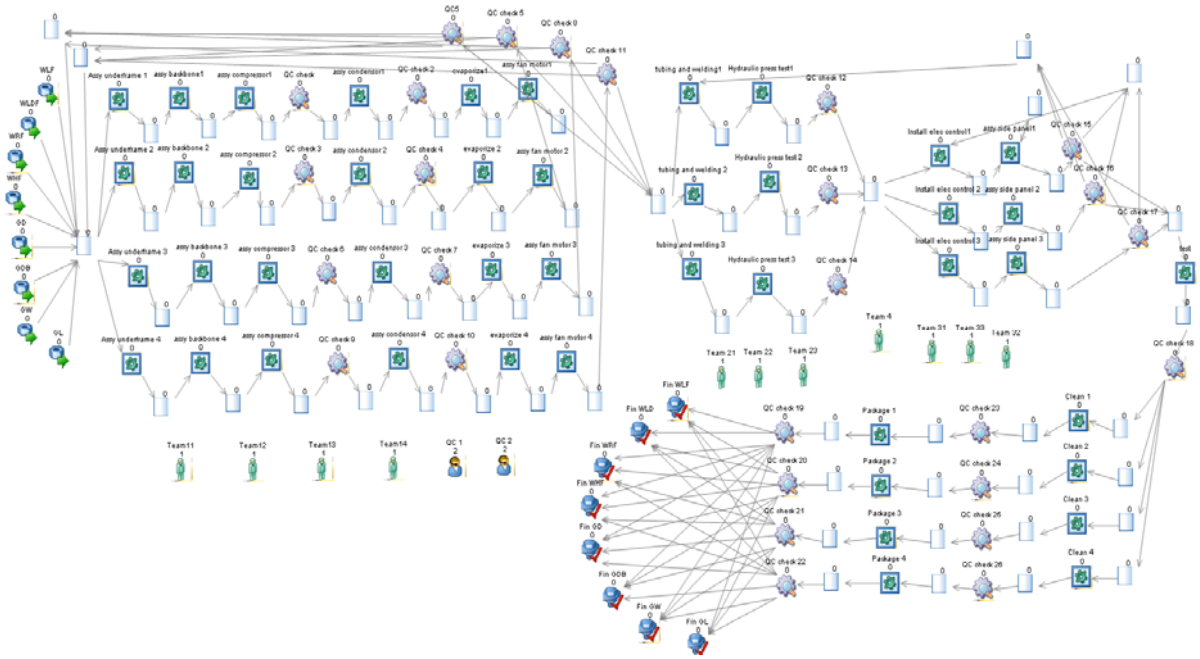


Figure 8.16 screen shot of Mixed MM and MA families' simulation model

To facilitate comparison of findings, Set 3 experiments were conducted using common scenario conditions to those for sets 1 and 2. The experimental results are shown in table 8.7.

Table 8.7 summary of Lead Time performance in mix MM and MA model

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
Order size / LT Days	MM 2 MA 2	MM 4 MA 4	MM 8 MA 8	MM 16 MA 16	MM 12 MA 2	MM 24 MA 4
LT of GD	3.8	3.9	5.8	107.3	4.3	7.7
LT of GDB	4.0	4.1	5.7	106.6	4.3	7.7
LT of GL	3.8	3.9	6.1	105.4	4.5	7.9
LT of GW	3.7	3.9	5.9	102.5	4.2	7.7
LT of WLF	10.9	11.0	13.8	113.8	11.2	13.6
LT of WLDF	11.3	11.5	13.5	114.4	11.8	14.2
LT of WRF	11.9	12.1	13.9	115.3	12.0	13.7
LT of WHF	11.6	12.3	13.5	112.0	12.1	14.1

The developed Case 3 EoSS simplification of the reality demonstrated similar behaviours to the real A2 shop. Provided that the MM and MA 'capacities' of the A2 shop (quantified during set 1 and 2 experiments) were not exceeded, different mixes of representative MM and MA A/C products could be concurrently assembled with similar lead times to those achieved by their Case EoSS simplifications and by the real A2 system.

8.6 Simulation modelling scenario testing the effect of purchase delays- B4

The results analysis generated from the simulation experiments (reported in section 8.5) was observed to provide a source of important knowledge and quantitative data which can be used by various AirCon decision makers concerned with planning and production system development activities in the A2 shop. Indeed the new quantified understandings about product specific behavioural differences in A2 were observed in principle to provide a basis for the formulation of key rules: to use when defining and deploying suitable planning and control policies; or when making resource assignment adjustments; etc.

However anecdotal evidence from AirCon managers had stressed the importance of synchronising the supply of 'make' and 'buy' A/C parts into the assembly shop; as poor synchronisation in this respect was already known to cause major behavioural problems. Essentially the synchronisation issues here are consequent upon poorly integrated 'planning' and 'realisation' of the make and buy streams of A/C 'components' into A2; because these components need to be in the right place at the right time to minimise over-all assembly system lead-times and queues, and therefore production costs. Hence it was decided to be necessary to further develop further and deploy the A2 simulation models to investigate impacts of purchase (bought component) delays- bearing in mind that although make delays are also important they are under the control of the production department whereas purchase delays are determined by purchasing rules applied in the purchase department of AirCon.

Bearing the forgoing considerations in mind the author designed a second experimental scenario which built upon results of the first experimental design to enable the author to develop and use the A2 simulation models she had developed as a means of assessing the impacts of purchase delays on: MM and MA capacities; lead times; and production costs. The same experimental design approach (described in section 8.5) was used by the author to investigate impacts of purchase delays on assembly shop 2 behaviours; while the overall purpose of the second scenarios was to identify possible improvements to purchasing rules

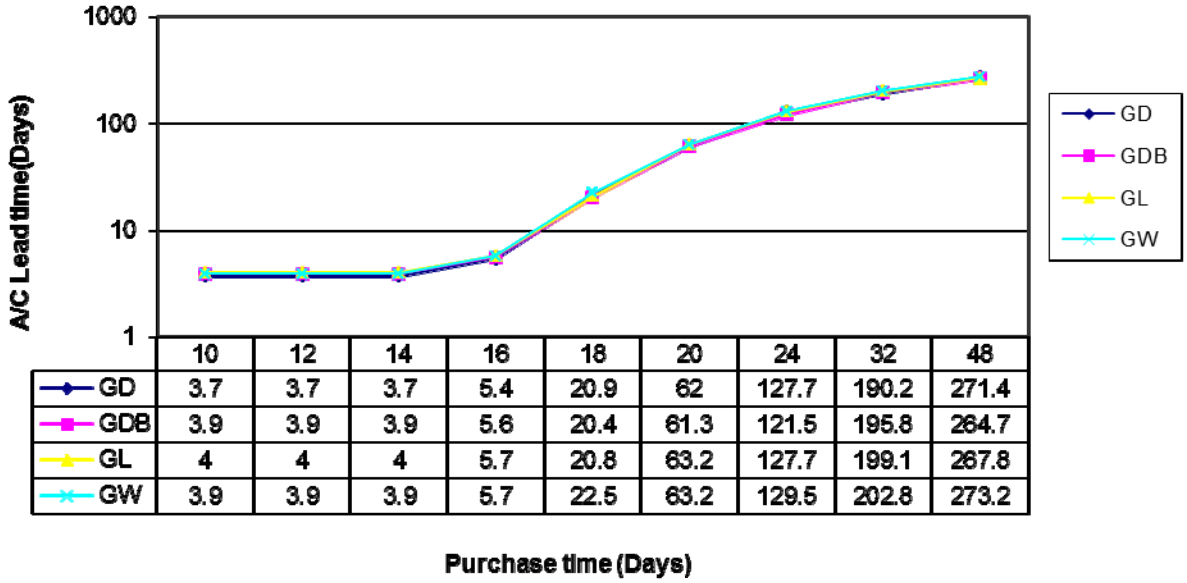
and policies that AirCon might beneficially adopt. However initial model parameters selected during execution of the second experimental scenarios were founded on experimental outcomes obtained during those 3 sets experiments. Particularly the origin set for this experimental scenarios and execution of the MM and MA simulation models respectively were:

- Maximum MM A/Cs capacity: 8 A/Cs per 17 days;
- Maximum MA A/Cs capacity: 24 A/Cs per 17 days

Also the purchase delivery time for (electronic control) parts were set as a variable for both models.

Therefore when testing the MM model it was operated within its maximum capacity but with a batch size of 25 items per purchase the lead time behaviours changed dramatically from every 10 days to every 48 days.

While the scenario setting for MA model execution was also within the maximum assembly system capacity for MA A/Cs, but with a batch size of 25 items per purchase how purchasing time change from every 10 to 64 days per patch (patch size 25 items each time) impact on the lead time behaviours of final products. The experiments results generated when studying impacts of purchase delays are summarised in figure 8.17 and 8.18.



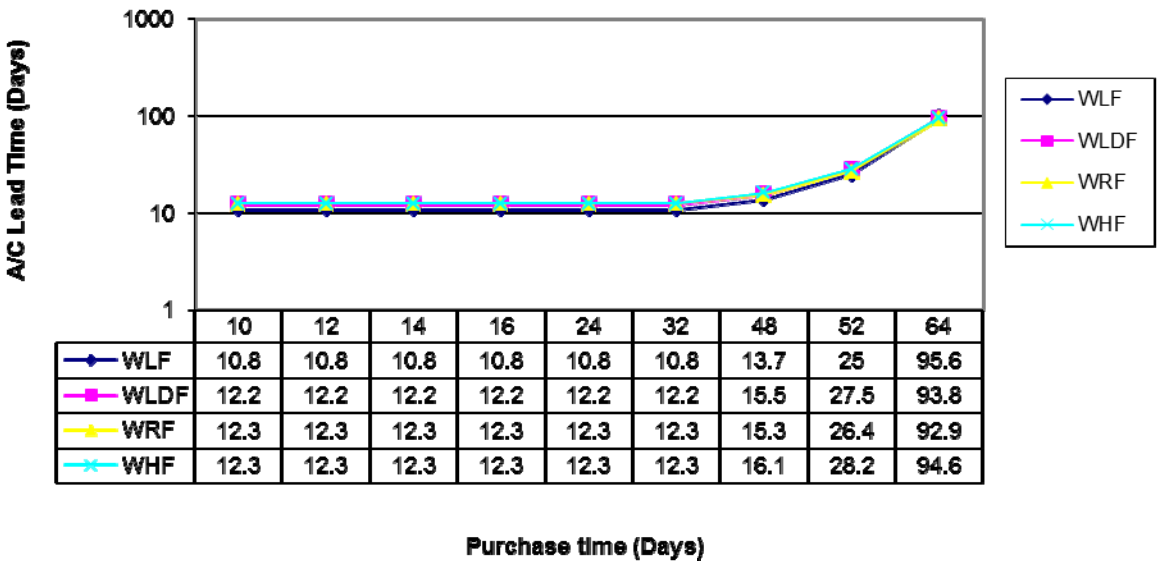
	10	12	14	16	18	20	24	32	48
GD	3.7	3.7	3.7	5.4	20.9	62	127.7	190.2	271.4
GDB	3.9	3.9	3.9	5.6	20.4	61.3	121.5	195.8	264.7
GL	4	4	4	5.7	20.8	63.2	127.7	199.1	267.8
GW	3.9	3.9	3.9	5.7	22.5	63.2	129.5	202.8	273.2

Figure 8.17 summary of Lead Time performance in MM model

It can be observed from figure 8.16 that

- if the model is run within the maximum capacity for the assembly of MM A/Cs, and
- the part purchase time delay is under 16 days,

Then purchasing delays will not affect the final product lead time significantly. But if part delivery takes longer than 16 days, this will increase assembly system delays and the final lead time.



	10	12	14	16	24	32	48	52	64
WLF	10.8	10.8	10.8	10.8	10.8	10.8	13.7	25	95.6
WLDF	12.2	12.2	12.2	12.2	12.2	12.2	15.5	27.5	93.8
WRF	12.3	12.3	12.3	12.3	12.3	12.3	15.3	26.4	92.9
WHF	12.3	12.3	12.3	12.3	12.3	12.3	16.1	28.2	94.6

Figure 8.18 summary of Lead Time performance in MA model

Whereas the results encoded into figure 8.17 show that when operating within the maximum capacity for producing MA A/Cs in the assembly shop 2, the longest acceptable purchasing arrival time, that will not adversely affect the final product lead time, is 48 days per purchase.

8.7 Outcomes of implementation of the EMM in respect of the AirCon Assembly Shop

Prior to this particular case study, AirCon believed that one of its primary production problems was caused by poor Assembly 2 shop behaviours, because major delays in that shop had apparently caused lead time estimates to frequently be exceeded and cash flow problems to be induced. The author learned from the company that 60-70% of orders are significantly delayed by un-anticipated problems occurring in the A2 shop. This necessitated ongoing (daily) re-scheduling of production and the need to deploy a full-time re-scheduler. This set of issues provided the prime motivation for the initial focus of this study to be on the A2 shop and for the company supporting the modelling work via needed data collection and aggregation, and the provision of support in validating the quality of the simulated behaviours and results.

The author had been advised by AirCon managers and engineers that there were really three possible main causes of uncertainty leading to poor planning, namely (1) because of unknown impacts of product dynamics, (2) as a consequence of unforeseen delays in the availability of components (mainly delays in purchased components but also delays in the in-house manufacture of components) and (3) because of unforeseen re-work requirements (when assembly operations had not been properly specified or had been carried out incorrectly by assembly teams, and typically had been reported as ‘design faults’ by the ‘contract planning’ section). Because the gut feeling was that reason (1) and (2) was the main problem issue, the initial A2 SM modelling work was focussed on the 2 sets of simulation scenarios aimed at A2 bottleneck analysis and described in section 8.5 and 8.6. This was therefore the main subject of initial testing the Extended Modelling Methodology which is reported in this chapter.

Under normal production conditions the A2 shop is operated as a complex case 3 (EoSS) system in which generated behaviours are difficult to understand and even more difficult to explain in quantified terms. This led to the proposed systematic simulation modelling approach based on decomposing, simplifying and thereby quantifying the reality by deploying a number of related EoSS Case 2 SMs. Experimental results obtained by running simulations with historical data input sets then showed how product dynamics within

individual product families impact on A2 behaviours; following which mixed family behaviours could also be systematically studied. Advised by company managers, the main KPI chosen was 'lead time', but the authors extended their investigation to include 'capacity' and 'production costs'. A summary of the KPI results generated from SM experiments is shown in table 8.8.

Therefore it was observed that A2 can processes A/Cs at maximum rates of: 1.4 MM products per day; or 0.45 MA products per day; or some combined rate of MM and MA product inputs as characterised by Table 8.8. Also important key product differentiators were established which clarify thinking about the differential loads on the business of different product groups. Here it was found that MA products have circa three times the lead time of MM products; that the capacity of the A2 shop is approximately three times greater for MM products than for MA counterparts; and that A2 related production costs of MA products are approximately three times those of MM products.

Table 8.8 summary of lead time result of experiment scenario 1

Experiment	Product family	Lead time within capacity (days)	Capacity of A2 shop	Manufacturing cost
Set 1	MM Air Cabinet	5	1.5 A/Cs per day	£ X per A/C
Set 2	MA Roof	15	0.5 A/Cs per day	£ 3X per A/C

Uncertain and changing product mix is the AirCon norm and depends primarily on customer demand patterns; and largely is outside of the control of AirCon. However it was observed that even partial attenuation of that demand dynamic, via use of an appropriate planning and control approach, could lead to better A2 performance. Such a planning approach needs however to be sensitive to and cognisant of EoSS phenomenon and this issue is a subject of study in chapter 9 of this thesis.

Following the generation of information gained from scenario 1 experiments, the conception and testing of scenario provided further key knowledge about how purchase delays impact on product lead time performance, as summarised in table 8.9.

Table 8.9 summary of lead time result of purchase delay scenario testing

Experiment	Product family	Lead time within capacity (days)	Max purchase arrive allowance
Set 1	MM Air Cabinet	5	16 days
Set 2	MA Roof	15	48 days

The experimental results were studied and analysed by the author and the findings were fed back to the company; and particularly to potential prime users of the results, namely: sales and technical staff in AirCon's business department; and production planners, purchase persons and real time schedulers in the companies planning department. The findings have since proven very useful to AirCon in the following ways:

1) Sales and technical staff in the business department can now better estimate due dates and production costs. While at the contract negotiation stage, improved understandings about differential production costs for MM and MA product types can be interpreted with reference to the ratio of MM and MA A/Cs in the current order book.
2) Production planners now have a better idea about the current capacity of A2 (and the main bottleneck production shop) and about ways coping with different critical paths and Takt times for MM and MA A/Cs. Based on this new information they can now realise improved production planning leading to significantly reduced re-scheduling needs.
3) Production and purchase planners have a common understanding of parts arrival time for given products. This provides the basis of a new approach to integrated planning and improved synchronous operation between production and purchasing departments of AirCon. The understanding of this should be updated by both departments on a regular basic.
4) Real time schedulers can adjust, on a near real-time basis, the deployment of human resources within existing teams, leading to better Takt time balances for different mixes of MM and MA products.

The use of A2 modelling results in different AirCon departments has provided a catalyst for the company adopting a more holistic approach to planning. Particularly it has set up a small cross department planning team who make more 'joined up decisions' about what can be made by when and at what cost.

8.8 Conclusions

This chapter has shown an advance in '**modelling science**' per say, by conceiving an innovative integration of modelling ideas which collectively have potential to enable the design of fit for purpose, re-usable discrete event simulation models. The proposed step-wise Extended Modelling Methodology is shown to allow the representation and computer execution of structural and behavioural aspects of an actual complex manufacturing system, which includes multiple production shops, realising thousands of product types, via their 'interfaces' to customers and suppliers. Those representations simplify the reality in a way which can support the decision making of mangers and engineers performing a variety of roles in the case company AirCon. The Extended Modelling Methodology has integrated the use of different modelling decompositions implemented using alternative modelling techniques. This has enabled complexity and uncertainty handling, by facilitating model creation and deployment with needed scopes of concern and levels of abstraction.

In the reported case, the modelling approach has laid necessary groundwork for gaining many new understandings; so that improved 'A2 shop configurations' and better 'A2 operating policies and conditions' can be conceived and tested. The A2 production shop is a Case 3 EoSS manufacturing system which requires: resource sharing amongst many types of product; and needed synchronisation of complex material and order flows through related make shops and a complex purchasing supply chain. This had proven very troublesome to the case company with major planning and re-scheduling problems leading to poor cash flow behaviours which have threatened the demise of the company, despite its current major influence within its product market. However via a systematic decomposition and simplification of the Air Con reality, the Extended Modelling Methodology has enable a holistic and re-usable conceptualisation of the case study business which has supported the conceptual design, deployment and aggregated re-use of a related set of Case 2 EoSS simulation models. Those models have facilitated the development of new insights into impacts of A2 structures and behaviours on the business as a whole. This was proven subsequently to enable the case company AirCon to make better and joined up decisions about product cost and due date estimates, linked to improve production planning and re-scheduling options, all of which contribute significantly to the medium and long term solvency of the company.

Also reported in this chapter are necessary steps that can be taken to create alternative holistic representations of any complex business; as configured sets of process-resource system couples linked via work flows. These conceptual designs are used to reason about the re-integration of models (of 'process', 'resource' and 'work' sub-system decompositions) within a required scope and at needed levels of detail. Following which the developed conceptualisations naturally facilitate the design and implementation of simulation models that fit their purpose i.e. incorporate suitable simplifications, system structures and dependencies and needed system parameters and operational data. Current applications of the modelling method now have a range of application areas covering: support for the selection of alternative manufacturing paradigms (including postponement, Lean and push/pull); integrated and distributed planning and control; and line balancing and optimisation. It follows that the author believes that the modelling approach described and case study tested in this paper can provide the basis of a significantly new way of life-cycle engineering discrete event simulation models, such that they can support and integrate very complex manufacturing systems engineering functions.

In the case of AirCon an on-going research study is investigating the impacts of other sectional behaviours on the final products assembly lead time. This has led on to the use of the essence of EoSS models to capture and reason about the current architectural designs and dynamic behaviours of the AirCon product realising system. This involves a multi-level decomposition and modelling approach that can qualify and quantify analytically the subject system. Chapter 9 will explain in detail the development and deployment of this multi-level modelling approach.

Chapter 9 Multi-Level Modelling of Case Study EoSS Systems

9.1 Introduction

The previous chapter described how the Extended Modelling Methodology (EMM) specified in Chapter 7 (which was conceived by the author out of earlier exploratory case study modelling) was case tested at a single lower level of modelling abstraction in the AirCon ME. This led to improved understandings about the operation of the AirCon assembly shop and showed how lead-time and bottleneck behaviours in response to complicated product dynamics can be predicted in respect of a Case 3 EoSS manufacturing system. During this study however it was observed that isolated simulation modelling of a make or assembly shop can only partially enable an analysis of ME-wide EoSS behaviours; because normally causally related product dynamic factors will impinged in various ways on different ME systems. Hence this chapter reports on an extension to the AirCon case study with a focus on using the EMM at multiple levels of abstraction to address the following research questions:

Q1: Is it possible to use the EMM to 'specify' and 'visualise' 'integration requirements' of 'multiple EoSS systems'? For instance, in the case of the AirCon business, the assembly shop behaviours are not only dependent on the behaviours of work orders placed upon that shop but also are influenced significantly by delays in the purchasing system of AirCon (and the behaviours of its associated material and component supply chains) and by the quality of assembly plans produced by the design unit and technical planning unit of AirCon.

Q2: Is it possible to use the EMM to systemised behaviour modelling of multiple EoSS systems?

Q3: Is it possible to use the EMM to quantify the relative cost behaviours of alternative product families and types in any given EoSS system?

9.2 Need for multi-level modelling

This section, reports on the need to apply the EMM at multiple levels of abstraction to 1) achieve structure and behavioural modelling in support of better systems integration; and 2) facilitate modelling analysis for different user groups in an ME.

9.2.1 Need for the EMM to support the modelling of multiple EoSS systems

Chapter 8 described how the; EEM was shown to systemise and enable 'structural' and 'behavioural modelling' of a single Case 3 EoSS manufacturing system. This was found to support a number of kinds of decision making within the case study ME, leading to improved planning and realisation of assembly operations within the EoSS system modelled. More formally stated, the case study testing in chapter 8 led to the development of various types of 'structural' and 'behavioural' model which were found to enable:

1. Improved understandings to be gained about the potential behaviours that a single subject EoSS system (of current or 'as is' design) can realise when subjected to alternative scenarios of input (i.e. work system) demand. Importantly this facilitated qualitative and quantitative reasoning about performance constraints arising from the 'as-is' EoSS system design and this could be linked to reasoning about how changes in planning and operating policies can intercept work system dynamics so as to avoid possible performance constraints.

2. Improved understandings to be gained and predicted about possible future behavioural and performance benefits that might arise as a consequence of EoSS system reconfiguration (individually and collectively amongst the 'work', 'process' and 'resource' sub-systems that comprise the current [or 'as is'] EoSS system being modelled); such that localise design optimisation of the modelled EoSS system can lead to better future (possible 'to be' system) designs.

During the study of the AirCon A2 (assembly) shop a number of significant business improvement opportunities under 1) and 2) were identified; each of which promised potential opportunities to generate increased profit and competitiveness for AirCon. A number of these opportunities were considered by the author and some of those opportunities were discussed with AirCon managers. Project constraints meant that only a reduced number of these opportunities could be investigated in an exploratory manner, as reported in Chapter 8.

However a key 'stumbling block' observed when trying to justify potential improvements was that although clear localised benefits could be gained the magnitude of these benefits could not be quantified within the bigger picture of AirCon EoSS operations; this was complicated as different areas of the business have their own problems and local optimisation goals and own set of 'pet projects' to get funded. To address this problem, which was assumed to be a general one particularly in large MEs making many different product families and types, it was clearly necessary for the author to consider ways of computer executing EoSS models of the whole business. Hence from this point in the study concentration of case study modelling was diverted from experimenting with single sectional EoSS models (that can inform localised decision-making and optimisation) onto considering ways of creating and deploying models of multiple and 'hybrid' EoSS systems (i.e. a number of different EoSS system Cases that need to interoperate) in support of higher level and holistic ME/business decision making. When using EMM decomposition and integration ideas it became evident that they had potential to facilitate systematic reasoning about the interoperation between a number of Case 2 and Case 3 EoSS systems in AirCon so that economies of scope and scale can be realised on an ongoing basis in response to changing and largely unpredictable patterns of customer order demand. This situation was designated as being one where 'hybrid' (i.e. different types of) EoSS product realisation systems need to function as a collective whole system; so as to respond competitively over time to external environmental stimuli impacting on the subject ME. Importantly this situation was also observed to require an extension to previously published thinking about EoSS. For example Teece (1980) had viewed EoSS benefits in two ways, namely from perspectives of (1) EoSS economies realised by a 'whole organisation' and (2) economies realised in respect of an 'individual product', as a consequence of that product being made in an EoSS system capable of realising more than one product. But the AirCon multiple hybrid EoSS system clearly involves a decomposition of the whole ME into hybrid EoSS systems each of which is required to realise local economies of scope and scale for it to be a competitive part of the parent ME. Hence this more localise view of EoSS was observed to constitute a third EoSS perspective to consider when designing and changing MEs making multiple families and types of product. Here it was expected that each of these three perspectives would align best to different decision making groups in any ME, which it was supposed would be likely aligned to: *business strategists* concerned with longer term holistic ME design and change; *product engineers* concerned with designing and introducing new products that a current or possible future ME design can realise; and *operations planners and mangers* typically with

sectional (such as purchasing, make, assembly and logistical) concerns. But of course it was expected that a competitive ME would need to achieve various compromises across these perspectives and across sectional concerns so as to realise *integrated* (and hence timely and effective) *operations* and *change* amongst ME systems.

Hence the present author determine to case study test the use of the Extended Modelling Methodology as a means of understanding and predicting potential behaviours and performance constraints on multiple hybrid EoSS systems; particularly as this might begin to address a key set of issues facing the various types of system engineers who have ideas about improving 'the bigger business' they are operating within, but currently with current best industry practice do not have the facility so to do.

In principle it was evident that the EMM, and its embedded three ('process', 'resource' and 'work') sub-system 'decomposition' and 're-composition' ideas, could form the basis of a multi-level modelling approach. Importantly it was envisaged that use of these formalisms should, in the future, allow various types of engineer to 'cut through' the high levels of complexity observed in MEs (like the AirCon organisation) to allow them to conduct 'structure' and 'behaviour' modelling at any level of granularity they require. But the practicality of this idea needed to be tested. Also evident from the literature is the fact that discrete event simulation (DES) models run out of power unless their detail or scope is curtailed (Law, 2007 and Banks et al, 1996). It was presumed that the EMM would help address this issue and allow multiple DES models that share common underlying modelling concepts to be produced. But for these models to be useful in support of multi-level decision making about multiple hybrid EoSS systems it would be necessary for this study to find a way of achieving some 'kind' and 'degree' of interoperation between multiple DES models running at different levels of abstraction. Here it was supposed was that the author's trump card would be the use of EM (Enterprise Modelling) decomposition formalisms; as this was expected to ensure that via appropriate 'conceptual design' of the EoSS models they should share a 'common ontology'. Here it was presumed that use of the EMM could help create, visualise and computer execute the basis of 'an ME specific language' (incorporating EMM's process modelling formalisms & decomposition & integration mechanisms; resource modelling formalisms & decomposition & integration mechanisms and work modelling formalisms & decomposition & integration mechanisms) which can lend support for DES model interoperation.

It was observed that the AirCon company case provided an excellent opportunity for the author to study the capabilities of the EMM as a means of understanding and then designing and changing multiple hybrid EoSS systems. The author had already gained relevant understandings about AirCon operations and its management decision making. Also she had access to a wealth of case study knowledge and data which could be architected /interconnected via use of the current and future developed versions of the AirCon EM. Already the AirCon EM provided a key foundation for the study, in the form of a structural model (and decomposition) of the process network used by AirCon to realise its 2000 plus product types. Essentially therefore the AirCon EM already naturally represented the relatively enduring structures of the operational 'process' sub-systems currently used by AirCon.

However to secure commitment of the in house AirCon team it was necessary to steer this academic study of hybrid EoSS phenomenon towards actual problem solving of current concern to the AirCon management team. Therefore this chapter describes how dual objectives were pursued by (i) seeking to solve 'integration problems' in AirCon and (ii) investigating hybrid EoSS phenomenon.

9.2.2 Multi-level modelling in support of AirCon problem solving

Due to the distance and cost involved in visiting the case company, on-site Company visits needed to be limited and mainly were focussed on two visits of one week in duration. As stated in the last chapter, the author and her colleagues first visited to the company in summer 2008. During the first visit, discussions and study of the company was based around interviews with high and middle levels managers from most company departments. It was reported that one of the biggest concerns of the entire business is unsatisfied due date fulfilment. Due dates were normally established by the sales team. This is often based on a somewhat informal study of customer requirements and relies on experience of the sales team who take into consideration target due dates of similar contracts. There is no established data (base) for analysing cycle times of any of the production shops or purchase delays and other likely order requirements. Sometimes, the Sales team have to give promises of early (and possibly even impossible dates for) delivery in order to win the contract. In reality all due date estimation in AirCon is done without knowledge of current workloads in design, in purchasing or in the production shops. During the year 2007 about 40% of contracts did not

meet their deadlines. For some products, contract documents need to flow between the departments before due date estimates are agreed and passed to customers, but there remained significant inaccuracies due to the fact that there are no 'standard operation time' data for any of the shops. Key to these issues was observed to be lack of synchronisation of purchase items and make parts. For most products due date estimates for purchased part arrival times were predicted inaccurately, partly because of external influences which impact on the timely arrival of these parts. But also because when cash flow problems arise there is a policy to delay some purchasing. Most importantly records do not indicate current operations or work loading conditions of the shops and since orders arrived randomly; hence 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 these front end decisions grossly impact on the entire business, the author considered it to be essential to take measures to make this kind of decision more accurate. But it was not at all clear what these measures should be. Figure 9.1 shows a general description of the causal effect of lead time delay on finance, sales and purchase factors/section of the company. This CLM model was developed by the author and her MSI colleagues while visiting the case company and illustratively explain key causal factors that impact on product lead times. These factors are: un-planned urgent due date; missing customer information; changes in customer information and incorrect product design. The qualitative behaviours deduced from the CLM model were discussed with company managers who felt that these and other factors are highly significant but that the strengths of these causal effects were not known. Also the casual loop illustrated does not account for differences in air conditioner types.

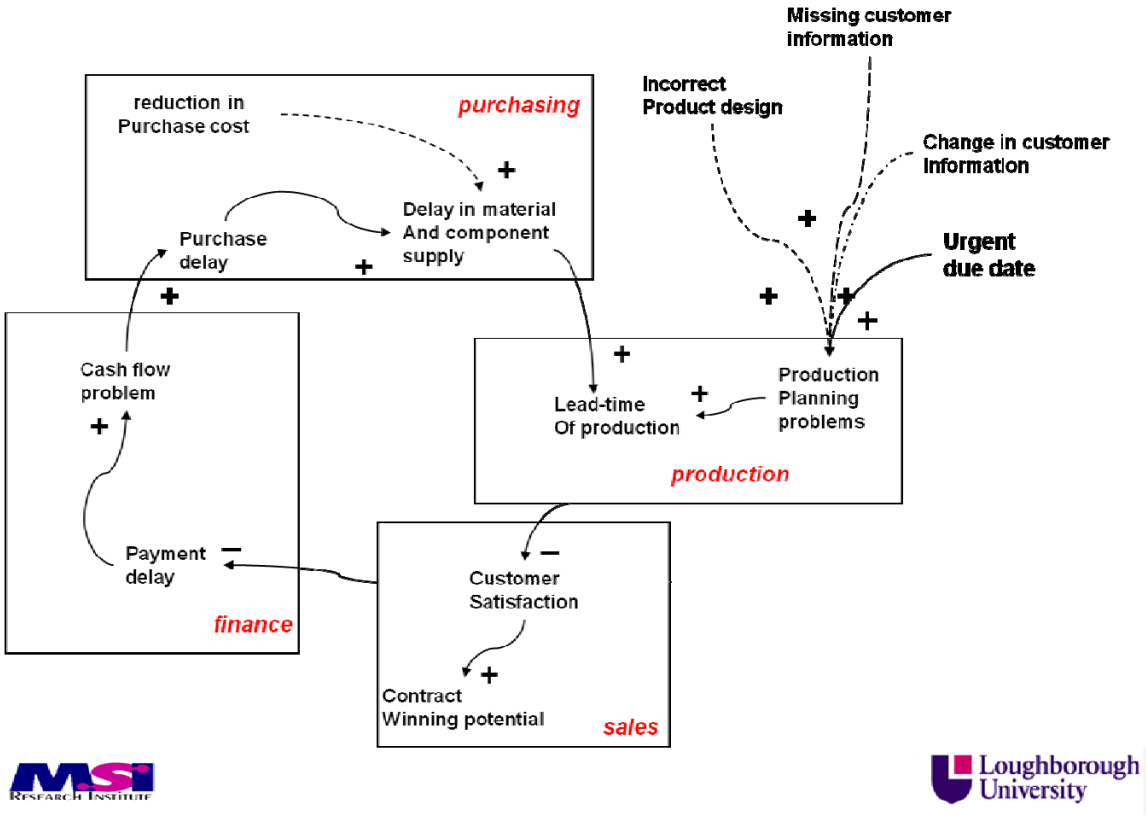


Figure 9.1 general description of bottleneck using CLM model

During the creation of the AirCon enterprise model and following interviews with middle and lower lever managers, it was observed that except for the incorrect estimation of due date during the 'contract winning' process, there are many internal factors that affect the ability of the production shops to meet due dates. They have been broadly classified into the following issues: missing customer requirement information; product design failures; in-appropriate infinite capacity planning; poor synchronisation of parts arrivals; purchase delays; lack of necessary resource competencies. Many of these issues were considered by the author and her colleagues to result as a 'lack of integration' amongst sectional units of the company. Indeed late during the first company visit the author and her MSI colleagues characterised many of the then AirCon operational problems to be as a consequence of 'over the wall' planning. This observation was widely accepted in the company. Indeed the over the wall planning activity in AirCon was conceptualise by the author in the form of figure 9.2. Each department in the company had its own embedded planners, and the visibility in other departments of their aims, activities and decision-making was observed to be poor.

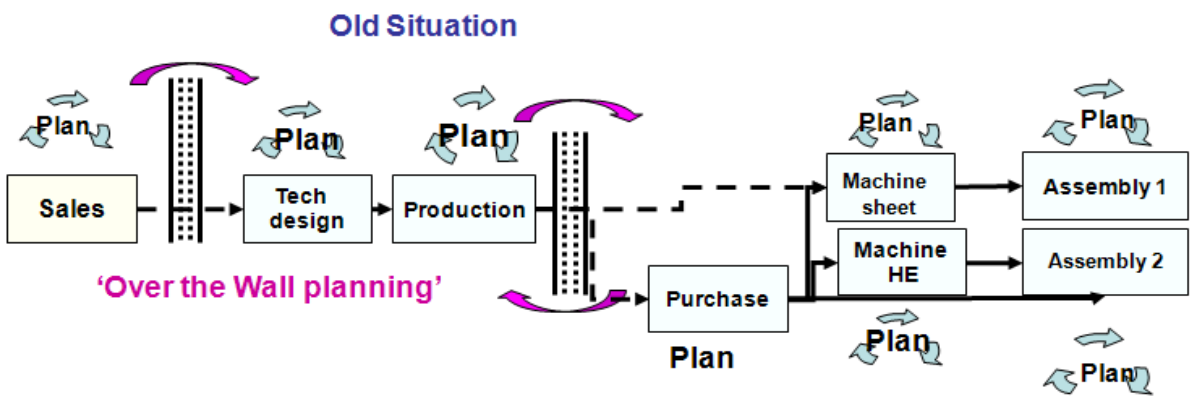


Figure 9.2 'Over the wall planning' situation in AirCon

Key outcomes that resulted from 'over the wall planning' were observed in terms of the following real ME system behaviours:

- Many late contracts/orders & hence late payments & contract penalties
- Significant work in progress
- Poor resource unitization
- Major cash flow problems
- High rate of machine/work station breakdowns and limited space availability

These ideas were presented to the company at the end of the author's first visit to AirCon. Since that time the MSI team, and the AirCon in house team, have worked in a 'loosely-coupled way' towards the goal of reducing the impacts of planning walls in AirCon.

The prime concerns of the senior AirCon managers centred on cash flow problems, which they believed result mainly from late product delivery and therefore significant cash being tied up in WIP (mainly in respect of high cost main air conditioner components). Also there are some contracts penalties that AirCon need to pay if delivery is late and late behaviours were assumed to result in loss of future sales. The author's qualitative analysis of this situation was based on the use of the structural/architectural models she developed by using the EMM, and more particularly models coded into the following forms: process maps, explicitly modelled as an integral part of the AirCon EM; and descriptions of product classes, families and types (and their related BOM, customer orders, works orders and financial data). Examples of these 'model types' were previously given in Chapter 8.

The first visit recommendations to the company and their internal team led in the same year to AirCon making a significant architectural/organisational change by forming a cross department planning group. Further details of this change are discussed later in this Chapter.

In April 2009, the MSI team made their second visit to the company. During this second one week visit, investigation and discussion showed that since the first MSI visit the company had made some significant improvements in areas of (1) cash flow management, (2) integration planning and (3) a 'new paradigm selection' (namely via the introduction of some Lean principles and tools). The initial EMM modelling results analysis carried out by the author and her colleagues were presented to AirCon. Also through detailed interaction with company personnel throughout the second visit, the author and her colleagues conducted further data gathering and knowledge finding; and provided a short training course on the fundamentals of Lean Engineering for AirCon middle-lower managers with responsibilities in AirCon production shops, which since has proven successful and useful.

Better integration of AirCon planning activities realised by the architectural re-organisation, coupled to a new focus on contract based cash flow management, has continued to realise very significant improvements in AirCon business performance. The re-organisation realised by the company as a result of this stimulus is illustrated conceptually by Figure 9.3. As expected the biggest impact of this re-organisation was a reduction in negative impacts of wall 2.

However further changes were identified, by the author and her MSI colleagues, which could in principle be made to further attenuate impacts of 'bad architectural behaviours'. For example even after the re-organisation, it was reported that 70 % re-scheduling of the A2 assembly shop (in which most of the companies special and customised air-conditioners are assembled) remains necessary to achieve satisfactory production performance in terms of due date adherence. However it was clear that although many improvement changes were possible, at that stage of EMM application it was not possible to test in virtual reality how different architectural changes would lead to benefits and costs.

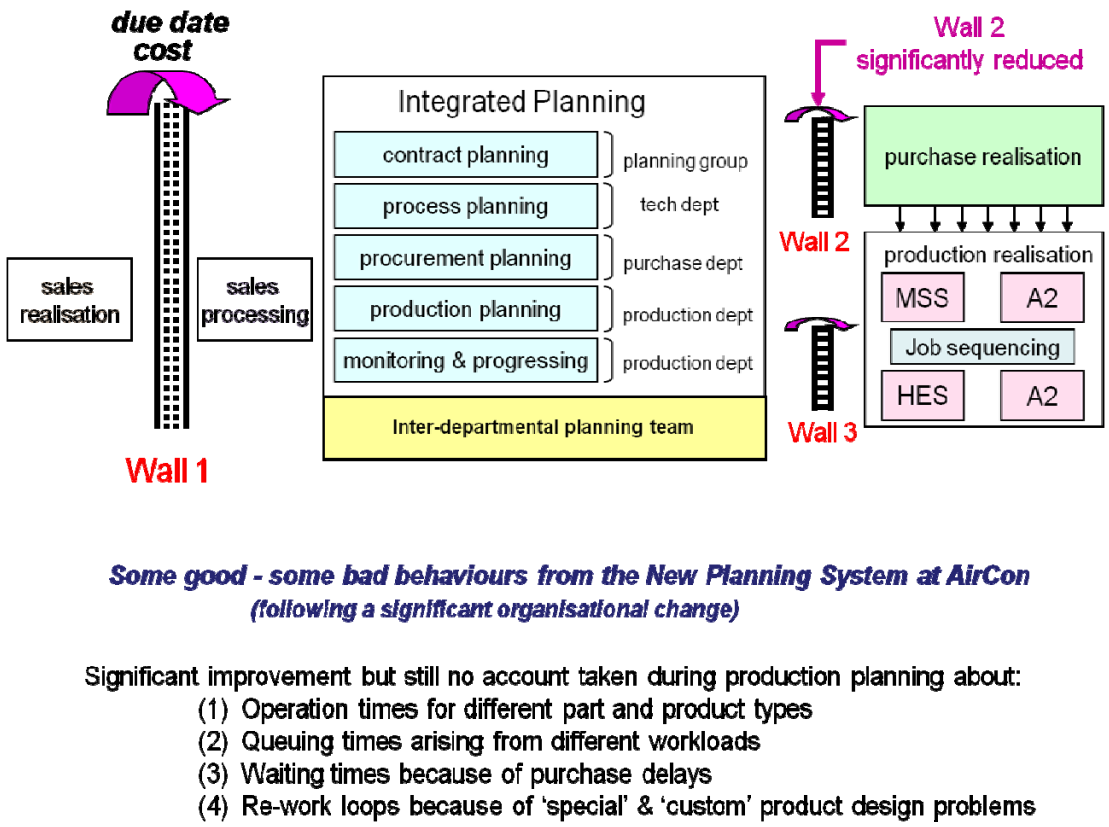


Figure 9.3 illustration of planning issues addressed by organisational change

Bearing in mind the need in AirCon to seek to eliminate remaining 'bad behaviours' articulated by the company and listed in figure 9.3, by becoming better positioned to test and quantify likely outcomes of possible architectural change prior to costly and risky real system change, the author decided to create two 'fit for purpose SMs' that operate coherently, but at distinctive levels of abstraction. One of these SMs was designed to operate at a high level of abstraction, in order to replicate and/or predict overall AirCon 'business behaviours'. The other SM was designed to operate at a medium level of abstraction with a relatively narrow scope to replicate AirCon 'production behaviours'; and particularly behaviours in the A2 assembly shop. Importantly the author's research would investigate the extent of possible consistency of modelling at these two abstraction levels to facilitate both 'top down' and 'bottom up' (re)-architecture design and testing via synergistic interchange of understandings gain from experiments at the two levels. By so doing the overall research aim was to prove, at least in selected manufacturing businesses (and particularly at this stage in AirCon) that a combination of SMs (derived from a common architectural structure) can indeed usefully model complex configurations of hybrid EoSS systems, in an essentially scalable and therefore feasible/practical manner.

The remainder of this chapter demonstrates how the author used the EMM, at multiple levels of abstraction to enable the conceptual design of two SMs operating with different scopes and foci of concern and a set of experiments which were designed to address key aspects of AirCon's integrated planning problems.

9.3 Multiple level structural modelling – Phase 1

The outcomes from lower level of abstraction, quantitative simulation modelling experiments performed in respect of the A2 shop model, as discussed in Chapter 8, helped to identify some key factors that most significantly influence lead time performance in the A2 shop. Some of these factors were causally related to phenomenon internal to A2 while others when causally related to phenomenon originated within other sections (departments) of the AirCon business. The structure (but not the behaviour) of these interdependencies and the interactions between sections had previously been modelled via the enterprise model of AirCon Company.

As earlier discussed it had been observed that different product classifications were needed at the two ('business' and A2 'shop') abstraction levels, primarily because of the different scopes of concern which meant that different distinctions in process routes were observed at the two levels. For example in the assembly shop products were observed to be best classified into two families, namely 'mostly make' (MM) and 'mostly assemble' (MA) air conditioners. The distinction between these two families arose mainly because some A/C types (within the MM A/C family) are assembled primarily from in-house manufactured parts (i.e. frames and panels constructed from metal sheets and AirCon heat exchanger types realised in AirCon 'make' shops) while the other (MA) A/C family of products are assembly from a significant number of bought in parts (normally to realise greater functionality A/C types relative to members of the MM family). It follows that in general MM and MA products have distinctive processing routes through the A2 shop. In some respects MM and MA also have distinctive processing requirements in the purchasing department of AirCon. Those purchasing processing distinctions needed to be accounted for when modelling AirCon business processes at a higher level but were not considered when modelling only the A2 shop (i.e. when modelling at a lower level and more detailed level of abstraction required to characterise assembly system behaviours). While when considering AirCon as a holistic

business (i.e. at a higher level of abstraction) observed processing route differences were primarily in respect of the flow of products (i.e. designs, plans, orders, made parts, purchase parts & assembled A/Cs) through sales, design, planning, purchasing and production departments. However at this higher level of abstraction it was necessary to simplify (or abstract away from some of the processing differences between individual product types and to focus only on major route and operation time differences in workflows within and between AirCon 'departments'. For example some specialist products require months of design and prototype testing processing while other standard (and sometimes repeated) products required close to zero design processing with a technical focus mainly of developing & deploying BoMs (Bills of Material) and drawings which had previously been defined and stored in an AirCon database.

This higher level study of processing routes and operation time differences led to the identification of three 'high level product classes', namely ''Standard' (ST), 'Customized' (CU) and 'Special' (SP) air conditioners. Here the major process route differences involved were visualised in the form of the high level process/activity diagram shown in Figure 9.4. Therefore SP and CU need to be routed through extensive engineering activity, with the former normally requiring greater design operation times; while products of the ST class only require straight forward process planning activities. The following definitions were therefore drawn to differentiate between the main processing differences between the three 'high level product classes'; differences which have an implicitly understood meaning when considering company business realisation as a whole and how this might (or might not) influence sectional and/or inter-sectional behaviours.:

- Standard (ST) - Various different product types that require little engineering processing other than planning. 'Standard' products constituted the large majority of instances of business process flows. But 'standard' products do not generate as much value per product unit for AirCon as customise products, which in turn do not generate as much value per product unit as special products.

- Customised (CU) – Air conditioners that need design engineering/change (such as size, shape, control programming). That change will be significant relative to standard versions of the same product type but that change will be normally be minor relative to that needed for Special A/Cs.

- Special (SP) - Air conditioners that need major design engineering/change relative to both customised and standard versions of the same product type. Special A/Cs may be required with significantly different functionality, or to work in untried environments, or may use yet to be proven technology, or technology sources. The special products are normally sold at a premium price but also incur significant risk, and therefore significant costs.

It follows those family members of the 'lower level product groupings' (MM and MA) have overlapping constituency with 'high level (ST, CU and SP) product classes'. For example MM A/C types can belong to the standard, customised or special class, as indeed can MA A/Cs. Therefore these classifications have context dependent meaning in the sense that when modelling at a higher level one method of process- oriented product grouping (into classes as defined above) is most meaningful. But in the context of A2, and other production shop modelling an alternative process- oriented product groupings (into families defined in section 9.3) are more meaningful in terms of characterising likely behavioural difference between product realisations activities currently being modelled, quantitatively studied and predicted.

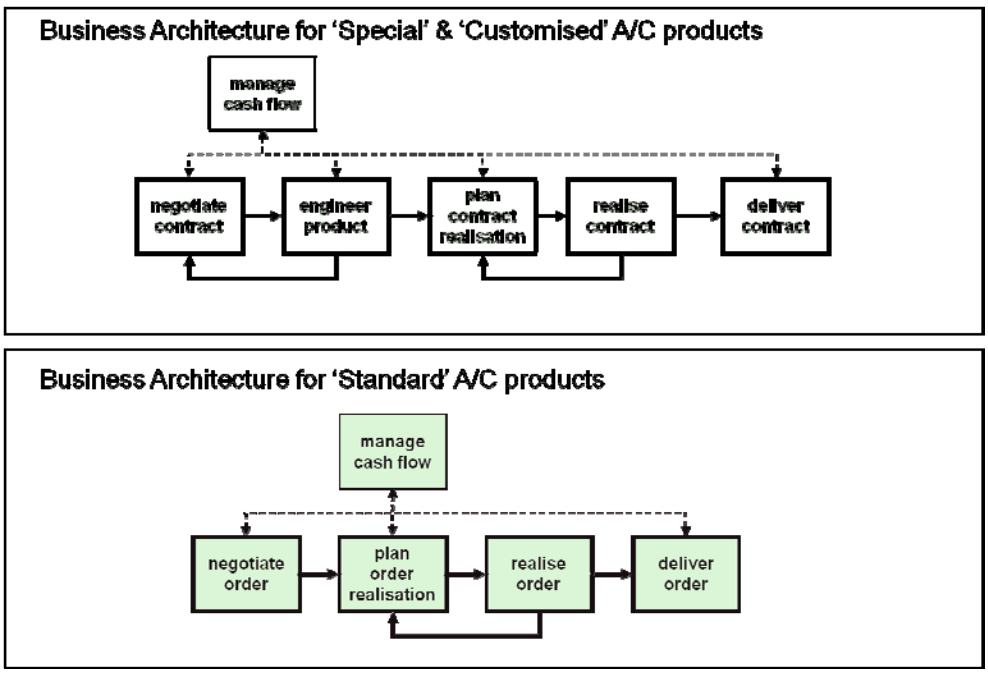


Figure 9.4: Main processing route distinctions for 'special', 'customise' and 'standard' products

9.3.1 Classifying EoSS Systems used by the AirCon ME – via linked use of EMM S 1, 2 & 3 models

As explained in Chapter 8, having developed the AirCon EM the author had created a process-oriented decomposition of the overall company which could be viewed at multiple levels of process-oriented abstraction (i.e. at DP, BP and EA levels of activity-based decomposition). Following the EMM steps outlined in chapter 7, the process sub-system decompositions so developed were then used to conceptually represent, using a new form of 'integration diagram', the flow of work (and therefore of different product families and types) through so called process- resource couples. Therefore at selected levels of granularity a new kind of integration diagram was conceived to conceptually represent different configurations of 'process', 'resource' & 'work' sub-systems then currently used by AirCon. As discussed in Chapter 8, Figures 8.6, 8.7, 8.8 and 8.9 are all examples of using integration diagrams to conceptualize the use of different EoSS systems instances.

Associated with the use of these diagrams therefore the author needed to group products in terms of their needed processing differences into families (where major processing differences were needed between families) and types (where significant but relatively minor processing differences were needed amongst products belonging to a family). A need was also observed, however, to re-apply this kind of process-based product classification at the various levels of abstraction represented by any given set of multi-level integration diagrams. To recap the purpose of classifying AirCon's products according to significant processing was to (A) cut through AirCon complexities arising because they make a very large number of different product types and (B) characterize impacts of product dynamics (as defined by Cui & Weston, 2010) on AirCon product realization. In the actual company this complexity was not being handled well and largely was ignored during planning; and the author believed this was a prime cause of poor cost estimation, poor due date planning and fairly major cash flow problems. But the need to have more than one product classification (i.e. corresponding to different levels of modeling) meant that a very simple classification of all products could not be conceived that would satisfy all for different classes of decision maker (such as strategists, product engineers, planners and process/production system developers). Hence the authors' subsequent modeling of hybrid EoSS systems at multiple levels of abstraction needed to find ways of suitably coping with the need for multiple product classes.

Figure 9.5 is a duplication of Figure 8.9, which is also included in this chapter to help the reader follow the thread of argument. Figure 9.5 provides a conceptualisation of the key hybrid EoSS systems use by AirCon to achieve product realisation. Having usefully classified AirCon product types in terms of assembly operation differences as part of the research reported in Chapter 8, the author conducted similar analyses in other parts of the AirCon business and particularly in the various cases of EoSS system conceptualised by Figure 9.5.

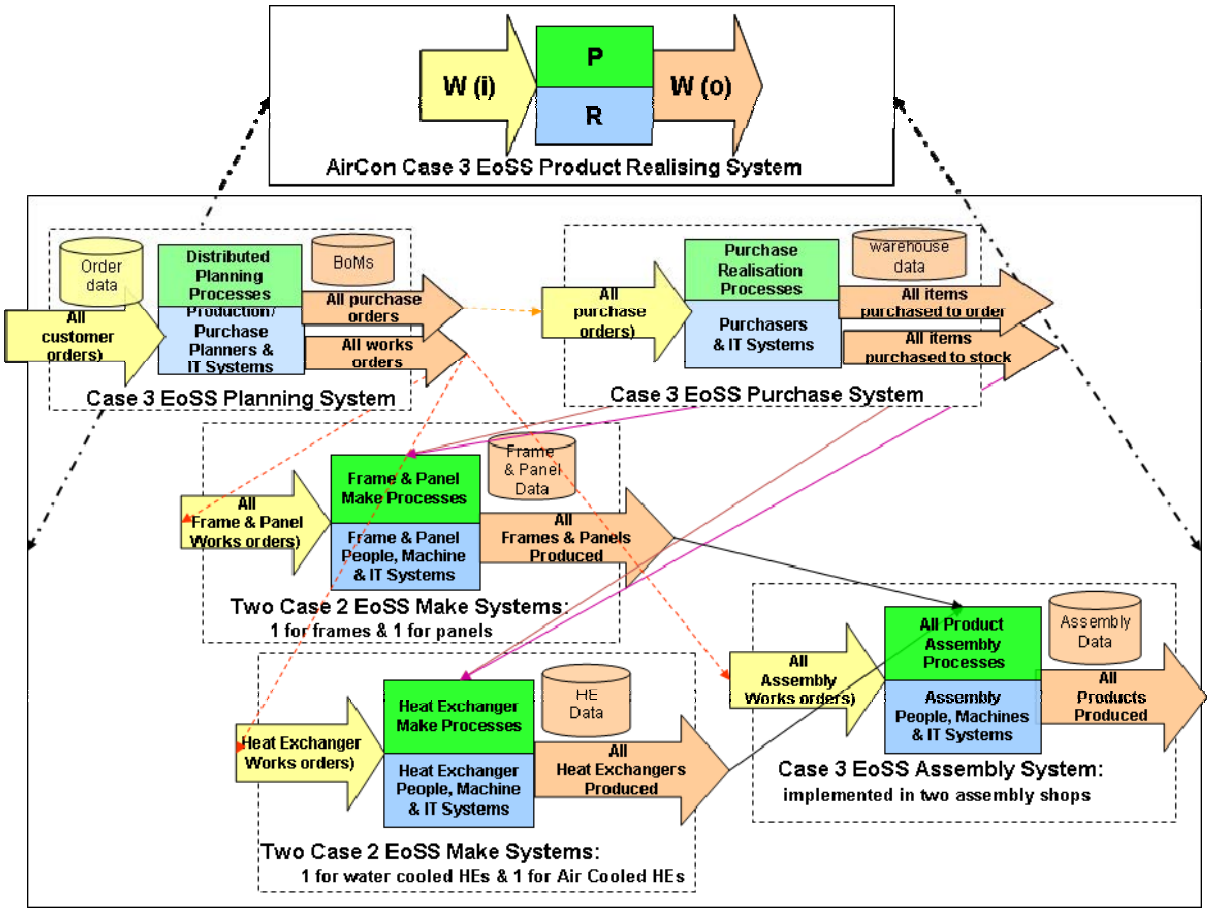


Figure 9.5 multi-level decomposition of hybrid EoSS system in AirCon

As depicted by Figure 9.5, AirCon deploys three distinctive production sections which carry out its production operations. Two sections, namely the 'Metal Sheet shop' and the 'Heat Exchanger shop', are used respectively to make 'metal framework structures' and 'heat exchangers' which are required components of all AirCon products. Two 'Assembly shops' collectively comprise the third production part. Physical space and lifting/handling constraints in AirCon have dictated that two assembly shops (A1 and A2) are needed to maintain sufficient throughput of assembly work; but logically the two shops operate in a similar fashion. Two other key parts of the AirCon product realisation system are: a 'Purchasing department' which is responsible for ensuring that raw material and outsourced

components are supplied in a timely and cost effective manner to the three production parts; and a 'Planning unit' which is responsible for integrated sales, technical, production & purchasing decision making such that negotiated customer expectations can be realised in acceptable time frames at acceptable costs.

9.3.1.1 Metal Sheet Shop and Heat Exchanger Shop (or Make System) EoSS Classifications

The study of the AirCon Metal Sheet (MS) shop showed that it comprises two Case 2 make systems. The MS shop machines, welds, surface treats and paint the framework, side, top and bottom panel components required to form the outer casing of AirCon air conditioners. One of the Case 2 EoSS systems comprising the MS shop makes tens of different panel types, while the other makes tens of different framework structure types. These 'component types' are assembled into final products in the Assembly shops and therefore their production rate is related to the rate at which final product contracts/orders are obtained by AirCon sales personnel. This relation is deduced from product specification and Bill of Material (BoM) information. Essentially the two (panel and frame) EoSS systems are resourced by different skilled operators, machines and tools but their operation is linked by a shared management system and common management personnel, and by a shared materials and component transportation system. Figure 9.6 conceptualises the Case 2 EoSS system of the metal sheet making shop, and visually illustrates processes routing differences between 'panel' and 'framework' families. Essentially this kind of classification activity formed part of step S4 of the EMM and was needed to facilitate qualitative thinking in preparation for multi-level quantitative analysis during the behavioural modelling steps of the EMM.

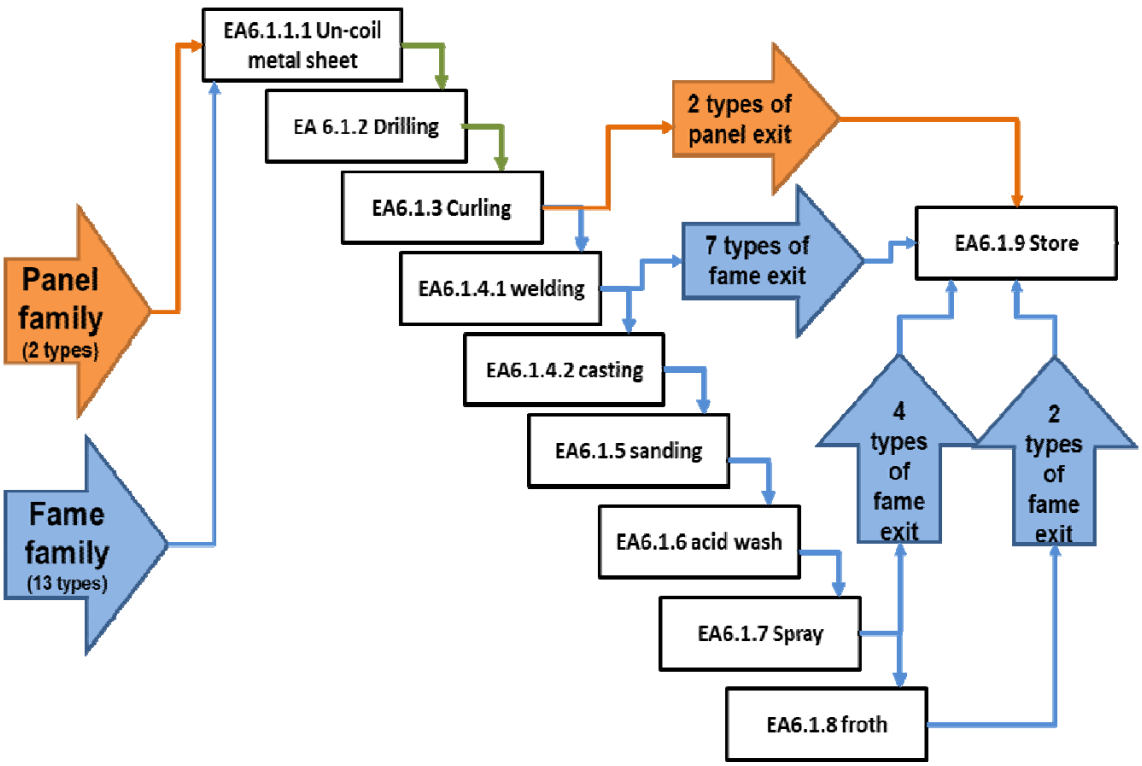


Figure 9.6 Processes routing differences between 'panel' and 'framework' families

Heat Exchangers (HEs) are a prime component of nearly all AirCon air-conditioners. Based upon their distinctive processing needs, the product types made in the HE shop were observed to fall into two main families; namely water cooled and air cooled heat exchangers (i.e. WC HE and AC HE). The HE shop was already using a similar product classification but the original classification had been made on the basis of distinctive functionality and composition. Indeed it was observed that the HE shop comprised two distinct Case 2 EoSS manufacturing systems one making approximately 10 types of WC HE and the other around 50 types of AC HE. The rate at which different HE product types need to be made is also largely determined by the rate at which final product contracts/orders are secured but AirCon also supplies a small fraction of HEs directly to external customers. As for the MS shop the two Case 2 EoSS HE systems have separate skilled operators, machines and tools but they share common management and transport arrangements, and when loads dictate they can also share some operators where they have appropriate skills. Figure 9.7 and 9.8 illustrates the processing differences of 'air-cooled' and 'water-cool' families.

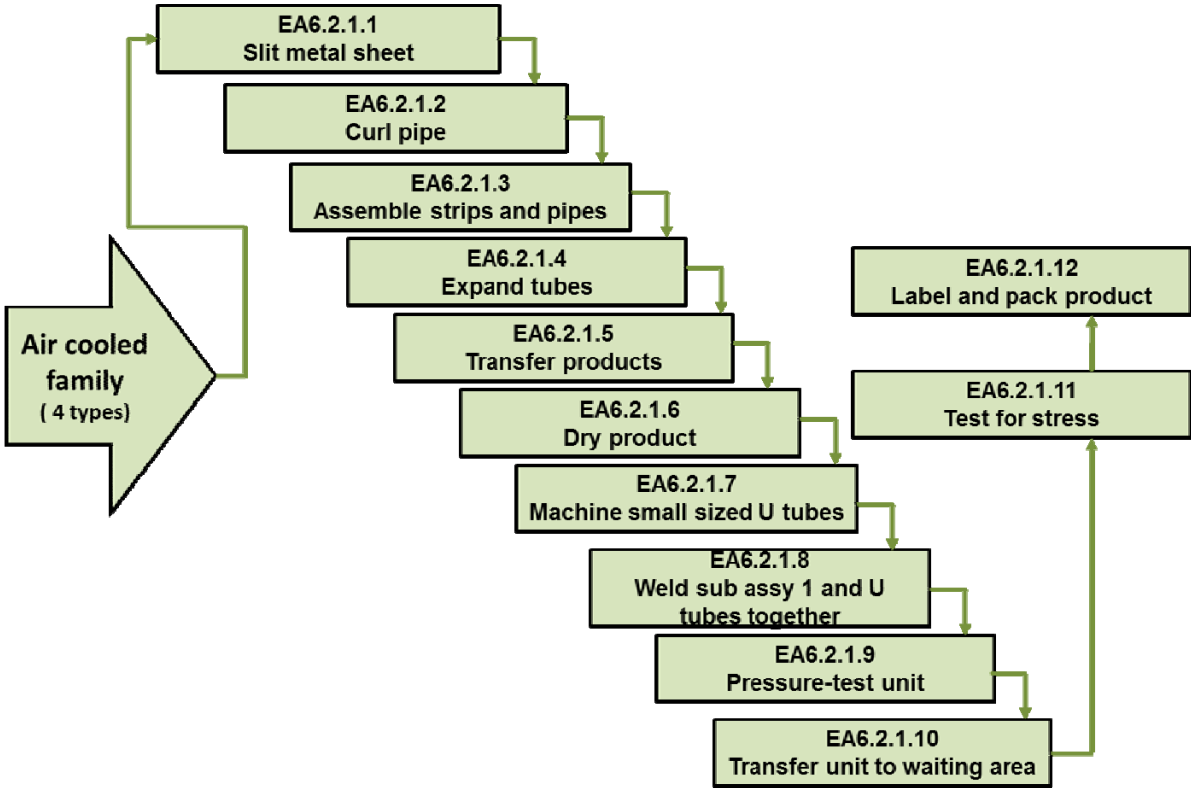


Figure 9.7 HE shop EoSS classification based 'W' & 'P' differences – Air cooled family

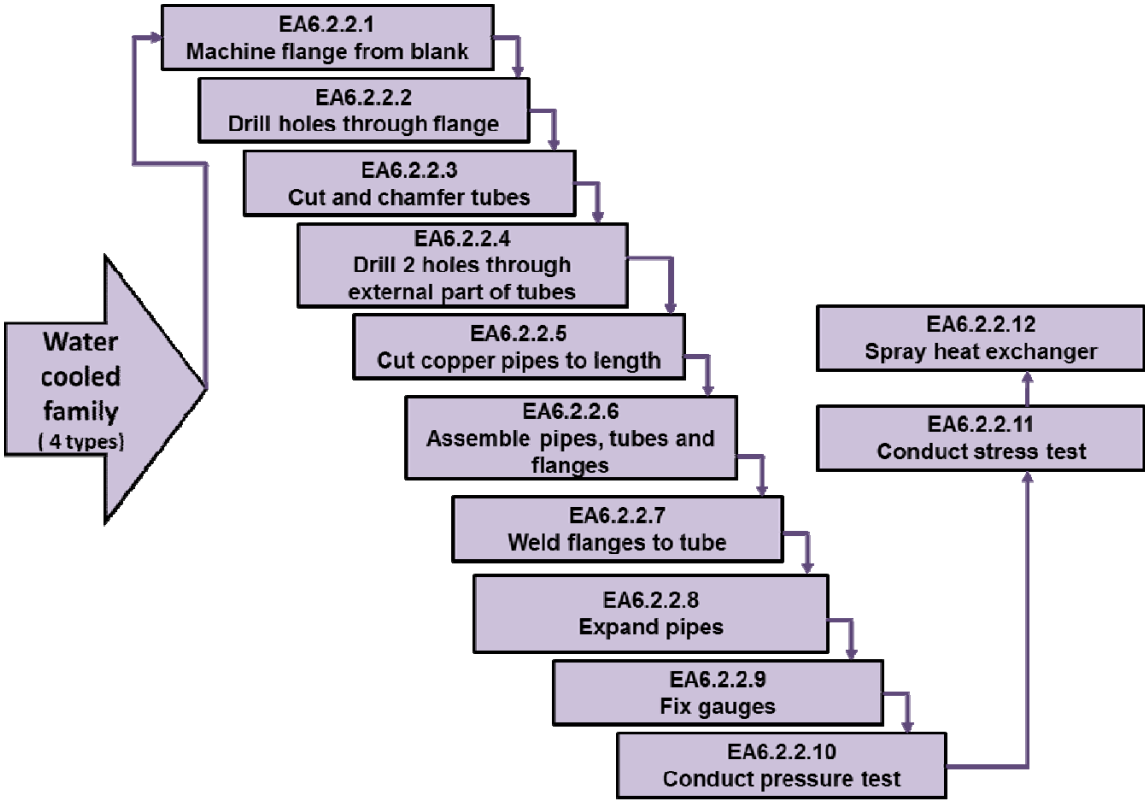


Figure 9.8 HE shop EoSS classification based 'W' & 'P' differences – water cooled family

9.3.1.2 Assembly System EoSS Classification

As previously discussed in some detail in Chapter 8, when modeling the two AirCon Assembly shops it was found to be beneficial to classify products with respect to their 'assembly operation differences' (mainly in terms of their processing routes and operation time differences but also in terms of needed differences in resource competencies to perform processing roles). This led onto an Assembly shop classification of all AirCon products into two families, namely 'mostly make' (MM) and 'mostly assembled' (MA) air conditioners. This distinction was drawn because although MM and MA products share certain assembly processing similarities they also had very major differences with respect to the complexity of assembly routings and needed assembly operation types. In reality both MA and MM product families comprised hundreds of different product types, where those types had been previously classified by AirCon primarily with reference to their functionality and component composition. Because of those compositional and functional differences there are relatively minor assembly operation differences between product types that comprise each family: but these differences are small, relative to assembly operation differences between product types belonging to different (i.e. MM or MA) families. Essentially by identifying MA and MM product classes and their significant assembly operation differences modelling simplifications were afforded which helped to visualise, and discuss with/explain to AirCon managers, ways in which key sources of differentiation in assembly processing leads to previously observed significant differences in assembly shop behaviours: where different families of products were incurring significantly different processing costs and causing distinctive bottlenecks in processing leading to signature lead time delays and cash flow behaviours.

9.3.1.3 Observations from the Qualitative Study of the AirCon Production System EoSS Classifications

Based on this qualitative analysis of Assembly shop operations and work flows it was observed that the AirCon assembly shops are Case 3 EoSS manufacturing systems (as defined by Figure 7.4) with an ability to assemble the full range of AirCon products. Essentially this is because with their current best practice AirCon assemble MM and MA product families with a common system of resources, and this affords the company

opportunities to realise significant economies of scope as well as economies of scale. In principle therefore the AirCon assembly area has opportunities to generate multiple income streams and thereby potential to attain high levels of efficiency (when this efficiency is expressed as the ratio of: 'income generated' divided by 'resource costs' times 100%). Also this affords opportunities to: increase the utilisation of resources (particularly because the demand for any one specific product type is uncertain); and extend the useful life-time of the assembly shops well beyond the life-time of any single air conditioning product. AirCon managers confirmed that the company was gaining advantage in these ways by running its assembly operations in a Case 3 mode, but they could not quantify the value of these benefits. However they also pointed out that the assembly area is normally the most difficult to manage production section, which necessitates runtime re-scheduling as the norm rather than an exception. But AirCon mangers were not certain about the source of such problems nor could they quantify the cost of additional complexity handling in this Case 3 EoSS system. However it was evident that achievable scope and scale economies are constrained as product demands increase so that they approached or exceed the capacity of the AirCon assembly shops. Also relative to the alternative use of two Case 2 EoSS Assembly shops, separately realising MM or MA air conditioning products, additional resource system competencies are needed to realise the current Case 3 EoSS assembly systems. This is because (a) there are some common competency requirements for MM and MA product realisation but also distinctive ones that must be possessed by resources that will perform assembly operations on either product family and (b) because additional change competencies are needed to: plan mixed MA and MM assembly operations; to synchronise these operations with the supply of a full range of make and purchased components; and to re-configure, programme and set up work teams, work tools and the like as a mixed variety of product types need to be made within constrained time frames. Indeed in the case of the AirCon assembly shops four teams of highly skilled people are required to realise Case 3 assembly and up to three shifts (each with four teams) are deployed when customer orders peak. Because of the nature of specific assembly air conditioning assembly operations coupled to the wide scope of products that AirCon needs to assemble there are very limited opportunities to automate assembly shop operations. This means that operation times and throughput rates will likely remain constrained by people characteristics and performances but on the other hand flexibility attributes of people have been marshalled systematically and effectively in the current AirCon Case 3 EoSS manufacturing system.

The forgoing discussion serves to illustrate that using Case 3 EoSS assembly operations has brought both benefits and dis-benefits to AirCon. Also it illustrates that it is not a trivial matter to determine whether Case 3 or Case 2 working is most appropriate. Indeed the best choice is likely to change over time as customer demand patterns change. Hence section 9.5 and 6 of this thesis illustrates how simulation modelling can help to predict likely benefits from using alternative EoSS styles of product realisation.

9.3.2 Integration modelling – 'EMM S4'

During the first MSI visit to AirCon the author and her colleagues were informed that the biggest production bottlenecks could be observed in the A2 assembly shop. Indeed as earlier mentioned, it was this element of the AirCon production system that required very frequent re-planning of workloads. Therefore a simulation model of the A2 shop at a medium level of detail was conducted and its deployment was reported in Chapter 8. The prime aims of so doing were to (1) understand A2 behaviours in some detail and (2) to determine how business structure & or policy change could induce changed (good and bad) in A2 behaviours. From the viewpoint of improving the integration of AirCon business planning, a second set of high level of abstraction DES models was then designed to better understand interactions between design, purchasing and production sections of AirCon. ***The outcomes of this higher level simulation modelling work are reported in the remainder of this Chapter***.

When designing the business oriented model, the main idea researched was that understandings gained from (lower level) modelled behaviours of A2 could be re-used (possibly via suitable 'recoding') to inform the modelling and understanding of higher level business behaviours whilst referencing performance measure of prime concern to the AirCon ME. Here AirCon specific aims were to generate critical information about production capacity and lead-times for different products such that their impacts and the impacts of other factors such as purchase delays could be quantified. Here it was envisaged that possible future business performances could be predicted when feasible scenarios of change are considered by AirCon senior managers.

To enable the conceptual and holistic design of these two SMs, such that they can function coherently, the author used the ideas embedded into the three sub-system decompositions earlier discussed, namely 'process', 'resource' and 'work' sub-system decompositions.

Essentially use of an extended AirCon EM was developed here following involvement of the author in some parallel theoretical modelling research aimed at realising flexible coupling and hence integration between models of process and resource sub-system decompositions at multiple levels of abstraction The outcomes of this theoretical research are published in the paper entitled '*On Modelling Reusable Components of Change Capable Manufacturing Systems*' (Weston et.al. 2010). In the case study reported herein the author used the ideas introduced in respect to characterising and flexibly attributing models of process–oriented 'Roles' to models of candidate 'Role Holders'. Here the process and resource sub-system decompositions provided the detail of the subject system under study to visually and flexibly define how different flows of AirCon product types routed through 'process-resource' (so called P-R or 'role'-'role holder') couples.

The definitions used for 'Roles' and 'Role Holders' are briefly described here to facilitate the readers understanding but the reader is referred to Weston et al (2009) for detailed understanding.

The resultant conceptual design of the first set of higher level business simulation models is illustrated by figure 9.9. This simulation model was conceived to encode and virtually test the behaviours of the 'plan order' and 'realise order' processes in the AirCon business. The model comprises the planning, purchasing, making and assembling sectional hybrid EoSS systems of the subject ME. Each of these sectional parts were 'structurally modelled' as comprising their 'process' 'resource' and 'work' subsystems. Here modelling of those subsystems is at a fairly high level of abstraction- while previously A2 modelling had been carried out at a more detailed level. In figure 9.9 the process subsystems are coloured green, the resource sub-systems yellow and the work flows are designated via multi-coloured arrows. Each of these three sub-systems can be 'drilled into' to create more detail visualisations in the form of graphical models. An example of this is given in Figure 9.9 for the A2 shop where the process sub-system is re-represented at two lower levels of granularity as a set of structurally related 'Roles' (defined in the form of activity diagrams at required abstraction levels) to which 'Role holders' with specific competencies can be attributed). It follows that figure 9.8 functioned as an 'integration diagram', as in a variety of ways it visually linked a number of decomposition ideas about sections (high level roles), processes, resources (medium and lower level role holders) and workflows. Furthermore many informational attachments were formally made to this integration diagram; which itself was

formally derived from the specific case parent EM of the AirCon ME. At required abstraction levels, use of the integration diagram allowed the author to flexibly position the following types of entity into the big architectural picture of AirCon: tabular descriptions of routes, operation times, and tabular descriptions of competency requirements of different product classes families and types; tabular descriptions of competencies possessed by candidate role holders; graphical models of roles and their standard operation procedures; and a tabular attribution of work flow rules and precedence constraints to work flows. Potential many other types of entity can be positioned; such as related to value generation and cost consumption aspects of sections, roles and the like.

The above reasoning and graphical representation of process, resource and work sub-systems decompositions led to a systematic and coherent conceptual 'STRUCTURAL DESIGN' of the two 'fit for purpose' SMs used in this case study; into which at the two chosen levels of abstraction AirCon was characterised in terms of its 'as is' 'business realisation' and 'final product realisation' respectively. These structural designs were therefore represented conceptually using visual maps that explicitly specify how different product classes, families and types are routed through configurations of P-R (or Role-Role holder) couples (thereby defining the structural architecture that needs to be embedded into each SM).

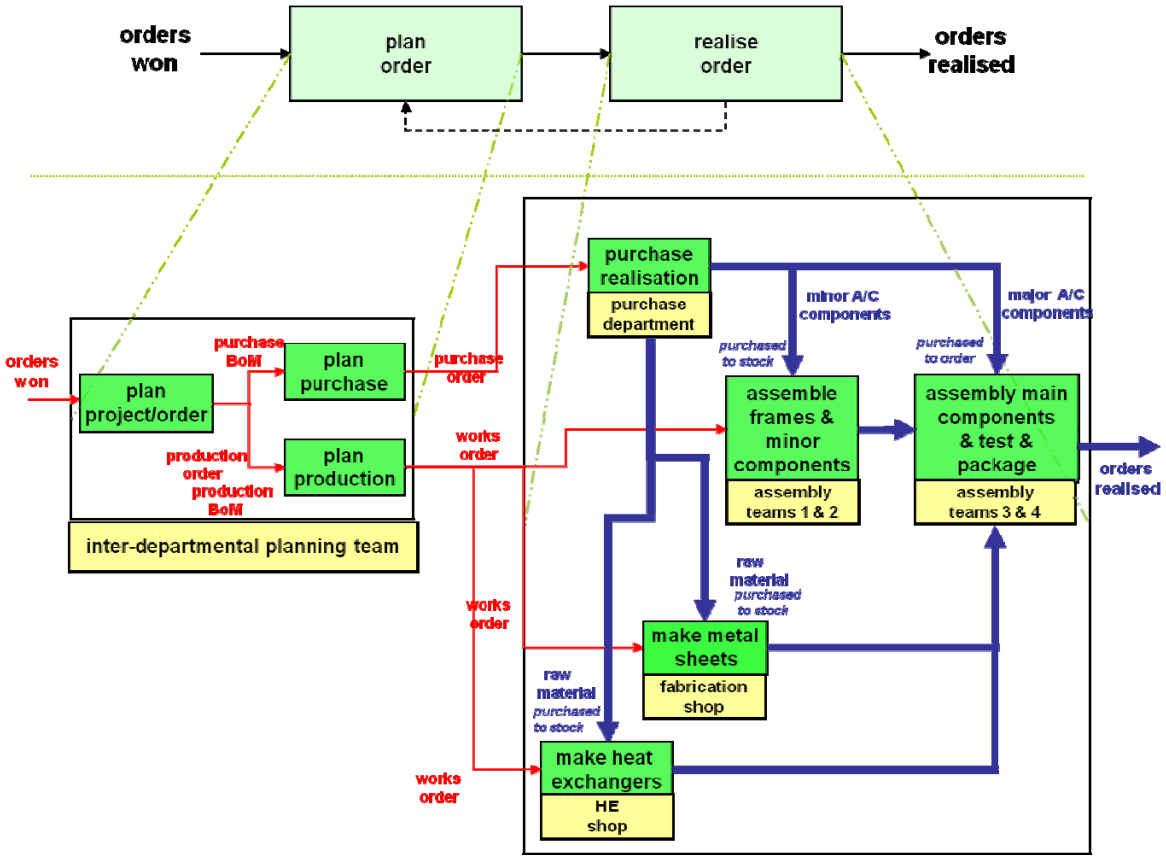


Figure 9.9 example material and information mapping into a structural model

9.4 Higher/ business level behavioural modelling –EMM Phase 2

As discussed in previous thesis sections, the AirCon ME was considered to be a hybrid EoSS (economy of scale and scope) system for which constituent EoSS systems realise different degrees of economies of scope and scale. Using the EoSS reference model introduced in Chapter 7 (and the three EoSS P, R & W sub-system ideas), EoSS structures (which were considered to be a kind of footprint DNA) were mapped onto AirCon product realisation. Here the decomposed work subsystem (in respect of product variance) was mapped onto the specific case AirCon EM model. According to 'work sub-systems' variation, it was made evident that there are a number of case 2 and 3 EoSS systems within the AirCon business. Some of these systems deal almost exclusively with information entity flows, while others need to handle both physical and informational entity flows. Good synchronisation of activity, information and physical flows amongst these hybrid EoSS systems was therefore viewed as being critical to achieving improved lead-time, cost and quality performance. After detailed

modelling and reasoning about assembly systems behaviours attention was then shifted towards the use of holistic simulation models with a view to improving synchronisation amongst AirCon's hybrid EoSS systems. Here it was presumed that the potential use of new and better integrated planning policies might be quantitatively investigated in a virtual world and this might lead onto new ideas about how improved policies might be better facilitated via process, resource and work sub-system re-configuration.

Figure 9.10 shows a screen shot of the A2 simulation model described in figure 8.11 section 8. As also mentioned in section 8.4 this simulation model was implemented using the proprietary Simul8 discrete event simulation modelling tool (Simul8, 2002). Much of the structural organisation of this model (including: the basic process logic of each product family executed by assembly workstations; current resource assignments made at workstations; and product family/type work flows, operation times and processing logic through work entry and exit points and workstations) was derived from understandings previously encoded by a combination of the AirCon EM and EoSS representations of the A2 shop visually represented by the integration shown in figure 9.10. This integration diagram also linked the conceptual design of the A2 simulation model to data tables describing related work and resource sub-system attributes elicited from the real A2 system by the AirCon internal project team.

The same AirCon EM, and graphical EoSS relations of the type described by figure 9.10 with its related data tables, also encoded structural relations needed to encode 'process', 'resource' and work sub-system structures into a higher level, holistic simulation model of the AirCon business. The abstract structural models created in this way naturally led to the development of the simulation model described by the screen shot of figure 9.10 This model of AirCon business behaviours has a scope which includes 'design', 'planning', 'make' and 'assembly' business units of the company. Because of high levels of complexity and uncertainty in the causal and temporal relationships that link variables within the sections and sub-sections of this model, many assumptions needed to be made during high level business simulation modelling. However much of that detail was handled previously during the structural design of the simulation models and particularly during lower level structural and simulation modelling work reported in chapter 8 (such as by experimenting with the A2 simulation model). Hence the prime focus of attention when constructing simulation experiments at the holistic level was on studying, at a fairly abstract level, how alternative company policies can

impact in terms of causal and temporal effects, and hence how it might be possible to generate synergistic behaviours between business sections. To provide a better focus for the higher level modelling, the simulation results were linked to prime business KPI's of concern to the company namely: throughput, lead-time and cash-flow behaviours of the company as a whole. However critical to the construction of the experiments was the previously discussed need to classify products into classes, families and types on the basis of their distinctive processing needs. Here though as a business view was being developed the main interest was on differentiating between the behaviours of workloads comprising 'standard' (ST A/C), 'customised' (CU AC) and 'special' (SP A/C) air conditioners. By nature the product realisation of any SP A/C product is more difficult to characterise than ST AC and CU A/C counterparts, because very extremes of design and prototyping may be needed for SP A/Cs (for example in military situations and equipment) which may or may not require very significant design and prototype production processing during product realisation. While particularly for ST A/Cs and many CU A/C types, corresponding processing routes and times are well established in AirCon.

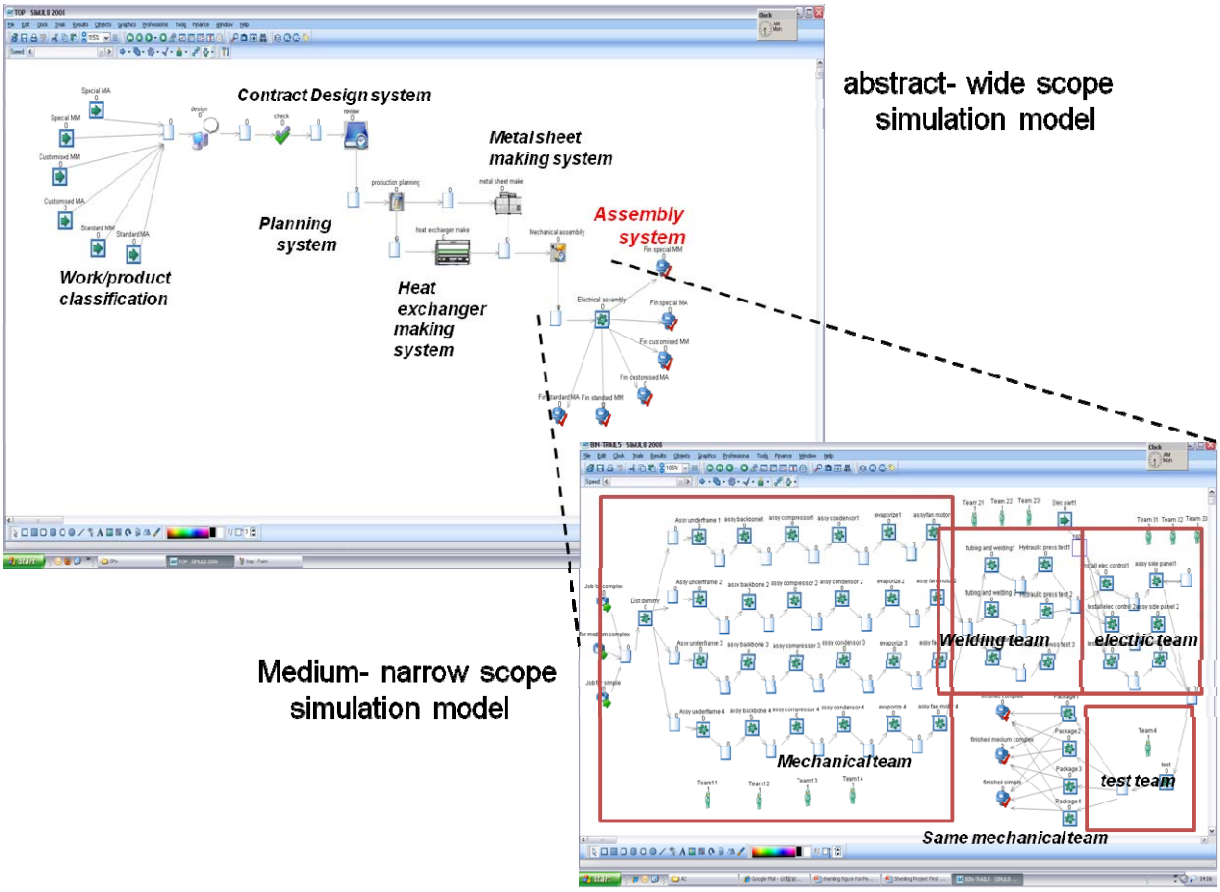


Figure 9.10 Demonstration of multi-level simulation modelling

The following sections presents the high level EMM behavioural modelling carried out by the author for AirCon and presents an analysis of the results she obtained.

The behavioural models developed during this part of her PhD study had 'specific case' and 'academic study' duality of purpose. The primary specific, AirCon case purpose when conducting high (business) level simulation experiments was to better inform 1) due date and 2) cost estimation; by quantitatively illustrating to AirCon strategists and planners how business behaviours are causally and temporally influenced by product variance and product volume demand changes. While the main focus of academic study was to illustrate a systematic way of analysing key cost behaviours arising from realising economies of scope and scale; which can be developed via future study into a comprehensive way of analysing benefits and cost of alternative forms of EoSS system configuration and operation.

9.5 Illustrative simulation-based business level, cost modelling in AirCon; to quantify key economic benefits realised by EoSSsystems

When developing and experimenting with the two level simulation models of AirCon it became evident that significant benefit could be gained from quantifying the economies of scope and scale that can be realised by a particular configuration of EoSS system(s); given a specified product dynamic. Such a quantification was of interest to AirCon for the purposes of medium to long term planning; and was of current interest to the company as it planned to expand and relocate it business, meaning for example that the company needed to decide whether to build future configurations of Case 3 assembly shops or to replace these with a number of Case 2 assembly shops. It was also presumed that such systematic method of quantifying EoSS benefits and dis-benefits would be of general interest during the lifetime of most, if not all, MEs making multiple products.

To achieve such quantification the author decided to conceive and illustrate the use of a 'systematic way of measuring scope and scale economies'; which within a specified planning window could be used to enumerate and contrast the 'values generated' and 'costs consumed' by a given configuration of EoSS systems when subjected to a well define product dynamic. Hence it was considered necessary to review relevant literature on manufacturing costs

bearing mind that the aim was to enumerate business benefits and related costs of alternative EoSS system configurations.

Many relevant methods of costing were observed from the literature; hence it was deemed necessary to focus the cost analysis. Here it was decided to concentrate on a study of (time based) behaviours of cost terms that were perceived to have a relationship with changes in the types and/or rate of execution of product realising activities within a subject MEs (Atrill and McLaney, 2009). Here it was observed that many authors referred to:

- ***Fixed Costs***: including costs that remain constant irrespective of the activities performed.
- ***Variable Cost***: including costs that vary in proportion to activity types and levels.
- Also observed was the occurrence of ***Semi-variable Costs*** that are partially fixed and partially variable.

Traditional costing systems cannot support accurate product costing when an enterprise produces multiple products (Gunasekaran and Sarhadi., 1998 and Gupta and Galloway., 2003). Various authors report that little attention is normally paid to the allocation to manufacturing overheads when production volumes are variable. Hence traditional costing systems cannot be relied upon for strategic decision making or for performance evaluation during product realisation (Andrade et al. 1999 and Boons 1998). Kee (2008) however illustrated the use of a non-linear cost effect arising from change in production volumes within multi-product MEs. This effect was shown to depend upon: human resource costs during capacity expansion; purchase discounts when purchased volumes increase; and when engineering materials are shared by multiple products. Bearing these ideas in mind, when considering relative economies of scope and scale for different AirCon EoSS configurations the following ranking of 'Cost Entity Types' was considered to be appropriate.

Material costs were considered to be: of low significance in the context of calculating 'relative economies' of EoSS systems; but high when considering the 'relative costs of AirCon products', such as during their pricing and cost estimation.

Production costs (fixed + variable): were considered to be of high significance. Here fixed costs might be tooling, machines and IT systems, and long term systems engineering costs

[all of which may be considered to be capital costs, written off over a number of years (e.g. 2 to 5 years)] while variable production cost might best be calculated using ABC costing principles (Kee, 2008).

Based on the analysis of results from the A2 experiments reported in chapter 8, the author also observed that it would help AirCon to enumerate: a) 'purchase delays costs' and b) 're-scheduling costs'. Here it was assumed that a) was of major importance to AirCon because significant purchase and production delays tie up money which needs to be borrowed (at relevant interest rates) or monies that cannot be re-invested. Also observed in AirCon was that within a) some WIP costs will be particularly significant and should be taken into account. With respect to b) as the number of number of instances of rework increase the cost of production will increase, not least because the need to repeat processing activities will increase as will likely production bottlenecks and WIP. Also the cost of b) will increase as purchase and make delays impact on production rates and late product deliveries to customers. Furthermore the cost of a) and b) will depend on the mix of products in any given time-period of the running manufacturing system.

In view of the forgoing reasoning a number of cost elements were included into newly developed versions of the two-level AirCon simulation models which enabled enumeration of: labour costs, technical resource costs, and resource usage costs.

The reason for modelling behaviours of these cost items (which were observed to be highly relevant to the AirCon business) was to quantify and better understand economies of scale and scope phenomenon in AirCon. Importantly also the aim was to provide a method of quantifying and understanding EoSS behaviours in other MEs; so that for example a similar framework of modelling steps could be taken but where case specific cost elements could be defined and included into models. As a study of processing cost behaviours in response to different product dynamic factors is important to the study of EoSS systems performance, it was decided that potentially processing cost behaviours could be studied from three points of view, namely:

1. When enumerating economies of scope and scale that can be realised by making alternative product mix decisions; given an existing configuration of EoSS systems.

2. In support of the longer term / strategic design of one or more EoSS systems; to improve the chances (and therefore reduce associated risks) of realising the strategic aspirations and plans of a given MEs.

3. In support of design for manufacture decision-making when introducing new products into existing manufacturing system.

The forgoing shows that modelling EoSS costs is actually a vast and complex subject, particularly as there are different user groups associated with 1. to 3. above (who are potential beneficiaries of EoSS cost models); and also because there are various schools of thought about cost modelling. However this was perceived by the author to be a challenge which can in part be addressed via the systematic design of fit for purpose SMs, which suit specified user group needs and therefore embody appropriate modelling simplifications and assumptions, so that the behaviours of relevant cost elements can be adequately predicted over time relevant frames.

Therefore the remainder of this chapter is focused on illustrating a particular view of cost modelling with its client users; and shows how these clients can be supported via use of the EMM and EoSS concepts described in Chapter 7 of this thesis. This has been linked directly to the AirCon case but study constrains have prevented more detailed company problem solving and it was observed that addressing both specific and general problem issues would need to be the subject of at least one following PhD study.

9.6 experiment SM designs and EoSS business case findings for AirCon

9.6.1 Costing assumptions and data inputs to the business level simulation model

Based on the forgoing analysis of relevant costing literature the following assumptions and data inputs were used when developing and experimenting with the business level simulation model of AirCon.

Unfortunately project time limitations coupled with limited availabilities of historical cost data about AirCon meant that many of the following cost variables needed to be estimated (i.e. were not actual AirCon case specific) values; but it is believed that those estimates are in the correct ‘ball park’ as verified through discussion with AirCon managers during MSI visits to the company and via subsequent web-based communications:

- Average Costs of AirCon engineers: £25,000 per year = £100 per day;
- Average Cost of AirCon workers: £15,000 per year = £60 per day;
- AirCon Computer Aided Design (CAD) system: capital cost £30,000; here a pay back over 5 years was assumed; hence CAD costs assumed to be £6,000/yr. = £24/day
- AirCon Product Data Management (PDM) system: capital cost £30,000 with an assumed pay back over 5 years; hence £6,000/yr. = £24/day
- AirCon Material Requirements Planning (MRP) system: capital cost £30,000 with an assumed pay back over 3 years; hence MRP cost = £40/day
- AirCon Remote Order Point (ROP) system: capital cost £15,000 with an assumed pay back over 3 years; hence ROP cost = £20/day
- Production Machines: average capital cost £20,000 with an assumed pay back over 10 years; hence production machine cost = £18/day
- Transportation, Crane and Storage Equipment: £30,000 over 5 years; hence assumed cost of £6/day/line (with 4 lines included into the AirCon SM)
- Fixtures and tooling: £15,000 per year assumed, hence £12/day/line

The proprietary simul8 software tool was observed to have a limited number of built in costing functions that are fairly easy to use. Also as discussed previously, the main costing approach selected during this research was that of Activity Based-Costing (ABC); as the ABC methodology & concepts aligns well with the process-oriented structural design of the EMM derived AirCon business level simulation model and its embedded notions about EoSS economies. Also an ABC modelling approach could be readily deployed because ABC costing is supported to some degree by Simul8 software; but the reader should note that other costing methods could have been adopted.

Hence in this study the main costing formulae conceived and used when developing the business level simulation model were as follows:

- Cost = labour cost + technical resource cost + usage costs
- Processing / resource cost = WC (work centre) working time x Cost per day (built in cost function)
- WC working time = working % x total time in system running

The data on process / resource cost of WC's (people + technical costs) input to the model are listed in table 9.1.

The average price information for each product is recorded into table 9.2. This lists the average selling price of finished A/Cs. When these 'selling price values' are multiplied by 'the quantities of different A/C types sold in a given time frame', the 'revenues generated' (in that time frame) can be estimated. Also the 'revenues generated' minus 'the sum of all costs involved in product realisation' will equate to the profit. However as indicated in the forgoing in this study the prime focus of concern is on contrasting 'relative economies of scope and scale' that can be realised by 'alternative EoSS system configurations when they are subjected to variable patterns of customer demand' (in which those demands are expressed in terms of product variances, production volumes and production mixes). Therefore the author assumed that it was not necessary when calculating 'relative economies' to include fixed 'total cost' items. Particularly as discussed above, material costs are significant when product pricing and cost estimation is of concern but they have minor significance when calculating relative scope and scale economies; excepting that purchase discounts can be obtain when purchased volumes increase but this kind of non-linear effect can be separately accounted for during product pricing and does not require the use of a discrete event simulator.

Table 9.1 Resource cost per day of WC's included into the AirCon business level SM

WC (work centre)	People	Technical resource	Sum
Design	5 @ £100/day	100% CAD @ £24/day 20% PDM @ £4.8/day	£529/day
Check	1 @ £100/day	40% PDM @ £9.6/day	£110/day
Review	1 @ £120/day	40% PDM @ £9.6/day	£130/day
Production planning	4 @ £100/day	80% MRP @ £40/day	£432/day
Metal sheet make	35 @ £60/day 5 @£100/day	10 machines @ £18/day	£2780/day
Heat exchanger make	15 @£60/day 5 @ £100/day	8 machines @ £18/day	£1744/day
Assembly (per line x4)	10 @ £60/day 1 @ £100/day	Transport equipment @ £6/day Fixture and tools @ £3/day	£709/day
Purchase planning	5 @ £100/day	ROP system @ £20/day 20% MRP @£40/day	£528/day
Negotiate with supplier	2 @£100/day		£200/day
Deliver purchase	External cost		

Table 9.2 Pricing / revenue information

Product types	Price (average)
Standard MM	£2,500
Standard MA	£36,000
Customised MM @ 120% of Standard MM	£3,000
Customised MA @ 120% of Standard MA	£43,200
Special MM @ 200% of Standard MM	£5,000
Special MA @ 200% of Standard MA	£72,000

9.6.2 Experimental runs and results documentation

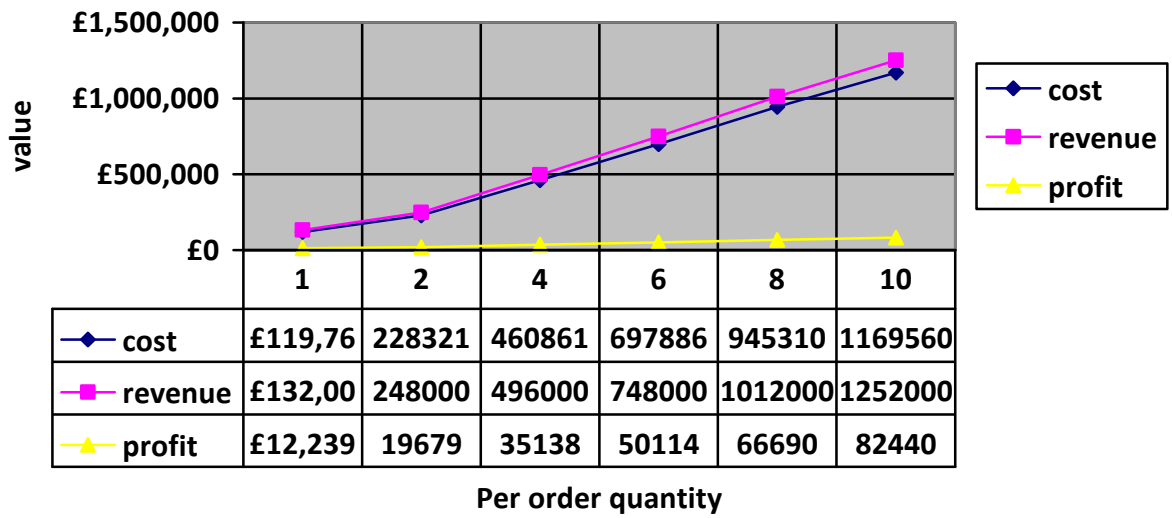
This thesis section reports on the experimental testing of the business level simulation model of AirCon. This testing was designed to complement the earlier experimental testing of the AirCon assembly shop simulation model, which is reported in chapter 8. It follows that this section illustrates EMM phase 2 behavioural modelling; with a focus on EMM step B4 (scenario testing) as defined in chapter 7.

Bearing in mind findings from the lower level simulation modelling experiments, the business level experimental design was centred on analysing value and cost outcomes under three scenarios of operation, namely:

1) Ideal scenario
2) Scenario with purchase delays
3) Scenario with rework scenarios

For 1) i.e. the ideal condition, the system is run under the assumption that all made and purchased parts arrive at the right time; also that there are no design or operation errors leading to rework. Whereas for 2) i.e. the purchase delay scenario, it was assumed that assembly of standard A/Cs involves a time lag of 7 days to deliver the parts, customised and special A/Cs require 15 days, while special A/Cs require an extra business process that involves 'negotiation with suppliers'. In the rework scenarios tested for 3), during each production run it is assumed that 10% of standard A/Cs is assumed to require rework (re-production); 30% of customised A/Cs is assumed to require rework; and 50% of special products require rework. The assumptions embodied into these three scenarios were discussed with AirCon production managers who accepted them as being representative of actually occurring situations.

The simulation results obtained during scenario 1 testing (i.e. ideal assembly conditions) of the current configuration of the AirCon business system are summarized by figures 9.11 to 9.16. .

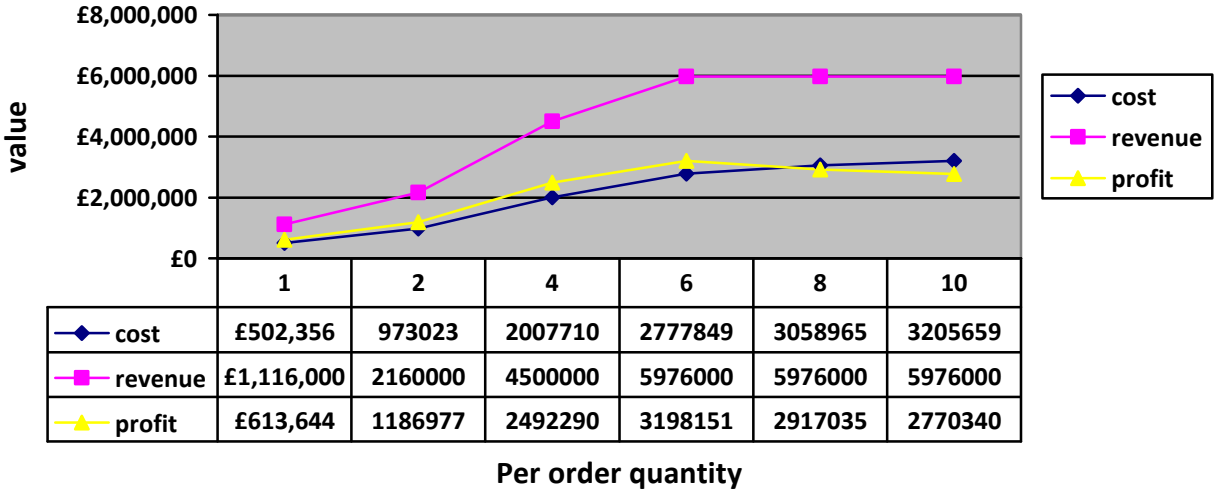


	1	2	4	6	8	10
cost	£119,76	228321	460861	697886	945310	1169560
revenue	£132,00	248000	496000	748000	1012000	1252000
profit	£12,239	19679	35138	50114	66690	82440

Figure 9.11 Standard MM trials: Results for the ideal scenario

It can be seen in figure 9.11, that when the business system runs under Case 1 EoSS conditions and is making only ***standard MM family A/Cs***, the profit generated is predicted to increase as the order quantity is increased through a range of batch sizes from 1 to 10 every 17 days; however saturation conditions were predicted to occur when the order rate or batch sizes are increased beyond those values. Furthermore it was observed that cost and revenue trends follow a similar pattern to that of profit generation.

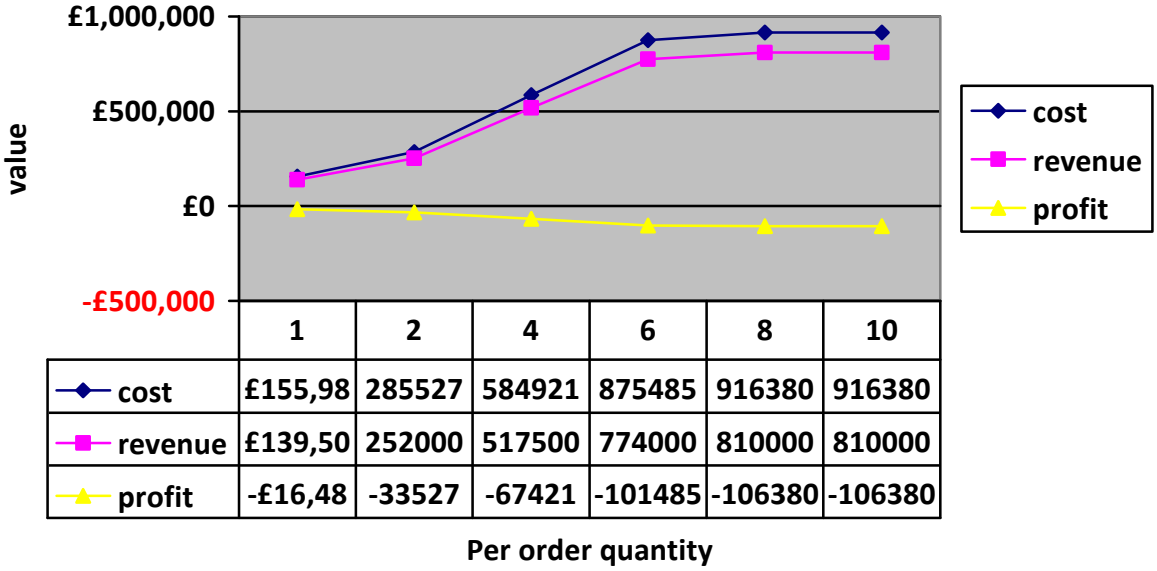
By contrast, when the model runs with a variable demand for a single product family of ***standard MA A/Cs***, the predicted results for this alternative Case 1 EoSS business system were as shown in figure 9.12. This illustrates that the revenues generated have levels that are approximately 50% higher than related cost consumption levels.



	1	2	4	6	8	10
cost	£502,356	973023	2007710	2777849	3058965	3205659
revenue	£1,116,000	2160000	4500000	5976000	5976000	5976000
profit	£613,644	1186977	2492290	3198151	2917035	2770340

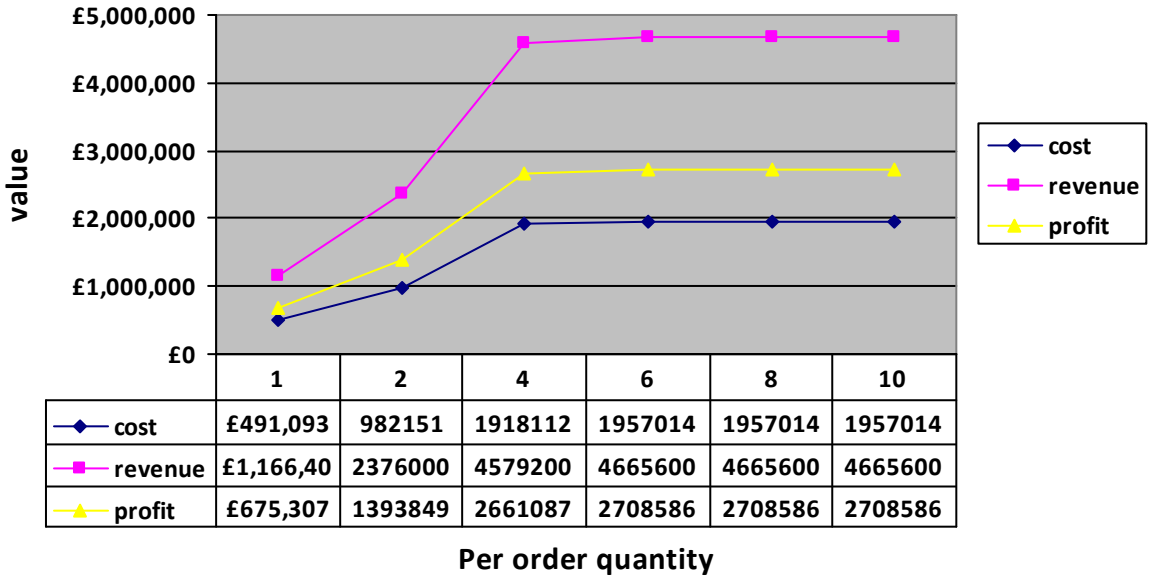
Figure 9.12 Standard MA trials results in ideal scenario

To compare and contrast predicted cost and revenue behaviours of the current AirCon business system when separately running the business level simulation model with other sub classes of each product family, the author conducted similar experiments for each of ***customised MM and MA products*** and for ***special MM and MA products***. The experimental results obtained are illustrated by figures 9.13 & 9.14 and 9.15 & 9.16 respectively. From where it can generally be observed that all sub classes of MM A/C generate significantly less profit for AirCon than corresponding sub classes of MA products.



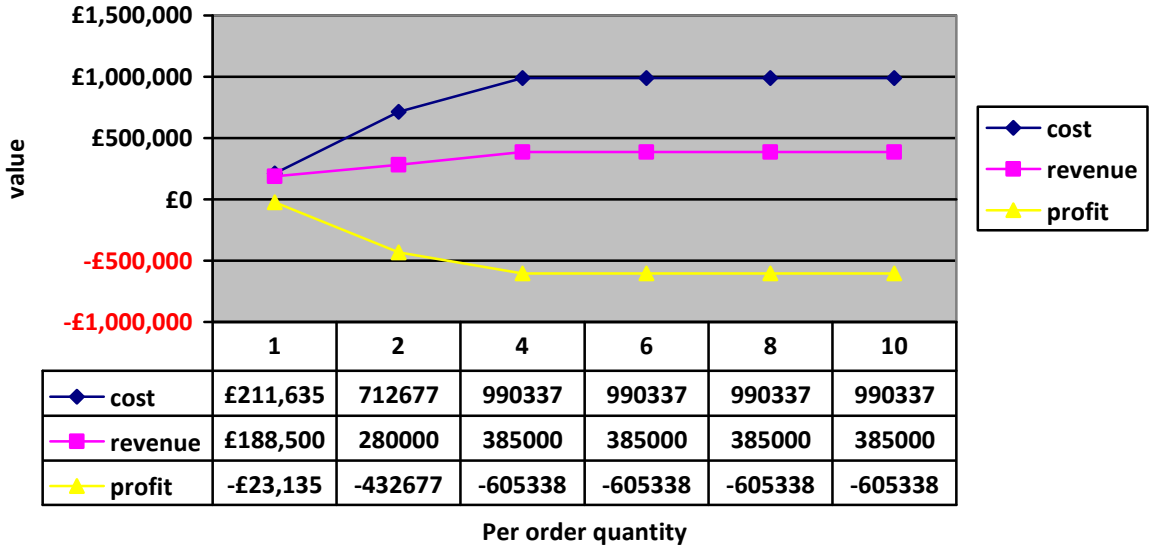
	1	2	4	6	8	10
cost	£155,98	285527	584921	875485	916380	916380
revenue	£139,50	252000	517500	774000	810000	810000
profit	-£16,48	-33527	-67421	-101485	-106380	-106380

Figure 9.13 Customised MM trials & results under ideal scenario conditions



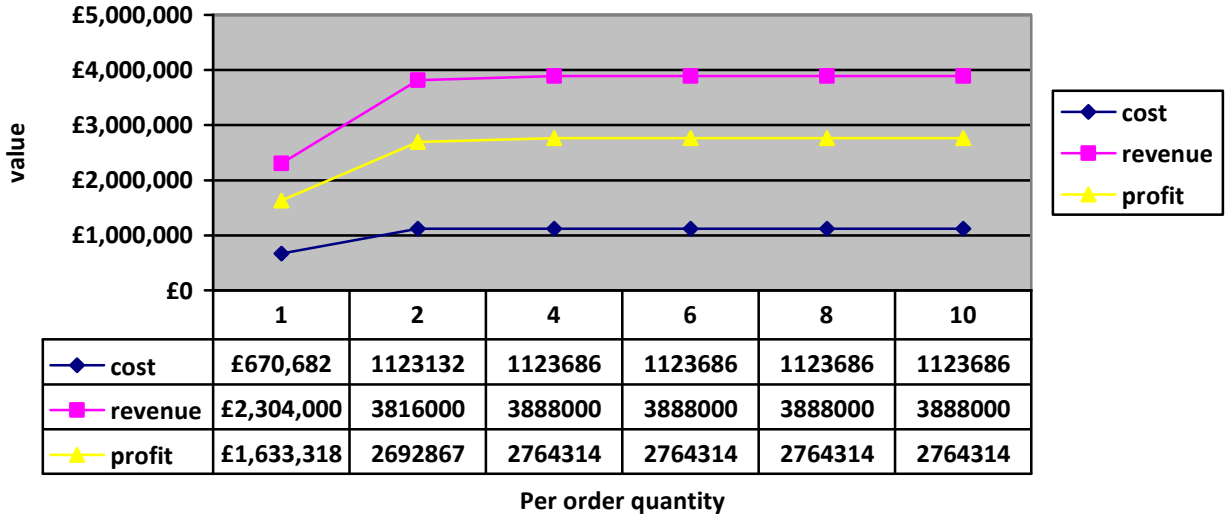
	1	2	4	6	8	10
cost	£491,093	982151	1918112	1957014	1957014	1957014
revenue	£1,166,40	2376000	4579200	4665600	4665600	4665600
profit	£675,307	1393849	2661087	2708586	2708586	2708586

Figure 9.14 customised MA trials & results under ideal scenario conditions



	1	2	4	6	8	10
cost	£211,635	712677	990337	990337	990337	990337
revenue	£188,500	280000	385000	385000	385000	385000
profit	-£23,135	-432677	-605338	-605338	-605338	-605338

Figure 9.15 Special MM trials & results under ideal scenario conditions



	1	2	4	6	8	10
cost	£670,682	1123132	1123686	1123686	1123686	1123686
revenue	£2,304,000	3816000	3888000	3888000	3888000	3888000
profit	£1,633,318	2692867	2764314	2764314	2764314	2764314

Figure 9.16 Special MA trials & results under ideal scenario conditions

After conducting the aforementioned tests for the set of ideal scenario of operation, the author used the same systematic behaviour modelling approach to conduct an additional two sets of business level models experiments corresponding to:

2) The purchase delay scenario of operation and

3) The rework scenario of operation.

Appendix III record the experimental results obtained.

9.6.3 Outcomes of the multiple level cost modelling

Table 9.3 was constructed to compare the simulation results obtained for the three scenarios of business level operation; namely scenarios 1) through 3). It should be noted however that experiments performed at this stage of modelling were run under the assumption that the AirCon business runs only as a Case 1 EoSS ME; but where its operation can be readily 'changed over' to separately (and sequentially) realise essentially six different product groups (i.e. three sub groups each [standard, customise and special versions] of MM and MA products). This modelling simplification was made to facilitate the development of understandings about relative value and cost performances of different product groups and also to become positioned to analyse key financial impacts of purchase delays and rework effects on the AirCon business. The results of the behaviour modelling obtained via this process of simplification were considered to be of major importance; because for the first time they provided important relative information about the impacts on the AirCon business

of 'accepting', 'planning' and 'realising' different product types- information which previously had not be available to managers and strategists in the AirCon enterprise.

Table 9.3 summary of three scenario testing results

Product class @ 10 batch size /17 days	Ideal Case Profit	Profit with purchase delay	Profit with rework	Cost of purchase delay	Cost of rework
Standard MM	£82,440	£-636,057	£-708,164	£644,497	£790,604
Standard MA	£2,770,340	£224,173	£2,079,275	£2,546,167	£691,065
Customised MM	£-106,380	£-616,176	£-423,720	£509,796	£317,340
Customised MA	£2,708,586	£204,786	£1,239,786	£2,503,800	£1,468,800
Special MM	£-60,074	£-408,746	£-308,075	£348,672	£248,001
Special MA	£2,764,314	£1,499,642	£1,324,314	£1,264,672	£1,440,000

In the actual AirCon business however the aforementioned six product groups are essentially realised simultaneously; i.e. the AirCon business as a whole runs as a Case 3 EoSS ME. But this multi-product working clearly introduces significant additional complexity: such as related to the complexity of planning and managing change between product groups; making physical set up changes during systems operation; and the need to deploy more flexible people and machine resources at those points in the ME where runtime change over needs to be realised. Each of these complicating factors had previously masked the relative performances within the AirCon ME of different product groups, and therefore it is believed that currently the AirCon business does not take these differences sufficiently into account or in adequate ways during related decision making.

The author was cognisant however that real case concurrent mix product realisation has potential to lead to: difficult to predict 'line balance differences' (e.g. because of variable Takt times); difficult to predict occurrences of 'bottlenecks' and WIP; difficult to predict change in throughputs and over-all lead-times; etc. Therefore appendix III reports on some sample experimental results obtained by the author when running her AirCon business model with ideal scenarios of ***mix product realisation***; i.e. when simulating the running AirCon as a Case 3 EoSS system. The author's project time did not permit more detailed study of the many possible complex scenarios that can be tested in a similar systematic way. However this

provides a template for experimentation that has been recommended to the ME concerned and may well be implemented in the near future.

It follows that the AirCon business level simulation model can be run under various scenarios of 'actual cases' and 'simplified actual cases' of product realisation; and by so doing can support various groups of decision maker with their specific concerns, operating in different AirCon business units. Importantly this study has shown that business relativities about of the realisation of different product types and product mixes can be quantified and predicted Also it is believed, but could not be proven because of project time constraints, that by coherently developing and using business and sectional level simulation models (via the application of EMM concepts and steps) that the AirCon ME can very beneficially re-configure its various EoSS systems and the way they interoperation. In the near future the AirCon business will be expanding and relocating; hence this kind of strategic guidance may well prove very useful to the company.

It must be remembered however that a number of assumptions and simplifications were made and pointed out during the experimental design, and when creating and running the model. Therefore the actual results are not claimed to be accurate but rather they are illustrative of trends. None-the less this scenario testing has demonstrated an effective use of a new quantitative modelling capability (based on the computer execution of a complex business situation) which has been enabled via a systematic application of EMM structural and behavioural modelling decompositions and formalisms. Furthermore this research has illustrated how decision making support can be enabled at multiple levels of granularity, in a holistic manner, in respect of different ME aspects and concerns. Key to consistent modelling with needed detail and focus on specific phenomenon and problems has been the systemisation and complexity handling afforded by the modelling method.

Specific AirCon case potential uses of the modelling approach and above results include:

1) Distinctive behavioural results about profit generation can help to identify needed policy changes; and particularly in respect of pricing for different product families.

2) Via a comparison of purchase delay impacts for different product families; the AirCon business can consider whether different purchase and stocking policies are needed?

3) Via a comparison of the cost of rework impacts, the AirCon business can consider and possibly justify the use of improved design tools; e.g. a 3-D CAD investment as potentially this will overcome much of the cost of rework loops that lead to late delivery and ineffective use of assembly resources.

9.7 Reflection and conclusion

This chapter has addressed questions Q1 to Q3 stated in section 9.1. The following table (table 9.4) summarises answers to those questions obtained through research reported in this chapter.

Table 9.4 Summary of answers to the research questions posed:

Question	Answer
Q1: Can the EMM 'specify and help visualise integration requirements' of multiple EoSS systems?	Yes, in the following respects: 1) To handle complexity, the EMM provides (process, resource & work) decomposition mechanisms to characterize EoSS systems 2) To represent and understand EoSS structural configurations at multiple levels of abstraction, the EMM facilitates integration modelling 3) The EMM was observed to support qualitative reasoning about alternative EoSS requirements and solutions 4) The EMM allows the structure of EoSS cases to be distinguished; thereby possible 'to be' EoSS system configurations can be documented and communicated amongst product designers, systems engineers, managers with short medium and long term responsibilities and roles and operatives.
Q2: Can the EMM help systemised behaviour modelling of multiple EoSS systems?	Yes, in the following respects: 1) The EMM can systemise the conceptual design of 'in context' simulation models with a specific purpose and set of users. 2) EMM based structural modelling explicitly defines a common context to maintain coherence between multi-user, multi-level simulation models 3) EMM based structural modelling also facilitates coherent simulation modelling of behavioural interactions amongst business and production systems

	4) The EMM allows the behaviours and selected performance indices of EoSS cases (and specific instances of those cases) to be distinguished.
Q3: Can the EMM help quantify the relative cost behaviours of alternative product families/types?	Yes, in the following respects: 1) EMM based structural modelling also helps structure the design of simulation experiments that systematically quantify impacts of product dynamics on alternative EoSS system designs 2) The EMM allows the relative cost behaviours of EoSS cases to be quantified.

The business level simulation results shown in this thesis are centred primarily on various scenarios of testing of much simplified case 1 EoSS systems). In order to investigate the cost and benefits of this business system running under case 2 (multiple product types) and 3 (multiple product families) conditions, so as to achieve the best balance design of economies of scope and scale, a similar but extended series of experimental designs with multiple input trails can be adopted. Appendix III illustrates how this might be done. However project time constraints, and to a lesser extent plant access constraints, prevented such an extended set of experiments to be conducted as part of this PhD study. But the author intends to conduct experiments of this type in the role of research associate immediately following her thesis completion and defence. In chapter 11 it is recommended that the basic cost behaviour modelling described in this thesis chapter should be significantly extended to enable the prediction of realisable economies of scope and scale in subject MEs; and thereby should form the subject of important future research.

Chapter 10 Re-use of the Extended Modelling Methodology in other MEs

10.1 Introduction

As discussed in Chapter 7, the author's early exploratory research enabled the conception and specification of a new Extended Modelling Methodology (EMM) for designing EoSS manufacturing systems. Also in the AirCon case study discussed in Chapters 8 and 9 the EMM demonstrated significant potential to cut through high levels of complexity to help systematically and quantitatively determine suitable balance points between scale and scope economies: (1) when the ME was viewed as a holistic entity and (2) when individual ME systems were considered that form part of the whole ME entity.

The primary strengths of the EMM relative to other enterprise modelling approaches reported in the literature were realised from its embedded decomposition and modelling formalisms which at multiple levels of abstraction enable modellers to create coherent structural and behavioural models that can be built, developed and deployed in a variety of ways. In this way both qualitative and quantitative reasoning is supported at chosen levels of abstractions.

During experimentation with the EMM the author formed the view that its decomposition and modelling formalisms can be used in a variety of systematic ways (i.e. via a some defined method or set of methods) to computer execute many different aspects of interest about the architectural design of subject MEs. Importantly for example the EMM can lend systematic modelling support which:

(1) Explicitly specifies and enables qualitative reasoning about the 'architecture' of organisations, in the form of alternatively configured sets of structural models; by visually describing organised groupings of modelled process, resource and work sub-systems and

(2) At needed levels of abstraction, allows selected behaviours of those structural models to be computer exercised, and thereby quantified, when they are subjected to alternative scenarios of work input. By such means the performances and costs of alternative complex systems architectures can be predicted in advance of potentially high cost and risky investment in large scale change.

From these experimental observations it was also presumed that the EMM has very significant potential to help manufacturing industry reason about its adoption of various manufacturing paradigms (such as Lean, Agile and Postponement) prior to their costly and/or risky implementation in one or more sections of any given ME.

However it was understood that this is a presumption and that a significant body of case testing is needed before any such a claim can really be substantiated. However after completion of EMM case study work in AirCon the author conducted two further EMM application studies in two world leading aerospace companies. Essentially these further studies concerned primarily qualitative, structural modelling work in support of feasibility exercises, but some fit for purpose behaviour models were also conceived. Only one of these further cases of EMM application will be reported in this chapter.

Therefore this chapter is conceived to begin to answer the following research question:

Is the EMM reusable, i.e. can it provide the basis of a systematic way of addressing complexity issues in other significantly different manufacturing enterprises?

But the reader should note that as expected it only proved possible to develop illustrative answers to this question. The developed of supporting quantitative arguments about the enhancement in capability provided by the EMM proved well beyond the scope of this study.

10.2 Background to the study of EMM reuse

Bearing in mind the various encouraging (industry focussed and academic focussed) outcomes of EMM case study modelling in AirCon, coupled to positive outcomes during prior exploratory case modelling in the Bradgate Furniture Company and the Wood-Team Group, it was presumed that the EMM has significant potential to improve the engineering of economy of scope and scale systems in MEs operating in various industries that require semi-predictable responses to changing multi-product market conditions. However although the feasibility of using the EMM had been demonstrated it was understood that significant modelling effort is needed to apply the EMM approach in any given ME; and insufficient time was available during this study to scientifically assess modelling costs so that it was only feasible to estimate the time and costs involved in the limited number of ME's (and their problem types) tested.

Further evidence of potential significant benefits arising from EMM application were however generated by this author during subsequent modelling work conducted for two world-leading MEs operating in the Aero-space Industry sector. One of these cases will be considered further in this thesis chapter. In this new aero-space industry case, however time and plant access constraints only allowed the capture of limited work flow and resource data; but the essential correctness of the EMM structural models developed was validated by relevant engineers and managers in the organisation modelled. Confidentially constraints have also limited the model details reported in this thesis but the author's emphasis in this case was on ideas testing not on specific problem solution. The author's EMM modelling in the second aero-space company case will not be described in this thesis, as this was primarily a subject of study of a following PhD student working in the MSI Research Institute.

10.3 Reusing the EMM to support the life-cycle engineering of an aircraft assembly line

This section considers the wider applicability of the EMM (Extended Modelling Methodology) with a focus on conceptually illustrating the feasibility of problem solving in a distinctively different industry case.

10.3.1 Definition of the research problem

During the third year of the author's PhD study, as a member of a group of MSI researchers, the author carried out advisory/consultancy work for a UK based aircraft manufacturing company; which will be referred to as AMC. Due to a confidential agreement between the company and University, details of the models cannot be published. However, how and where the EMM can be applied and potential outcomes are discussed.

AMC is a major aircraft manufacturer which operates out of a number of European countries. The UK section of the company has product realising activities centred mainly on wing box assembly. AMC produces many types of aircraft wing for military purposes and for many commercial airlines around the globe. Therefore AMC realises various types of aircraft wing which are later assembled into a range of military and commercial aircraft. For confidentiality reasons these types of wing will be referred to as: O30; O32; O33; O38; O40; O44, etc. Each of these product types is built using a separate production line.

Prior to this study a new air craft design project had been launched aimed at developing a 'next generation aircraft'. This new aircraft was targeted as being competition for the Boeing 787 'Dream liner'. Wings for AMC's next generation aircraft will be referred to as O35. For AMC, O35 required a step change in the design of the product and the product realising processes, which significantly causally impacted on the design of the manufacturing/assembly systems deployed.

Key life phases in the design a new aircraft (Huckin, 2009) are illustrated in figure 10.1. This life-cycle was presented to the author and her MSI colleagues by senior project engineers in the company. The aim of this so called DNA (Develop New Aircraft) 'high level process map' is to document activities needed at each life stage; so that planning and monitoring of projects is enabled. When the authors AMC modelling work was conducted it was reported that the new O35 project was in late 'feasibility' and early 'concept' stages of DNA (DNA being a term used within AMC to mean 'Design New Aircraft' which has an implied message that some 'well structured approach to aircraft design and engineering' is needed by the company. These stages involved then ongoing activities which included: 'define manufacturing requirements'; 'design for manufacturing'; and 'conceptual validation of production line balances'.

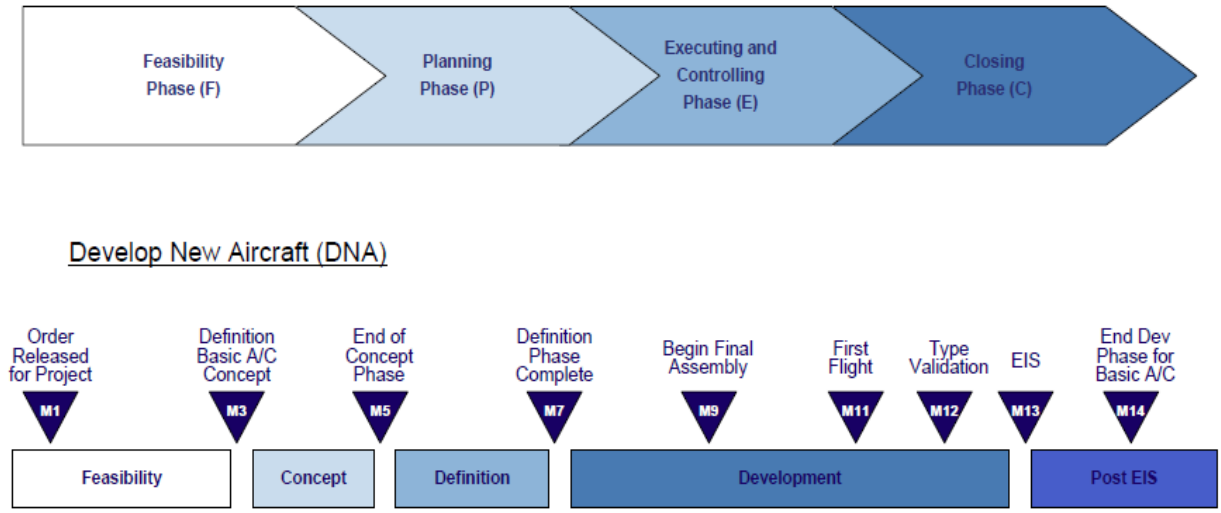


Figure 10.1 life phase of designing new aircraft (presentation from ABC)

Specific MSI project work assigned to this researcher was to use the EMM to support the balancing of the new O35 assembly line design. Furthermore an explicit focus of modelling was that of O35 'wing box' assembly. Bearing in mind this researchers EoSS reference model (see figure 7.4) the proposed and initial prototype O35 wing box assembly line was observed to be a Case 1 EoSS manufacturing system; as it was required to produce only one type of product (i.e. O35 wing boxes) in quantities and over timescales determined by

customer orders secured by the AMC company group and defined via related forecasted aircraft production plans. Therefore production volume variation (or 'rate' of production) was the key product dynamic factor for the proposed O35 line, while product variances were expected to be limited over the timescale of O35 operations. Some minor customer required variations in the design of O35 products (and design changes were expected episodically through the lifetime of O35 wing boxes) were expected but at this stage of conceptual design of the line a standard product with standard operating procedures was assumed. Therefore relevant AMC 'standard operating procedures' would need to be determined during conceptual design of the line and adhered to when AMC assembly operators, and their supporting automated systems, carry out wing box assembly operations at the workstations comprising the wing-box assembly line. Essentially therefore the wing box assembly line would only realise economies of scale in respect of O35 (i.e. there would be no opportunity to realise scope economies in the O35 wing box area of the company); and that the production rate at which the line would operate would very likely ramp up during early life stages of O35 aircraft field operations, reaching some higher (production) rate for a number of years, until later in the life-time of the O35 aircraft a ramp down was anticipated. Coping with this ramp up and down was of critical concern to AMC, as this would require some degree of flexible line operation, whilst ensuring that an adequate line balance is maintained; so that the 'values generated', relative to the production costs incurred by the line, remained acceptably high through the life-time of the O35 assembly line.

On the other hand the wider AMC business sells, designs, engineers, plans, purchases and assembles multiple wing types (for many types of aircraft) so that overall the AMC enterprise is a case 3 EoSS system which realises economies of scope and scale; and that when viewed as a whole AMC comprises a number of case 3 systems that manage and deploy multiple case 1 wing box assembly lines for O30, O31, O35, etc. This use of case 1 assembly lines is the norm in AMC but the economics (and indeed the practicability) of running separate lines as opposed to multiple product assembly lines is unknown.

Therefore when the author conducted her AMC case study work the prime focus of modelling was on balancing one case 1 (O35) wing box assembly system; but that balancing work needed to be cognisant of the bigger AMC picture and of how that bigger picture was expected to change over the time frame of the life-time of O35 aircraft with its 'semi-uncertain' customer demand patterns.

As reported from Rooks (2001) 'A wing box is made up of three major components: the ribs (up to 41); the longitudinal spars (between four and seven); and the skin panels (up to four on the top and four on the bottom), which are strengthened with rows of stringers attached by thousands of rivets and bolts.' A resultant wing box structure is as shown in figure 10.2. From the viewpoint of producing such a wing box, a key issue is the synchronisation of parts arriving during different stages of the whole assembly process. Achieving good synchronisation of arrivals is vital to the balance of the line. Hence it is also vital to consider the supply chain as a whole, when engineers consider how the operations of wing assembly systems are to be balanced and optimised. As such an assembly system is an integral part of a more holistic product realising system. As outline previously, such a holistic product realising system will in this case include related systems that 'make', 'purchase', 'plan', 'product engineer' and 'on-going plant re-engineer' wing boxes; and production systems that realise wing boxes.

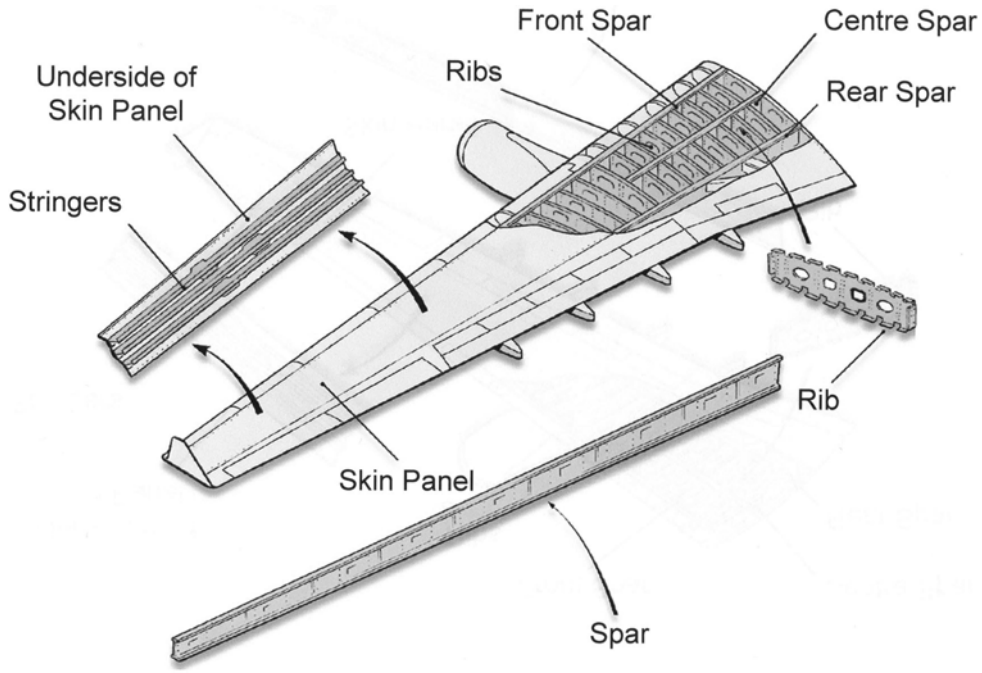


Figure 10.2 basic structure of a wing box (Brian Rooks 2001)

From the discussion above, it was observed that in the AMC case study, line balancing needs to be designed and implemented in (1) a focused way (where there is a balancing of the local wing box work flows) and (2) in an holistic way (where the entire supply chain of the production line is balanced).

This was observed to require:

1. Use of multiple levels of modelling using selected structural and behavioural modelling tools;

2. Reuse of the models during the various life phases of the O35 product and of it related production line design and build life stages.

10.3.2 Proposed use of EMM for problem solving

Therefore, the author developed a proposal to deploy the extended modelling methodology (EMM) as previously defined (in chapter 7) to support the design and dynamic balancing of the O35 production line. Previously AMC had carried out static analyses of line balances but had not developed means of dynamically balancing its make and assembly lines. As discussed previously, the area of focal concern comprised a single product case 1 EoSS system; namely an O35 wing box assembly system that needed to be designed to realise economies of scale.

Hence it was proposed that the EMM would help AMC to answer the following questions:

A) How can the O35 wing box assembly line be designed so that it delivers scale economies through its life-time?

B) How can the cost and lead time involved in manufacturing systems design and during subsequent re-design of the same or similar lines be reduced?

To answer A), the author envisaged that the EMM would facilitate the development of 'consistent' and 'fit for purpose' structural and behavioural models of the O35 wing box assembly system. Here the behaviours of the 'line design' in response to various ramp up and ramp down scenarios would to be encoded by and virtually executed by EMM simulation models that were derived systematically from an AMC EM; which it was assumed would have previously been captured so that it structurally detailed both the organisational context of the O35 line and specific standard sequences of wing box assembly activities needed at workstations to achieve wing box assembly.

Also assumed was that the AMC EM could be constructed by the author primarily from:

(ii) Previously defined process maps; that had previously been captured by AMC production line designers and visually represented by using an AMC defined (ad hoc) process mapping technique and

(ii) Information provided to the author by AMC mangers and engineers; describing primary engineering and business processing activities that impact of the operation of the wing box assembly line.

Hence to answer A) it was proposed that the EMM could systemise (I) detailed line balancing of the O35 line to reduce bottlenecks and production costs during ramp up and down) and (II) at a more abstract level of modelling to balance the holistic operation of the O35 line with its supply chain make, purchase and product testing and delivery elements. This would be achieved through a step wise use of P, R and W structural models at two levels of abstraction and by systematically creating coherent simulation models; with one set of low level SMs executing behaviours of various O35 assembly line work station configurations and the other business level set of SMs executing collective behaviours of alternative designs of the O35 assembly line and its associated supply chain entities.

Regarding B), it was anticipated that structural and behavioural models created via the EMM could be readily repositioned into the AMC EM and re-used: (a) when latter product or production system design changes need to be engineered; and (b) as 'benchmark production systems designs', when next generation aircraft requirements require a modified DNA.

Bearing in mind the overall O35 line balancing modelling requirement, from an academic standpoint it was observed that when compared to the authors EMM approach the ad hoc process mapping technique that had been used by AMC engineers (to develop 'piecemeal process maps') was inferior because:

(I) Resultant ad hoc process maps could not readily be re-coded so that they can be computer executed to facilitate behavioural modelling and quantification of line balances

(II) Resultant ad hoc and piecemeal process maps could not formally model wing box assembly operations with reference to the bigger picture of AMC network of business, engineering and product realising processes.

(III) Multiple user views of the process maps could not be developed in a systematic and coherent manner

(IV) Reasoning about multiple level of abstraction P,R and W structural configurations was not enabled, nor could it be systematically linked to dynamic behaviour modelling (such as dynamic line balancing) and therefore realistic predictive quantification of line operations.

By contrast it was envisaged that use of the EMM would help to conceptualise and quantify benefits of line balances of any (including O35) wing box assembly line through its life time. After the focused more detailed modelling of O35 wing box assembly line, it was expected that EMM enabled structural and behavioural modelling of the complete AMC supply chain would support of decision making about outsourcing, as well as informing assembly and purchase planning decisions and the control of stock holding.

10.3.3 Subsequent application of the EMM in AMC

Understanding and developing a holistic view of balancing will invariably be vital to the company's medium and long term business concerns. Indeed whether the focus is on 'localised balancing and optimisation' or 'holistic balancing and optimisation', long, medium and short term activities need to be involved to ensure that assembly systems are appropriately designed, implemented, operated and changed as requirements change during the useful lifetime of that assembly system; see figure 10.3.

To ensure that synchronism is achieved between assembly processing operations and the supply of purchased material, components and sub-assemblies, a supply chain perspective should also be considered during assembly line design (Graves and Willems 2000). Furthermore to optimise the design of any assembly system, and its supply chain, there is a need to choose a suitable manufacturing paradigm and its related types of human and resource system configuration, covering such options as: pushed and/or pulled synchronously operated process-oriented lines; Lean engineered and operated assembly systems; use of flexible and cellular manufacturing; and use of economies of scope and scale production,

with late postponement of customisation options; etc. Linked to use of these philosophical ideas should be the use of concepts such as Group Technology (GT).

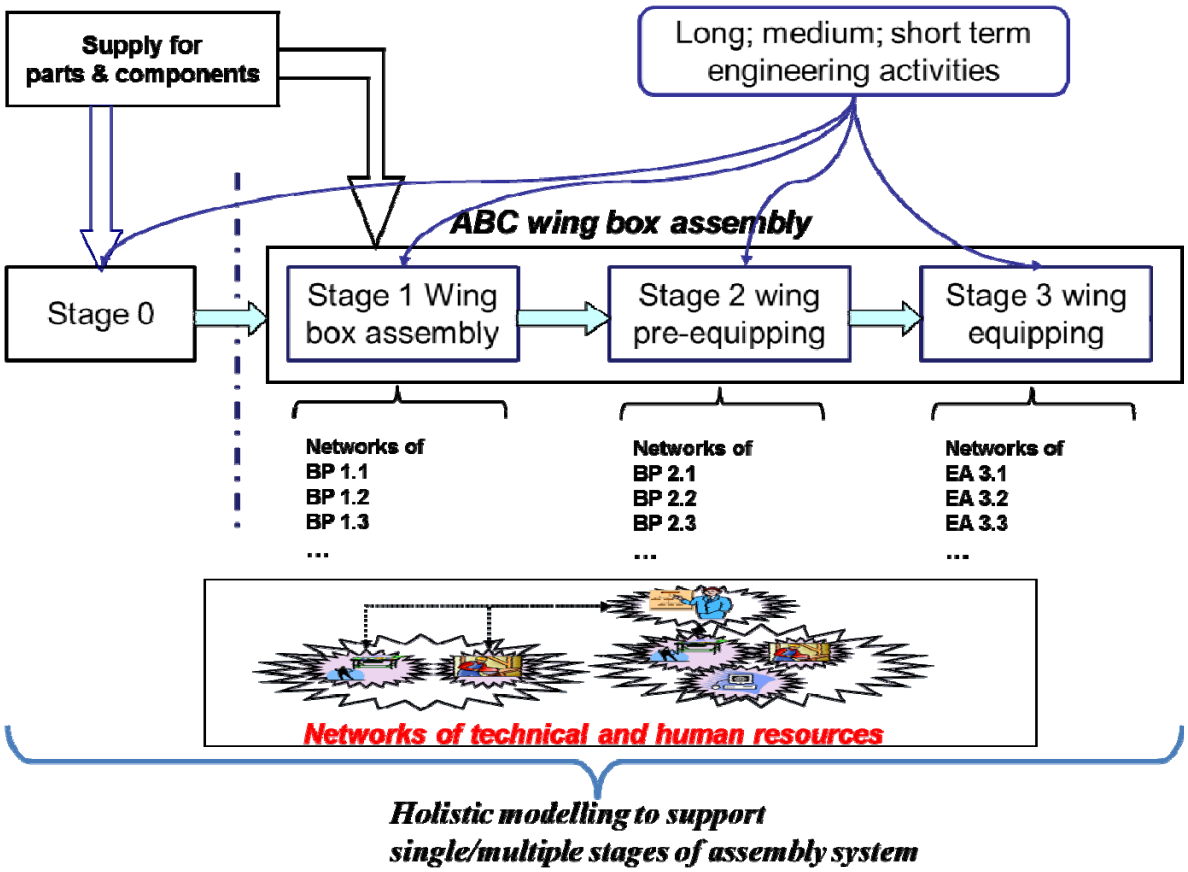


Figure 10.3 Conceptualisation of holistic modelling approach in ABC assembly

Further during the useful life-time of assembly lines, production planning and scheduling techniques will play an important role in linking customer induced variations in product types and volumes to required changes in human and resource system configurations; where these configurations will be used to realise the operations performed by 'make' and 'assembly' segments of lines (ELMaraghy, 1982). Also during the on-going operation of assembly lines, production and plant analysis can typically lead to an identification of potential process and resource system improvements.

Bearing in mind the forgoing considerations this researcher applied the EMM to the AMC wing box assembly case. To do this the following modelling steps were taken.

During the first phase of EMM application in the AMC case an enterprise model of the AMC organisation was created. This captured information gained through: analysis of ad hoc process maps produced previously by AMC engineers; question and answer discussions with various AMC managers and engineers; and from discussions with their main automation

suppliers for wing box assembly systems. The AMC EM so created formally described the network of processes realised by AMC and its suppliers; following which CIMOSA process decomposition concepts were used to detail an 'in context' model of O35 production including stages 0 to stage 3, related parts supply and the final delivery of assembled and kitted wings.

Figure 10.4 shows a conceptualisation of the EM created during the first stage of AMC modelling. This 'holistic' view of the AMC process network formally defined the working context of the O35 assembly system.

Next the author documented

(1) At a medium level of abstraction, the purchase and assembly roles; to which 'as is' role holders were assigned.

(2) At a more detailed level of abstraction, the activities, (and related standard operating procedures) performed during wing box assembly.

The models created under (1) and (2) led to the use of EMM integration diagrams which conceptualise 'as is' and possible 'to be' configurations of process- resource system couples through which various work flows could be routed. These couples were diagrammed at multiple levels of abstraction and use the author's EoSS reference model to qualitatively consider how different AMC system configurations could be organised to achieve scale and scope economies

At the next stage of (dynamic) EMM modelling the integration diagrams and model structures encoded into (1) and (2) were re-used to facilitate the conceptual design of various simulation models.

Particular attention was paid to developing fairly detailed simulation models of the wing-box assembly system, which as mention earlier was previously conceptually designed by AMC engineers to operate as a Case 1 EoSS system, such that the dynamics of the work sub system would mainly arise in the form of a volume dynamic (i.e. a ramp up and down of the production rate). Therefore the experimental and scenario testing for this previously conceived wing box design was mainly focused on changes in the P & R sub systems to achieve the best line balance. When the volumes ramp-up, the models can be reused to achieve a new line balance; similarly when the line needs to ramp down (towards the end of life of the aircraft), further re-balancing can be achieved. Alternatively it may prove appropriate towards the end of aircraft life to develop a Case 2 or Case 3 EoSS system, so that the low volume production can be achieve economically.

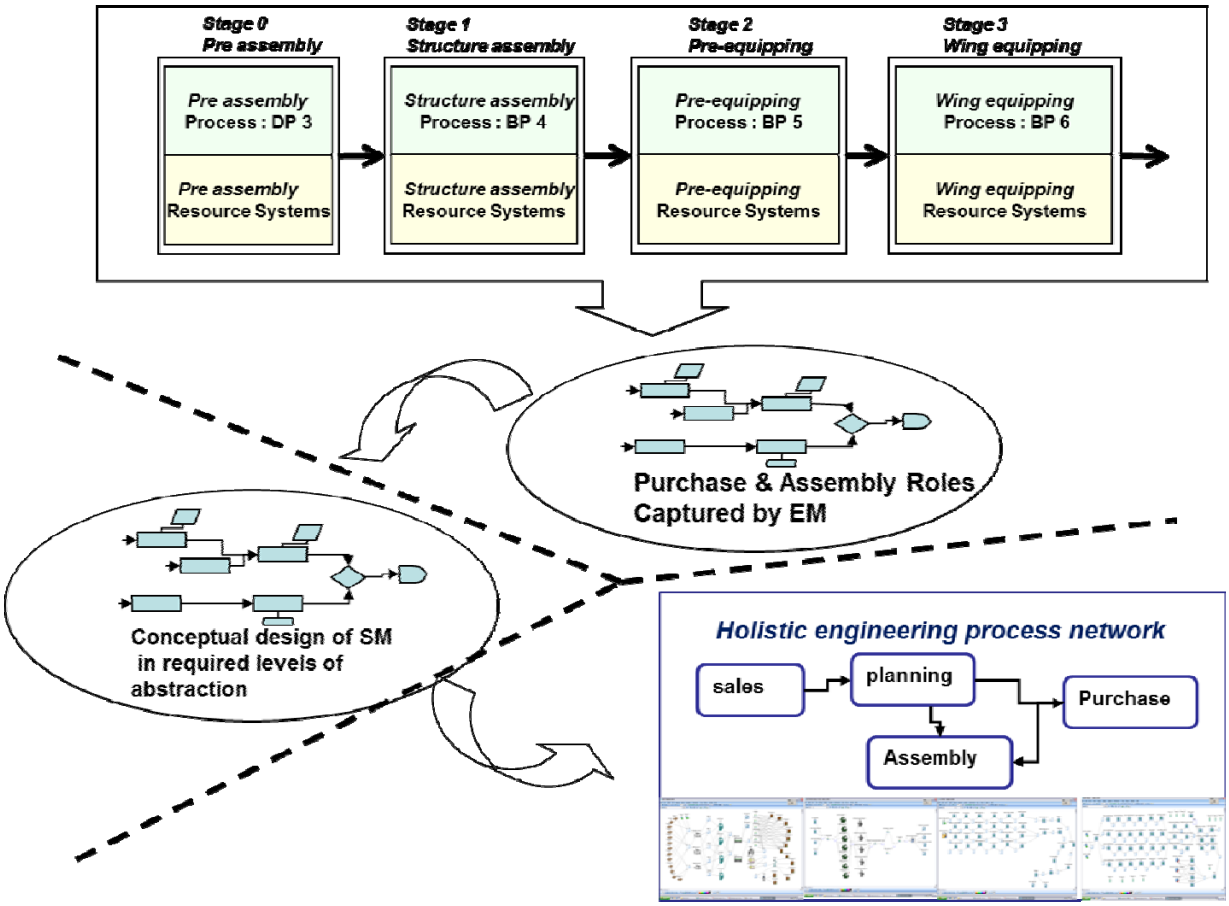


Figure 10.4 conceptualisation of integration used of multiple models

10.3.4 Potential outcomes

Following the research of the author and her MSI colleagues it was suggested that AMC should deploy enterprise and simulation (integrated DES and 3D) modelling technologies to formally conceptualise their assembly system designs. Our recommendation went on to say: when executed in virtual environments and work loaded with predicted scenarios of product dynamic, the simulated line designs and their elemental workstation designs should be holistically balanced and optimised. This would mitigate extremes of OEM costs and enormous risk associated with the purchase of automation systems. It should also facilitate commissioning, training and associated IT systems specification.

For example in the medium term it could well prove possible to utilise Enterprise, DES and 3D simulation modelling technologies to achieve the following goals:

- Integrated specification and commissioning of assembly line automation and IT systems; potential target (through sharing models with OEMs/System Vendors) to specify, design and install fit for purpose

- Optimised runtime performance of assembly lines; with synchronous assemble, make and buy operations at variable Takt times in conformance with customer & market induced dynamics;

- Rapid and effective process improvement projects will be enabled- targeted at maintaining optimise performance of assembly lines despite on-going environmental and business disturbance through the life time of assembly lines- via introducing fit for purpose flexibility and where appropriate minimising wastes;

- Developing strategic and tactical plans for advance, by enabling 'what if' and value and cost analysis on an holistic scale- such as to consider the use of alternative business models, possibly centred on alternative economy of scope and scale options to enable resource sharing and/or specialisations as aircraft programmes and sales ramp up and down- potential integrated model based planning of this ilk could give AMC a very major competitive edge.

In the longer term it was proposed that the EMM would facilitate the design of possible future mixes of case 1 and case 2 EoSS systems. Such as to achieve economies of scope when end of life wing type ramp down occurs (where for example shared wing type assembly lines operate with designed switch over policies and/or highly flexible workstations). This could prove a viable and economic choice of line design near end of aircraft life such that more than one wing type can to be produced in small and unpredictable numbers.

Also proposed was that medium to long term AMC could investigate a company wide deployment of EMM ideas to enable re-use of, 'in context', 'fit for purpose' SMs; e.g. to create SMs that re-use DNA in specific product realising areas and when conceptualising holistic line balances. This could much reduce the time and effort leading to enormous savings in terms of engineering and re-engineering costs during aircraft lifetimes.

10.4 Lessons learnt

From the prototype study of wing box assembly in AMC, it was deduced that the EMM is indeed reusable as it provided systematic and quantitative support for different life phases of assembly line engineering.

It is true however that EMM application in the AMC case was largely restricted to feasibility analysis centred mainly on structure modelling in support of qualitative reasoning. This helped greatly in presenting quite revolutionary ideas to AMC managers and engineers. In this respect this EMM proved to be of significant benefit whilst the modelling costs involved were relatively small. Furthermore significantly greater (but un proven) life-cycle engineering benefits were promised had EMM modelling been significantly extended in respect for example of detailed dynamic modelling of the O35 assembly and/or in many other areas of the AMC business; but clearly this would have also have incurred significantly (but unknown) greater modelling costs. Therefore because of these observations, and despite the caveats mentioned, it was presumed that at least to acceptable degree the re-usability of the EMM had be proven by the AMC case study; bearing in mind that the Aerospace industry (of which AMC is a part) is distinctive from the white goods industry to which AirCon belongs, primarily in terms of the nature of the product and the product dynamics impacting on the assembly systems deployed.

Some other lessons learnt from the AMC study included:

1) Structural modelling at multiple levels of granularity can usefully support qualitative analysis of complex manufacturing system designs to investigate short, medium and long term changes;

2) Modelling in context enables the reusability of system elements and models of system elements through the life time of complex manufacturing systems;

3) Multiple levels of simulation models, supporting multiple user views, can facilitate ‘fit for purpose’ engineering ;

4) ‘Executing architectural’ ideas can facilitate an effective integration of multiple models, which includes models of business, engineering and production architectures and their behaviours. In the AMC case key aspects of the integrated working of AMC

Engineering Architecture with AMC Production and AMC Purchasing Architectures was modelled. Whilst in the AirCon case major emphasis was on modelling of key aspects of the integrated working of AirCon Business Architecture with the AirCon Production Architecture.

5) Reusable models of business, engineering and production architecture are needed to underpin benchmarking for next generation manufacturing systems design

Figure 10.5 demonstrates conceptually the reuse of business, engineering and production architecture models that can support various life phases of a subject manufacturing systems.

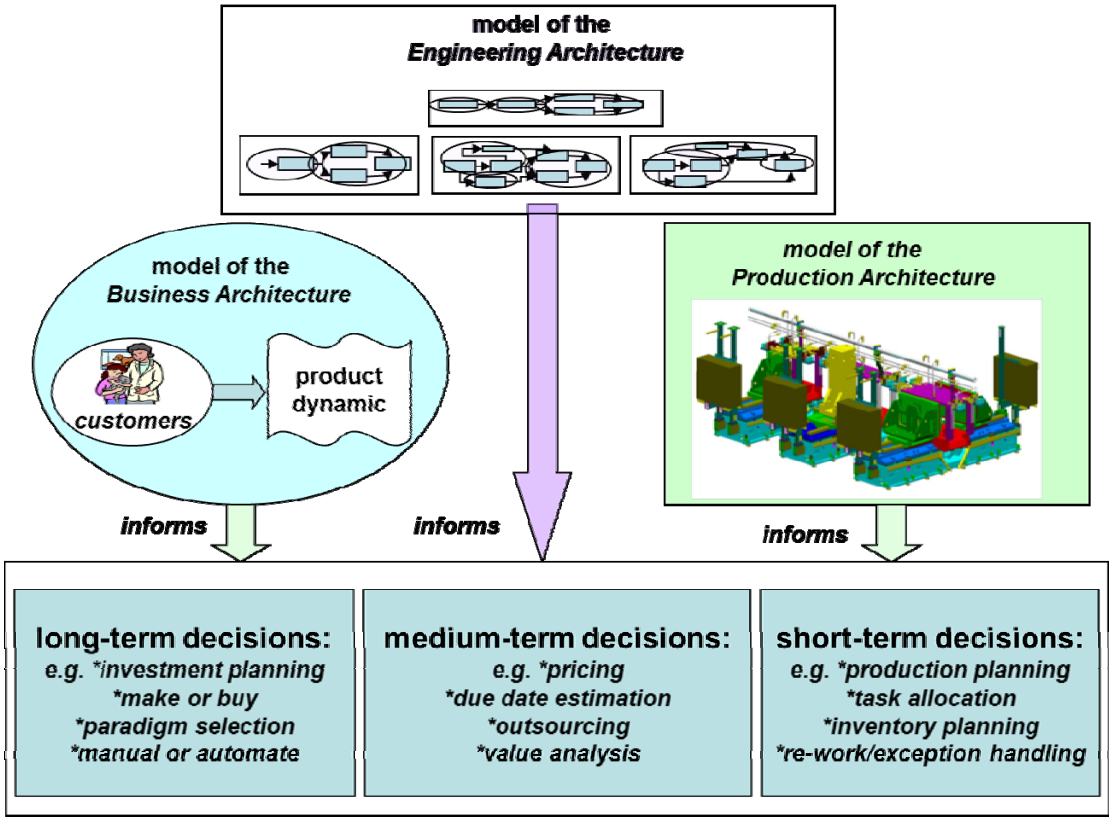


Figure 10.5 executing architecture views on support system engineering

Chapter 11 Reflections on the research outcomes and conclusions

11.1 Research summary

This research has conceived, developed and case study tested 'a new systematic model driven method of conceptually designing and virtually testing the operation of EoSS systems'. Table 11.1 summarizes the overall research achievements made by the author and reported in this thesis. The following subsections provide a background description regarding those achievements.

Table 11.2 Overall objective achievement summary

Research objectives	Work completed and achievements	New knowledge gain	Future work identified
Objective 1 ***Extended Modelling Methodology development***	- Stage 1: Early learning using then state of the art, complementary modelling technologies during the exploratory research stage: ➢ Use of enterprise modelling to capture and visualise process networks used within each subject manufacturing enterprise; ➢ Applied causal loop modelling technique to reason about underlying relationships within and between product realising systems; ➢ Adopted simulation modelling to study dynamic factors of the subject systems that form part of the ME and to determine suitable performance measures - Stage 2: Identification of gaps in the capabilities of the modelling methods and techniques used during the exploratory research, to define needed modelling methodology enhancements - Stage 3: Developments, implementation and testing of the extended modelling method during detailed case study work, which	✓ How to apply enterprise modelling concepts with specific focus on 3 sub-system viewpoints: namely 'work'; 'process' and 'resource' sub systems decompositions ✓ Improved integrated representations of structures that characterise different EoSS system configurations, in ways that facilitate coherent and qualitative reasoning about EoSS system structures ✓ New modelling concepts and steps were defined to facilitate multiple level of abstraction structure modelling of EoSS systems ✓ Modelling concepts and steps were defined to facilitate multiple level of	➢ Further resource modelling construct development is recommended ➢ Further Enterprise Architecture framework development and formalisation is required to achieve better big system decomposition and integration and to support 'Architecture Execution' in virtual environments;

	included: ➢ Multi-level product classifications and mapping product flows onto structural and behavioural models of subject systems ➢ Development of decomposition ideas and integration diagrams to systemise simulation model development and the design of variance scenario experiments in support of system optimisation and change	abstraction behaviour modelling of EoSS systems	
Objective 2 ***Economies of scale and scope theory development***	- Study of state-of-the-art theories on economies of scale and scope and their linkage to the field of manufacturing systems engineering - Developed understandings about customer driven 'Product Dynamics' and defined variance perspectives of dynamic factors - Classified different cases of EoSS system based on the defined product dynamic characteristics - Studied relationships between EoSS theory and published descriptions of manufacturing paradigms; - Product classifications developed based on process requirement differences and linked that to EoSS new EoSS Case classifications	✓ New understandings developed about classifying economies of scope and scale systems in relation to customer driven 'product dynamics'; and represented the essence of these findings in an reference model of EoSS systems ✓ Positioned other manufacturing theories in relation to the design of EoSS system; and published findings	➢ From perspectives of re-programming and re-configuring of manufacturing systems classifiy of scope economies in a way which compliments the EoSS ➢ Further development of value and cost related issues pertaining to EoSS systems design

Objective 3 ***Use of modelling methodology to model E-o-Scale and scope systems in case study MEs***	➢ Enterprise and simulation modelling techniques applied in a systematic stepwise manner at multiple levels of abstraction in respect of the 'process' and 'resource' sub-systems of subject MEs; ➢ Mapped 'work' system classes and flows into the multi-level models and systematically used simulation modelling to study and test the dynamics of the work sub-system in a manner which cut through inherent complexities ➢ Initial application of EoSS value and cost analysis via use of 'fit for purpose' simulation modelling	✓ Showed how various sets of coherent structural and behavioural models can be deployed to qualitatively and quantitatively analyse the impacts of product dynamics; and also showed how linkage can be made between economies of scope and scale phenomenon	➢ Further value and cost analysis is required to achieve best product mix decisions; and to specify the basis of a new form of decision-support tool ➢ Further value and cost ideas should be developed to identify &quantify the best balance point between economies of scale and scope in a given EoSS system and predicted product dynamic

11.1.1 Exploratory Research & Need for the EMM

The requirements of the EMM was conceived and developed during exploratory case study research; where enterprise, causal loop and discrete event simulation modelling techniques were separately deployed to conceptually design enhancements to the operation of manufacturing systems used by two collaborating MEs. One of these collaborating MEs 'makes to order' a wide variety of catalogue furniture items for home users, while the other ME 'engineers to order' commercial furniture to meet specialist customer needs. Both of these MEs make multiple product types using Case 1, 2 and 3 EoSS systems.

The exploratory research identified a need to lend model-driven support to many types of decision making made by persons fulfilling various strategic, tactical and operational roles. Those persons are typically be involved in 'conceptually designing', 'planning', 'running' and 'changing' EoSS manufacturing systems; such that they continue to fit a changing environment.

But to usefully and coherently support the range of decisions made by these different user groups the exploratory research confirmed a need to model the structures and behaviours of the various elemental process, resource and workflow sub-systems that comprise business, engineering and production systems, which themselves collectively comprise any given ME. Furthermore the sub-system entities that comprise ME systems need to be viewed in different ways and at different levels of detail dependent upon the life-cycle engineering phase involved and the types, scopes and timeframes of concern of decisions requiring support. Hence to cope with the levels of complexity involved in EoSS systems used by MEs, and in the environments in which they must operate, a need was observed to:

(1) Decompose ME systems, in a coherent fashion at various levels of abstraction, so that key architectural structures of MEs can be represented and communicated in support of collective qualitative reasoning about possible deployments of various elemental ME systems;

(2) Recompose ME system elements, in a coherent fashion at various levels of abstraction, so that alternative ME system configurations can be represented and communicated in support of collective qualitative reasoning about EoSS systems designs and interoperations; and

(3) Systematically computer exercise selection of recomposed ME system elements, in a coherent fashion at various levels of abstraction, so that their collective behaviours can

be qualitatively predicted given alternative scenarios of demand placed on ME's and their EoSS systems.

(4) Formulated a reference model of alternative ways of recomposing ME system elements such that, in a coherent fashion at various levels of abstraction, economies of scope and scale system configurations can be represented, distinguished and referenced when carrying out qualitative and quantitative reasoning about EoSS system configurations.

During the second year of the author's study the EMM was conceived to satisfy requirements (1) to (4) above. The additions to knowledge (in the research fields of Enterprise Modelling, Enterprise Integration and Enterprise Engineering) afforded via the conception and development of the EMM is discussed later in this Chapter in section 11.2.

11.1.2 Case study application of the EMM

The EMM was successfully applied in the AirCon case study ME to (1) characterise, (2) qualitatively reason about and (3) quantitatively analyse benefits arising from and cost of deploying Economies of Scope and Scale manufacturing systems. The modelling approach devised provides a systematic modelling framework and a modelling methodology for understanding and quantifying key impacts of product dynamics on EoSS manufacturing systems.

Table 11.2 describes keys aspects of the case studies carried out and the research outcomes.

Table 11.2 Summary of modelling in case studies (PV: Product Variance; VD: Volume Dynamic; PM: Product Mix

Case Study Identifier	***Case 1*** **Exploratory BGF : home furniture production**	***Case 2*** **Exploratory WT: commercial furniture production**	***Case 3*** **AirCon Prime Case: air conditioner product assembly**	***Case 4*** **AirCon Prime Case: business system modelling**	***Case 5*** **AMC Illustrative Case: aircraft wing box assembly**
Method of Data Collection Used & Source of Data Collected Reporting to the Companies Concerned	Data collected mainly by previous MSI researchers Under went training on home furniture assembly Relatively simple models created and validated Product classification study completed	Interviews and data collection from many company managers Models created and verified Product classification study completed Initial recommended uses of the models presented to company employee	Interviews and data collection from many company mangers & engineers Models created and verified Product classification study completed Recommended uses of the models; recommended policy changes presented to company employees	Interviews and data collection from many company managers Models created and verified Product classification study completed Recommendations for improved integration between sections made to the company	Interviews and data collection from company mangers Models created and verified Product classification study completed Report on adopting modelling methodology for improved line balancing made to company
Nature of Product Dynamic in the ME's Environment	PV – Low to medium VD – Low to medium PM – Low to medium	PV – High VD – Low to Medium PM – High	PV – High VD – Medium to high PM – High	PV – Medium to high VD – Medium to high PM – High	PV – Zero VD – Low to medium PM – Zero
Case Study Identifier	***Case 1*** **Exploratory BGF furniture**	***Case 2*** **Exploratory WT furniture**	***Case 3*** **AirCon assembly system**	***Case 4*** **AirCon business system**	***Case 5*** **AMC airplane wing box assembly line**

EoSS System Types Studied	Case 2 Economies of Scope & Scale system (E-o-Scope)	Case 2 E-o-Scope & Scale (machine systems) Case 3 E-o-Scope (assembly systems)	Case 1 E-o-Scale (heat exchanger make system) Case 2 E-o-Scope & Scale (metal sheet make system) Case 3 E-o-Scope & Scale (assembly system)	Case 3 E-o-Scope & Scale (whole product realisation)	Case 1 E-o-Scale (Airplane wing box assembly system)
Models created	EM of the organisation CLM of the primary interactions between and within sections of the company SM of the assembly section	EM of the complete enterprise, which includes 5 companies in the group Production system (make &assembly shops) SMs	EM of the complete organisation detailed in the assembly area CLM to identify primary bottlenecks SM of assembly shop	EM of the complete organisation with detail regarding sectional interactions Multi-level SM of the entire product realisation system	EM of the organisation SM of the Wing box assembly line, and its supply chain interactions
Case studies	***Case 1*** **Exploratory BGF furniture**	***Case 2*** **Exploratory WT furniture**	***Case 3*** **AirCon assembly system**	***Case 4*** **AirCon business system**	***Case 5*** **AMC airplane wing box assembly line**
Potential model users	high & middle level managers; production planners	high & middle level managers; project managers; shop managers	high & middle level managers; production engineers; sales/business staff; purchase planners; production planners; shop managers	company strategists; high & middle level managers; production & purchase planners	high & middle level managers; production engineers; line developers ;

Research findings	Enterprise modelling (EM) and Simulation modelling (SM) have their specific strengths and weaknesses, to cope with complexity & quantify behaviours of a subject ME; an integrated used of these technologies is required.	Different processing-oriented product classifications are required to characterise & simplify workflow modelling in different organisational units; To facilitate change Work, Process and Resource sub-systems should be modelled separately.	A multi-level study of product dynamic impacts is critical for strategic, production and purchase planning; and for pricing and due date estimation, especially in engineer to order MEs Fit for purpose behaviour modelling is needed to realise scope economies	Multi-level modelling is essential to achieve 'architecture execution' & big system engineering and integration; Fit for purpose SMs with costing analysis can usefully support best product mix decisions hence quantify balances pertaining to E-o-Scale & E-o-Scope	Localised optimisation in line balancing is in-sophisticated, fit for purpose use of multi modelling can support holistic production line balancing

11.2 Novelty of the research

Incorporated into the EMM were three complementary forms of knowledge contribution that are summarised in the following.

1) A new systematic approach to decomposing and representing EoSS manufacturing systems was proposed and instrumented. The approach devised is based on general systems engineering principles which facilitate complexity handling by separating the capture and representation of 'systems requirements' from 'systems solution conception' and from 'work flow classification and behavioural characterisation'; then subsequently visually integrating these viewpoints into a holistic system description onto which model parameters and data can be systematically attached. To facilitate such a systematic process in respect of ME systems engineering, in this research the author conceived and developed an innovative use of state of the art modelling concepts and techniques that:

(a) *Implement decomposition and representational ideas related to 'separated models' of 'process', 'resource' and 'work' sub-systems*; where: process network models are used to explicitly capture and represent ME requirements; resource models are used to explicitly represent candidate resource system configurations; and work models are used to explicitly describe the nature of time varying work and work flows that an ME must process in any given timeframe.

And subsequently

(b) *Provide graphical means of representing 'integrated re-configurations' of 'process', 'resource' and 'work' sub-systems, at multiple and coherent (explicitly connected) abstraction levels*; so that new or old ME system designs can be conceptualise in qualitative terms then computer exercised in response to current and possible future scenarios of business needs.

2) Ways of characterising and thinking about customer related dynamics were conceptually linked to common ways of structuring the behaviours of manufacturing systems. This resulted in:

a. A new classification of EoSS manufacturing systems; which visually characterises prime structures of three EoSS system classes; these EoSS classes can serve as alternative reference configurations of process', 'resource' and 'work' sub-systems

b. Developed new thinking about product classifications with reference to differences in their product realising needs; which complements various previously published methods of product classification. Those classifications were found to be necessary to facilitate appropriate modelling simplifications in support of the multi-level of abstraction modelling of EoSS systems

c. A step-wise method of virtually experimenting with DES simulations of EoSS systems. This used illustrative value and cost analyse to support the design of a best balance of economies of scope and scale. It also used both qualitative and quantitative reasoning support capabilities of the EMM so that the complex behaviours of different EoSS system Cases and scenarios of partially uncertain customer demand can be systematically modelled

3) The Extended Modelling Methodology (EMM) was conceived, which systemises an application of the new knowledge generated under 1) and 2) in ways that facilitate the conceptual design and virtual testing of EoSS manufacturing systems.

Figure 11.1 has been constructed to position the state of the art in public domain Enterprise Frameworks prior to the initiation of this research study. Here the use of the ***ANSI/IEEE STD 1471-2000*** definition of 'Enterprise Framework' is referenced, which states that: An ***architecture framework*** is a foundational structure, or set of structures, which can be used for developing a broad range of different architectures; It should describe a ***method for designing a target state;*** It should contain ***a set of tools and provide a common vocabulary; It should also include a list of recommended standards and compliant products*** that can be used to ***implement the building blocks.*** With reference to this ANSI definition**,** Figure 11.1 compares three principle public domain architecture, namely CIMOSA (which as chosen in this research to model complex system requirements as a network of processes), Zachman

(1987) which has been widely used to structure complex IT systems engineering and TOGAF which is also centres on complex IT systems engineering and has been the subject of very significant development within the standards communities in the USA. In this study there has been a greater emphasis on business analysis as a front end to the design of MEs and their constituent EoSS manufacturing systems; hence the starting point architecture (in this case CIMOSA) needed to have a relatively strong common vocabulary and framework for MEs.

	CIMOSA provision	***Zachman provision***	***TOGAF provision***
general requirement	***contrast & comparison of main strengths & weaknesses***		
architecture framework	***strong for MEs***	***very strong & broad***	***relatively weak & IT focussed***
method	***relatively weak but literature reports good ME engineering***	***none provided***	***relatively strong but IT focussed***
common vocabulary	***very strong but limited coverage***	***none provided***	***piecemeal modelling concepts***
set of tools	***limited availability of CIMOSA specific tools***	***piecemeal tool use recommended***	***piecemeal use of tools recommended***
recommended standards	***limited***	***not provided***	***piecemeal use of standards recommended***

Figure 11.1 Overview Comparisons of Prime Public Domain Enterprise Architectures at the Outset of this Research

Relatively to this starting position, and relative to other research conducted in academia, during the development of the EMM significant advance was made in the following respects:

(1) A new ***Method*** of systematically designing EoSS systems at multiple – levels of abstraction was specified, case tested and further developed

(2) A significantly extended vocabulary for complex ME systems modelling was conceived, case tested and further developed

11.3 Criticism of the research

Significant potential benefit was demonstrated for collaborating MEs through case study applications of the EMM, where its systemisation of modelling functions was proven to be extensively useful for enterprise decision makers. However limitations of this research were observed as follows:

1) Time did not permit a further development of the modelling method so that it can explicitly describe the extent to which systems re-configuration and/or re-programming of a subject manufacturing system is needed to facilitate the economies of scope and scale required by a given ME and its customer driven environment. This was considered to be outside the scope of the present research as it primarily concerns 'implementation aspects' of systems engineering; whereas the remainder of this study has concerned 'requirements capture', 'conceptual design' and 'model execution' aspects of systems engineering.

2) In its current state of development and application the EMM has involved the use of fairly simple resource modelling constructs and resource modelling decompositions. This was because the case study applications did not require explicit and detailed descriptions of resource systems; such as a precursor to making qualitative and quantitative choices between alternative configurations of (modelled and actual) candidate human and machine resources; e, g, during detailed design and implementation of manufacturing systems. However during her study the author, along with other MSI researchers, contributed and published conceptual ideas about the modelling of re-usable manufacturing system components (so called 'dynamic producer units') at various levels of abstraction (Weston et al, 2009)

3) Case study applications of the EMM in its current form will be limited by the choice of discrete event simulation modelling technology; and further by the specific choice of the proprietary DES tool Simul8. Therefore the types of models of systems and system elements that could be computer exercised were limited by these choices. The choice of DES technology was proven to be appropriate for the case study manufacturing system types, entities and KPIs, but Simul8 was observed to place certain modelling constraints on the authors

study e.g. when seeking to quantify the cost of tardiness, the cost of non-value activities, and various human system behaviours.

4) The costing analysis conducted as part of the AirCon case study was carried out in an exploratory way, with a view to illustrating how economic aspects of EoSS systems can be quantified and compared. However more comprehensive experimental designs and plant data collection activities will likely be required to provide a general purpose EoSS cost and value modelling approach which can usefully be applied in many different ME types.

11.4 Future work

The agenda set for the present research reported was ambitious. The modelling ideas and methods devised, and their case study testing has sought to significantly advance (1) the design EoSS systems and (2) to provide a basis for quantifying the benefits and costs of alternative EoSS manufacturing systems when they are deployed in distinctive forms of enterprise and environmental setting.

A secondary and related intention of this study has been to gain better understandings about inherent tensions between manufacturing 'agility' and 'costs'. Key to this secondary intention has been to seek ways characterising and comparing alternative ME designs by computer executing essential DNA of common manufacturing theories currently adopted by industry at large. The aim of so doing has been to reduce the risk of inappropriate investments and poor ME performances should in-appropriate manufacturing paradigms be selected and/or deployed in ad hoc and piecemeal ways. This was because prior to this study no formal basis was available to assess the efficacy of paradigms prior to their actual implementation. Although only limited progress has been made by the author towards realising model driven paradigm selection the work completed has been shown to have significant potential. For example during the last year of her study this researcher has authored (or co-authored) and presented four conference papers describing her ideas under the banner '***architecture execution***', Also many of these ideas have been reported in an invited refereed journal paper for a special issue of the International Journal of Enterprise Transformation (Weston and Cui, 2010)

Therefore it is recommended that future research should:

1) Realise further Enterprise Architecture development to achieve enhanced big system structural decomposition and integration modelling; centred for example on the use of 'Role', 'Dynamic Producer Unit' and 'Competency' modelling concepts.

2) Consider how the EMM can be further developed to support Enterprise Architecture Execution; such as by providing means of using the EMM to create specific case ontology that facilitate simulation model interoperability. This should begin to address key limitations of current industry practice where piecemeal simulation models are developed and used which have limited re-usability.

3) Further develop the ideas on EoSS system value and cost modelling reported in this thesis to provide decision support tools. These tools could for example: facilitate best product mix decisions; and quantify the best balance of economies of scale and scope when designing ME systems.

4) Seek ways of developing and using the EMM to facilitate model driven paradigm selection.

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Appendixes

Appendix I: WT full enterprise model

Appendix II: AirCon full enterprise model

Appendix III: additional simulation results of AirCon business model