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Enhanced Integrated Modelling Approach to Reconfiguring Manufacturing Enterprises

By

Tariq Masood

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Submitted in partial fulfilment of the
Requirements for the award of

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Dedicated To My Parents

For all their love, care,

Hard work and patience!!!

Especially dedicated to

My Father who passed away

During this research!!!

May Allah forgive him

With best rewards in the life

Hereafter and grant him the

Highest place in Jannat ul

Firdous (Heavens)!!!

Ameen!!!

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[2] Manufacturing System Integration Research Institute at Loughborough University, UK

[3] UK Centre of Excellence in Customised Assembly at Loughborough University, UK

[4] Higher Education Innovation Fund, UK

[5] Engineering and Physical Sciences Research Council, UK

[6] Ford Motor Company, UK

[7] Bradgate Furniture Manufacturing Company, UK

[8] ACM Bearings Company, UK

[9] Unified Modelling of Complex Enterprise Systems (with industrial collaborations from: BAE Systems, Ford, ACM, Fujitsu, Siemens and McKinsey&Company)

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Abstract

Dynamism and uncertainty are real challenges for present day manufacturing enterprises (MEs). Reasons include: an increasing demand for customization, reduced time to market, shortened product life cycles and globalisation. MEs can reduce competitive pressure by becoming reconfigurable and change-capable. However, modern manufacturing philosophies, including agile and lean, must complement the application of reconfigurable manufacturing paradigms. Choosing and applying the best philosophies and techniques is very difficult as most MEs deploy complex and unique configurations of processes and resource systems, and seek economies of scope and scale in respect of changing and distinctive product flows. It follows that systematic methods of achieving model driven reconfiguration and interoperation of component based manufacturing systems are required to design, engineer and change future MEs.

This thesis, titled *"Enhanced Integrated Modelling Approach to Reconfiguring Manufacturing Enterprises"*, introduces the development and prototyping a model-driven environment for the design, engineering, optimization and control of the reconfiguration of MEs with an embedded capability to handle various types of change. The thesis describes a novel systematic approach, namely *enhanced integrated modelling approach (EIMA),* in which coherent sets of integrated models are created that facilitates the engineering of MEs especially their production planning and control (PPC) systems. The developed environment supports the engineering of common types of strategic, tactical and operational processes found in many MEs. The EIMA is centred on the ISO standardised CIMOSA process modelling approach. Early study led to the development of simulation models during which various CIMOSA shortcomings were observed, especially in its support for aspects of ME dynamism. A need was raised to structure and create semantically enriched models hence forming an enhanced integrated modelling environment.

The thesis also presents three industrial case examples: (1) *Ford* Motor Company; (2) *Bradgate* Furniture Manufacturing Company; and (3) *ACM* Bearings Company. In order to understand the system prior to realisation of any PPC strategy, multiple process segments of any target organisation need to be modelled. Coherent multi-perspective case study models are presented that have facilitated process reengineering and associated resource system configuration. Such models have a capability to enable PPC decision making processes in support of the reconfiguration of MEs. During these case studies, capabilities of a number of software tools were exploited such as *Arena®, Simul8®, Plant Simulation®, MS Visio®,* and *MS Excel®.* Case study results demonstrated effectiveness of the concepts related to the EIMA.

The research has resulted in new contributions to knowledge in terms of new understandings, concepts and methods in following ways: (1) a structured model driven integrated approach to the design, optimisation and control of future reconfiguration of MEs. The EIMA is an enriched and generic process modelling approach with capability to represent both static and dynamic aspects of an ME; and (2) example application cases showing benefits in terms of reduction in lead time, cost and resource load and in terms of improved responsiveness of processes and resource systems with a special focus on PPC; (3) identification and industrial application of a new key performance indicator (KPI) known as P^3C the measuring and monitoring of which can aid in enhancing reconfigurability and responsiveness of MEs; and (4) an enriched modelling concept framework (E-MUNE) to capture requirements of static and dynamic aspects of MEs where the conceptual framework has the capability to be extended and modified according to the requirements.

The thesis outlines key areas outlining a need for future research into integrated modelling approaches, interoperation and updating mechanisms of partial models in support of the reconfiguration of MEs.

Keywords: Manufacturing enterprises, Reconfiguration, responsive manufacturing, organisation design and change, CIMOSA, enterprise modelling, causal loop modelling, simulation modelling, integrated modelling, production planning and control, business process.

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List of Abbreviations

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).

ACM: ACM Bearings Company, UK

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

Arena®: A proprietary discrete event simulation software by 'Rockwell Automation'

ARIS: 'ARchitecture of Integrated Information Systems'

AS-IS: Present situation

ASME: 'American Society of Mechanical Engineers'

ATO: 'Assemble To Order'

BOM: 'Bill Of Material'

BP: 'Business Process' - as defined in CIMOSA

Bradgate: Bradgate Furniture Manufacturing Company, UK

CAD: 'Computer Aided Design'

CAM: 'Computer Aided Manufacturing'

CAPP: 'Computer Aided Process Planning'

CECA: 'UK Centre of Excellence in Customised Assembly' at Loughborough University, UK

CEO: 'Chief Executive Officer' of a company or business

CIM: 'Computer Integrated Manufacturing'

CIM-BIOSYS: 'CIM Building Integrated Open SYStems'

CIMOSA: 'Computer Integrated Manufacturing Open System Architecture'

CLM: 'Causal Loop Modelling' – a stage in EIMA to reconfiguring MEs proposed and case tested in this thesis

CM: 'Cellular Manufacturing'

CNC: 'Computer Numerically Controlled'

CO: 'Customer Order'

CODP: 'Customer Order Decoupling Point'

ConWIP: 'Constant Work In Process'

DD: 'Due Date'

DM: 'Domain'

DP: 'Domain Process' - as defined in CIMOSA

EA: 'Enterprise Activity' - as defined in CIMOSA

EDC: 'Enhanced Data Capturing' – as used in MUNE presented in this thesis

EE: 'Enterprise Engineering'

EI: 'Enterprise Integration'

EIMA: 'Enhanced Integrated Modelling Approach' – an enhanced structured modelling approach to the reconfiguration of MEs as proposed and case tested in this thesis

EM: ‘Enterprise Modelling’ – used as general term as well as a stage in IMA/EIMA to reconfiguring MEs proposed and case tested in this thesis

EMI: ‘Enterprise Modelling and Integration’

E-MPM: ‘Enhanced Multi Process Modelling’ proposed by (Chatha 2004)

E-MUNE: ‘Enhanced MSI UNified Environment’ - proposed in this thesis

ERP: ‘Enterprise Resource Planning’

ESPRIT: ‘European Strategic Program on Research in Information Technology’ which was an European Union initiative managed by the Directorate General for Industry (DG III) of the European Commission. Five ESPRIT programmes ran consecutively from 1983 to 1998.

ETO: ‘Engineer To Order’

FCFS: ‘First Come First Served’

FIFO: ‘First In First Out’

FE: ‘Functional Entity’ - as defined in CIMOSA

FMS: ‘Flexible Manufacturing System’

FO: ‘Functional Operator’ - as defined in CIMOSA

Ford: Ford Motor Company, UK

FUSION: A proprietary MRP software procured (but not implemented) by ACM Bearings Ltd.

GERAM: ‘Generalized Enterprise Reference Architecture and Methodology’

GLOBE: ‘GLObal approach to Business re-Engineering’

GRAI-GIM: ‘GRAI Integrated Methodology’ for designing CIM systems

HPP: ‘Hierarchical Production Planning’

I*PROMS: Network of Excellence on ‘Innovative Production Machines and Systems’ that comprises 30 core member institutions representing 14 European countries.

IBIS: ‘Integrated Business Information Systems’

ID: ‘Internal Diameter’

IDEF: ‘Integration DEFinition’ - a family of modelling languages in the field of systems and software engineering released by National Institute of Standards and Technology, USA (Knowledge Based Systems Inc 2009b).

IDEF0: ‘IDEF for function modelling’ - a function modelling standard

IDEF1X: ‘IDEF for information modelling’ - a data modelling language for development of semantic data models

IDEF3: ‘IDEF for process description capture method’ - a business process modelling method complementary to IDEF0

IEEE: ‘Institution of Electrical and Electronics Engineers’

IEM: ‘Integrated Enterprise Modelling’ method used for process reengineering

IET: ‘Institution of Engineering and Technology’

IFAC: ‘International Federation of Automatic Control’

IFIP: ‘International Federation for Information Processing’

IIMB: ‘Integration In Manufacturing and Beyond’

IIS: ‘Integrating Infra Structure’

IMA: ‘Integrated Modelling Approach’ – a structured modelling approach to the reconfiguration of MEs as proposed and case tested in this thesis

IMechE: ‘Institution of Mechanical Engineers’

INTEROP-NoE: ‘INTEROPerability research Network of Excellence for Networked Enterprises application and software’

ISO: ‘International Standards Organisation’

ISO14258: International standard titled “Industrial Automation Systems - Concepts and Rules for Enterprise Models” (ISO14258 1998).

IT: ‘Information Technology’

iThink®: A proprietary dynamic simulation software by ‘isee systems’

JIT: ‘Just In Time’ a ‘pull’ based PPC strategy

Kanban: A PPC strategy based on ‘pull’ signals which is used as PO in one of the future ACM model reconfigurations in this thesis

KPI: ‘Key Performance Indicator’

L: ‘Length’

LT: ‘Lead Time’

LU: ‘Loughborough University’, Loughborough, UK

ME: ‘Manufacturing Enterprise’

MRP: ‘Material Requirement Planning’

MS Excel®: Microsoft Office Excel - a spreadsheet application software written and distributed by Microsoft for Microsoft Windows.

M Shop: ‘Machine Shop’ of ACM Bearings Ltd.

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

MSPO: ‘Machine Shop Production Order’ – used in Bradgate Furniture Ltd.

MST: ‘Minimum Setup Time’

MS Visio®: ‘Microsoft Office Visio’ - a diagramming application software that uses vector graphics written and distributed by Microsoft for Microsoft Windows.

MTO: ‘Make To Order’

MTS: ‘Make To Stock’

MUNE: ‘MSI UNified Environment’

NIST: ‘National Institute of Standards and Technology’, USA

NML: ‘New Model Launch’ department of Ford Motor Company

OD: ‘Outer Diameter’

OOA/OMT: ‘Object Oriented Analysis/Object-Modelling Technique’

OPAL: ‘OPtimized Applicative Language’ - a functional programming language

Op Shop: ‘Operations Shop’ of ACM Bearings Ltd. that comprises M Shop and SS Shop

PCE: ‘Product Cost Estimation’ department of Ford Motor Company

PD Factory: PD Factory of Ford Motor Company, UK

PD: ‘Product Dynamic’

PERA: ‘Purdue Enterprise Reference Architecture’

P^{3}C: ‘Percent of Production Plan Complete’ – ‘a state of completeness of a production plan in percentage form at a given instance’ e.g., percentage of completed POs at a planned due date to the total POs issued.

PfM: ‘Performance Metrics’ - used in MUNE/E-MUNE

Plant Simulation®: A proprietary discrete event simulation software by ‘Siemens PLM Software’

PM: ‘Performance Metrics’ - used in MUNE/E-MUNE

PN: ‘Petri Net’

PO: ‘Production Order’ – ‘concern’ in Ford case, ‘sales order picking list’ in Bradgate case, ‘job card’ in ACM case

POLCA: ‘Paired cell Overlapping Loops of Cards with Authorization’

PPC: ‘Production Planning and Control’

PPCS: ‘PPC System’

PPMix: ‘Production Policy Mix’ - used in MUNE/E-MUNE

PPM: ‘Pre Production Management’ department of Ford Motor Company

Pr: ‘Process’

Pr-Re: ‘Process-Resource’ couple

PROMOTER-2: ‘PROcess MOdelling TEchnique Research-2’ project

Pull: A PPC strategy based on sending ‘pull’ signals to initiate production

Push: A PPC strategy based upon ‘push’

QOP: ‘Quote-One-Pager’ – used in Ford Motor Company

QRM: ‘Quick Response Manufacturing’

RBC: ‘Repeat Business Customizers’

Re: ‘Resource’

RFID: Radio Frequency IDentification

RME: Reconfigurable Manufacturing Enterprise

RM Shop: ‘Raw Material Shop’ of ACM Bearings Ltd.

RT: Release Time

SADT: ‘Structural Analysis and Design Technique’

SEE: ‘Society for Enterprise Engineers’

Simul8®: A proprietary discrete event simulation software by ‘Simul8 Corporation’

SM: ‘Simulation Modelling’ – a stage in IMA/EIMA to the reconfiguration of MEs proposed and case tested in this thesis

SME: ‘Small and Medium Enterprise’

SS: ‘Solution Space’ - used in MUNE/E-MUNE

SS Shop: ‘Saw and Sanding Shop’ of ACM Bearings Ltd.

T: ‘Thickness’

TO-BE: Future prediction

TOC: ‘Theory Of Constraints’

TT: ‘Throughput Time’

UEML: ‘Unified Enterprise Modelling Language’

UML: ‘Unified Modelling Language’

VMC: ‘Versatile Manufacturing Companies’

VVA: ‘Verification, Validation and Accreditation’ – a stage in EIMA to the reconfiguration of MEs proposed and case tested in this thesis

W: ‘Width’

WD: ‘Work Dynamic’

WERS: ‘World Engineering Release System’ – an engineering release system used at Ford Motor Company

WfM: ‘Work flow modelling’ – a stage in future extension of EIMA to reconfiguring MEs (EIMA-2) presented in this thesis

WfMC: ‘Workflow Management Coalition’

WIMS: Wireless Integrated Manufacturing System

WIP: ‘Work In Process’

WLC: ‘Work Load Control’

List of Definitions

Agile Enterprise: An agile enterprise is defined by many as one that is easily reconfigurable, innovative, and able to respond quickly to changing customer and market requirements (Cheng et al. 1998; Gunasekaran 1998; Kidd 1994; Kusiak et al. 1998; Monker 1994).

Customer Order Decoupling Point (CODP): It is normally defined as the point in the flow of goods where forecast driven production and customer order driven production are separated (Wikner; et al. 2005). It is sometimes also referred to as the order penetration point (OPP) which defines the stage in the manufacturing value chain, where a particular product is linked to a specific customer order (Wikner; et al. 2005).

Enterprise Model: "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).

Enterprise: "A group of organisations sharing a set of goals and objectives to offer products and services" (ISO14258 1998). Enterprises are systems that can be analysed and modelled using systems theory (ISO14258 1998).

Gross Domestic Product (GDP): Gross Domestic Product (GDP) is used as an indicator of economic progress that measures the value of final goods and services produced in a given period of time (Gutierrez et al. 2007).

Industrial Collaborators: The industrial partners who collaborated with Loughborough University (MSI Research Institute and CECA) for the purpose of the research reported in this thesis. Ford Motor Company, Bradgate Furniture Ltd and ACM Bearings Ltd are reported as main industrial collaborators in this thesis.

Manufacturing Enterprise: An enterprise doing business in manufacturing field.

Model: "A simplified description of a system or process, to assist calculations and predictions" (Oxford English Dictionary 2009). Any type of model, whether it is mathematical, graphical, or physical, provides an abstraction of reality for the purposes of creating a comprehendible and consensual depiction of a given real world scenario.

Pull: This production system makes use of information about customer orders (and forecasts) which is processed to the finished goods inventory or to the last production stage. If demand can not be satisfied directly, this stage will order and withdraw parts from the buffer storage of the preceding stage and so on, hence providing a serial ordering system of successive production orders and transportation orders.

Push: A traditional production management system in which information regarding demand forecasts or customer orders for end products are released at first stage and then the order is processed (pushed) through all stages in the production system (Olhager et al. 1990).

Reconfigurable Manufacturing Enterprise (RME): Reconfigurable manufacturing enterprise (RME) works on sharing principles of lean, mass, flexible and reconfigurable paradigms and will be able to rapidly and cost-effectively change according to the market requirements. During this research wherever the term 'RME' is used, this stands for virtually reconfigurable enterprise and does not involve machine or plant level reconfiguration unless it is stated otherwise.

Reconfigurable System: "Reconfigurable system is defined as a system that is change-capable" (Weston 1999) the aim of which is to enhance responsiveness to market changes by rapidly and cost-effectively adjusting production capacity and functionality (Koren et al. 1999; Mehrabi et al. 2000). During this research wherever the term 'reconfigurable system' is used, this stands for virtually reconfigurable system and does not involve machine or plant level reconfiguration unless it is stated otherwise.

Scenario: "A scenario is a generally intelligible description of a possible situation in the future, based on a complex network of influence factors" (Gausemeier et al. 2006).

Small and Medium Enterprise (SME): Micro, Small and Medium-sized Enterprises (SMEs), according to the revised definition, are made up of enterprises which employ fewer than 250 persons and which have an annual turnover not exceeding 50 million Euros, and/or an annual balance sheet total not exceeding 43 million Euros (European Commission 2003; European Commission 2005).

Chapter 1

Introduction

1.1 Motivation and introduction

Globalisation, shorter product life cycles and international business competition has triggered significant changes and posed greater challenges to manufacturing enterprises (MEs). This has given rise to a need for faster, better and cheaper production. Quick and timely responses to change is vital to the long term existence of many MEs (ElMaraghy 2009; Mehrabi et al. 2000; Weston et al. 2009).

Present day MEs cannot be sustainable if they concentrate only on their current set of products and services. Due to shortening life spans of products profits gained from production vary significantly over time. Hence the long-term success of any company lies not only in the capabilities and attractiveness of its products but also in the processes used to make products and in processes used to engineer change to products and processes (Hammer et al. 1993). According to a recent survey (The Manufacturer 2006b), it is evident that many companies seek to change their systems (see Figure 1). For instance, in 2006 57% of manufacturers thought that new product development was a key priority in their business. This kind of change will often lead to needed changes in production lines, raw materials and or supply chains which was another strategic area of importance for 58% of manufacturers in 2006. There are many other challenges to present day MEs like growing business competition, increased complexity of products and processes, and increasing a need for rapid response to the changing requirements of customers. Although MEs are typically supported by different resources, information systems and organisation structures, non-responsiveness to threats may mean an end to any business. The future manufacturing systems therefore need to be reconfigurable and responsive (ElMaraghy 2009; Mehrabi et al. 2000; Weston et al. 2009).

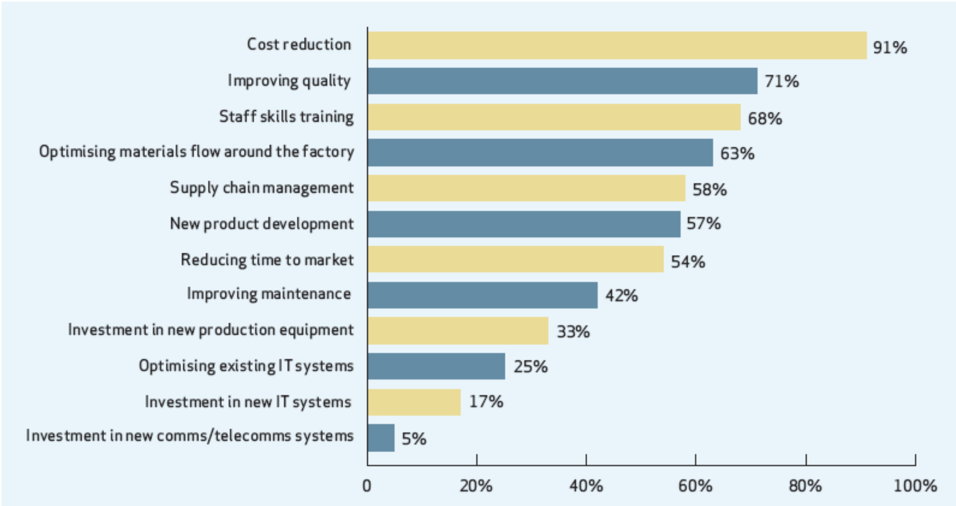

Figure 1: Key priorities in business strategy (The Manufacturer 2006b)

The present day customer typically imposes significant problems to and constraints on MEs. For example they may request change in product qualities, quantities, cost, delivery and service performance. Implications of a customer focus are: time to market is shortening, products need to be tailored to meet a breadth of customer needs, and demand is variable (Ladet et al. 1995; Suri 2003; Vernadat 1996). However, normally MEs cannot simply respond by rapidly deploying new processes and resources. Generally they need to redeploy (i.e. re-configure and re-integrate) their existing processes and resources such that they can respond competitively on an ongoing basis.

1.2 Future MEs

The manufacturing world is continually changing. It is moving focus from economy of scale to an economy of scope and is becoming a global economy for mass customization (Vernadat 2002). For many companies around the world, staying in business means to: meet customer requirements and be innovative, reduce the time-to-market of products, and manufacture quality products at competitive cost. In the wake of this rapidly changing business environment reconfigurable manufacturing enterprises (RMEs) are emerging and new ME structures and systems are forming. Industrially advanced countries have initiated research and development programs viz: Manufacturing - 2020 (UK); Next Generation Manufacturing (National Science Foundation, USA); Intelligent Manufacturing Systems (Industry led R&D initiative from EU countries, Japan, Korea, Switzerland and USA).

1.3 Need to design MEs

The identification of methods by which manufacturing improvements can be achieved is ongoing and has led to a range of approaches in recent years including lean, agile, changeable and reconfigurable manufacturing (Backhouse et al. 1999; Davis 2006; ElMaraghy 2009; Gunasekaran et al. 2002; Naylor et al. 1999; Womack et al. 1990). Progressive improvements in information system capabilities continues to offer support for improved decision making (Maropoulos 2003; Young 2003). It also follows that ME personnel must have (individual and collective) in-depth understandings about specific processes and resource systems and that these processes must be flexible enough to change whenever the need rises. The complexity of manufacturing systems is reaching that of many natural (e.g. economic and political) systems, thus ongoing re-design and re-engineering of such MEs requires the use of systematic approaches which deploy various types of system model to understand current and possible future behaviours and to inform systems engineering decision making (Weston 1999).

Technological innovation has induced very significant change in industry during recent times. This has impacted significantly on the way that MEs operate and compete with each other. But in general MEs are complex entities: designed, managed and changed by people and the supporting systems that people design; to realise customer and stakeholder (people) requirements; by deploying operational (technological and people) resources in innovative, systematic and timely ways that generate competitive behaviours. Because typically MEs have multi purposes and stakeholders it is difficult to decide how best (and therefore near optimally) to design, select and develop the technological systems (such as ERP and CAD/CAM systems) they deploy. Also for many reasons it is difficult to change them rapidly and in ways that enhance competitive ME behaviours. Whereas comparatively it will likely be simpler, easier and faster to design and realise change to systems with a single well defined purpose and small set of stakeholders. Evidently therefore there arises a need to seek to deploy decomposition principles aimed at breaking down complex systems into readily understood, and reusable human and technical building blocks; which can be used as interoperating ‘components’ (or modules) of wider scope and complex MEs that can be reconfigured as requirements change (Weston 1999). Globalisation is one outcome from technological innovation within MEs, but this raises further complication and a need to deploy decomposition principles. With sufficient resources, many entrepreneurs can now physically or virtually relocate themselves and their products (knowledge, experience, ideas and artefacts) to various locations around the globe. This has enabled knowledge sharing on a worldwide basis and technical systems globalisation.

The combination of global competition and customer oriented manufacture implies that modern manufacturing systems must be; flexible, agile, reactive, integrated, and cost efficient (Ladet et al. 1995). It follows that designing or re-designing MEs requires the adoption of systematic approaches provided that ME must have in-depth understanding of its processes and that these processes must be reconfigurable enough to change whenever the need rises.

1.4 Problems with ME design

In general current approaches to ME design do not enable processes, and their under pinning resource systems and support services, to be readily implemented and changed (Chatha 2004). Therefore achieving effective levels of agility, flexibility, postponement, systems and departmental integration, and globalization have posed real challenges for present day MEs. Hence commonly organisations face the challenge of transforming their operations to match dynamic not static business environments (Chandra et al. 2007). Significant change is ongoing in environments in which modern MEs must operate competitively. Pontrandolfo and Okogbaa (1999) presented a review of global manufacturing and identified two problem levels: (1) a configuration level related to strategic decision making and (2) a coordination level related to operational issues (Pontrandolfo et al. 1999). Quick and timely responses of various production system types are vital for MEs to remain competitive (ElMaraghy 2009; Mehrabi et al. 2000; Weston et al. 2009). One key common response is for MEs to have a broadened product portfolio. But to compete on such a basis they must deploy an effective and change capable set of human and technical resource systems. Also because of falling product lifetimes and growing customisation requirements, the deployment of these resource systems will increasingly need to give rise to economies of scope and mass customization (Vernadat 2002). For many companies around the world, staying in business necessitates: (1) meeting specific customer requirements innovatively and effectively; (2) reducing the time-to-market of products and (3) manufacturing quality products at competitive cost.

1.5 Model driven ME design

Enterprise modelling and integration (EMI) techniques have been developed based on decomposition and configuration concepts, with modelling methods provided to analyse and engineer business processes (BPs). The application of these techniques has potential to reduce risks arising from uncertainty; thereby increasing chances of realising successful BP operation and interoperation. These innovations also have potential to enable organisations to capitalise knowledge and react to change effectively and efficiently. Systematic decomposition and analysis of complex systems is possible with the aid of supporting EMI architectures, approaches and tools. However realising the potential of EMI technologies gives rise to far from trivial problems. The skill with which EMI technologies are used in conjunction with other modelling technologies, such as SM and IT systems engineering technologies, will determine the extent to which benefits of improved ME systems design and interoperation can in practice be realised. For example the models developed using these various technologies need themselves to be reconfigurable and interoperable to synchronise their development and deployment of specific and targeted change-capable environments (Weston et al. 2006; Weston et al. 2007; Zhen et al. 2009).

There is a wide scope of adopting modelling methods to enhance reconfigurability during the design and re-design phases of manufacturing processes/systems. The models for such systems also need to be reconfigurable and interoperable in order to synchronise with the change-capable environments. There have been recent advancements to extend the coverage of public domain open systems architectures and to bridge the gap between static modelling and dynamic or SM. Some important developments include: a component based approach for the design and construction of change capable manufacturing cell control (Monfared 2000; Monfared et al. 2000) and its applications in the automotive industry (Monfared et al. 2002) and electronics SMEs (Monfared et al. 2008); a multi-process modelling (MPM) approach (Chatha

2004); the enriched MPM approach (Chatha et al. 2007); and an enhanced use of enterprise and SM techniques to support factory changeability (Rahimifard et al. 2007). It is noted that use of the Computer Integrated Manufacturing Open Systems Architecture (CIMOSA) has been central to these developments. Current approaches to modelling complex MEs adopts the use of multi perspective views of present day problems. However, there is a great need for integration of different manufacturing system modelling views and technologies in order to make the models and hence manufacturing systems reconfigurable and responsive to upcoming change (ElMaraghy 2009; Mehrabi et al. 2000; US National Research Council 1998; US National Science and Technology Council 2008; Weston 1999; Weston et al. 2009; Zhen et al. 2009).

1.6 Scope of research

Since the integration and reuse of models is of paramount concern during ME design and re-design phases, this research explores the use of a new modelling approach designed to support the reconfiguration of MEs, with particular emphasis on responsiveness of their PPC systems. It assumes that there is a need for a process orientation while designing present day MEs and that a new modelling approach in support of ME design and enactment can play a key role to satisfy the need. Hence, the overall aim of this research is to develop and prototype a new modelling approach to reconfiguring MEs. The research aims to create prototype design of ME which addresses industrial collaborator problems. A prototype simulator of the newly proposed modelling approach is also developed and tested in respect of case studies drawn from production environments of industrial collaborators. The simulation and design of different case study system configurations will enable an evaluation of the pros' and cons' of the developed concepts.

The fundamental questions that this research aims to answer, through development and application of the new modelling approach to reconfiguring MEs, are: (1) how can model driven reconfigurability be induced into future MEs so that they become more responsive to change?; and (2) how PPC systems of MEs can be improved and in particular using the newly proposed modelling approach? The main deliverable expected at the completion of this research is a partially tested enhanced modelling approach including modelling stages, concepts and methods for capturing aspects of

MEs, and new understandings about techniques and tools that can be deployed to develop integrated models.

1.7 Research approach

The key activities of the adopted research approach are summarised in this section. An extensive literature review will be undertaken covering: (1) current manufacturing trends; (2) previous research and key developments in MEs and their future; (3) enterprise modelling and integration; and (4) selected PPC methods. Based on understandings gained from the literature review, ways of addressing the challenges posed will be explored. This will lead to the specification of a new modelling approach. Methods and toolsets to realise the new approach will also be considered. The newly proposed approach will then be instrumented with concepts and will be tested through case studies carried out with industrial collaborators. Based upon understandings gained through partial industrial testing, components of integrated models of collaborators' systems will be created and proposed.

1.8 Structure of the thesis

The remaining thesis is composed of eleven chapters and fourteen appendices. Chapter 2 reviews literature on manufacturing system philosophies and emerging paradigms. The research focus and design is presented in chapter 3 based upon the need for current research in the form of a gap analysis. Chapter 4 presents a detailed analysis of EMI approaches and further details about the chosen CIMOSA architecture for the current research. The IMA is proposed in chapter 5. Chapter 6 is based on an exploratory case study of the Ford Motor Company. An EIMA is proposed in chapter 7. In chapter 8, a case study of Bradgate Furniture Ltd is presented. A case study of ACM Bearings Ltd is presented in chapters 9 and 10. Chapter 11 presents results, analysis and discussion on the undertaken research work. Conclusions, and a discussion about contributions to knowledge and further research directions are included in chapter 12. This is followed by a list of references followed by the appendices. A list of author's selected publications during this PhD research, IMA/EIMA extensions, additional case study work or related literature, that are not included in respective main chapters of this thesis, and a draft paper on EIMA-2 (future extension of EIMA) are included in appendices A-F. An index is also given for selected key word search.

Chapter 2

Manufacturing System Philosophies and Emerging Paradigms

2.1 Motivation and introduction

This chapter will review modern day manufacturing along with state of the art manufacturing system philosophies and emerging paradigms.

2.2 Modern day manufacturing

In a globalization survey of US for year 2005 (The Manufacturer 2006b) in which 174 manufacturers responded, 80% said that globalisation has affected their business, and 50% have moved their business to a low cost country. Manufacturers, based in industrialised countries in Western Europe and North America, have to increase efficiency and competitiveness on a variety of facets in order to compete with increasingly sophisticated low cost producers (DTI 2004). More than six out of ten have said in the recent survey of UK manufacturers (The Manufacturer 2006b) that they are under significant pressure from their customers to become more efficient. The manufacturers are under pressure to evaluate and refine their existing operations in order to increase competitiveness with respect to quality, time, and technological advantage as it is becoming increasingly difficult for industrialised countries to compete only on cost.

Manufacturers based in industrialised countries do have the option of outsourcing aspects of their business i.e. removal of activities that are considered peripheral (Backhouse et al. 1999). This could be done for the purposes of taking advantage of lower labour rates of Eastern Europe, for instance, and/or for the purposes of concentrating on those areas that the enterprise deems value added or core to its operation. This results in a shift up the value chain for both the ME and its first and second tier suppliers (Backhouse et al. 1999). However, this action alone will not improve an enterprises' outlook and efforts must be made to address efficiency throughout the enterprise by taking a holistic approach (Deaves 2004). The outsourcing may introduce challenges that were not previously evident e.g. an unreliable supply chain, logistical management of a geographically diverse production network, employee skills or productivity (Deaves 2004). The following sections aim to enhance understanding of the context in which MEs operate and how existing supporting philosophies aim to address challenges posed by today's manufacturing environment.

Strategy plays an increasingly significant role at every level of an enterprise, from defining performance measures for operational activities to deciding which markets to enter. An analysis of organisational environments (both internal and external) is a prerequisite to formulating and implementing organisational strategies (Worthington 1994). Furthermore, properties of the organisational environment eventually have impact upon processes and systems within an enterprise. The recent survey of UK manufacturers (The Manufacturer 2006b) also explored the most important business strategies of manufacturers in order as:

- Cost reduction (91%);
- Improving quality (71%);
- Staff skills training (68%);
- Optimising materials flow around the factory (63%);
- Supply chain management (58%);
- New product development (57%);
- Reducing time to market (54%);
- Improving maintenance (42%);
- Investment in new production equipment (33%);

- Optimising existing IT systems (25%);
- Investment in new IT systems (17%); and
- Investment in new communications / telecommunications systems (5%).

Understanding the current market position, and projecting ahead to define a realistic future market position, allows a series of short and medium term milestones to be set in order to realise long term ambitions of an enterprise. There are a number of considerations to be made with respect to the competitive environment in order to understand the current and potential position of an enterprise. Competitive strategy impels an enterprise to identify competitive advantage and build on that, effectively plugging gaps of vulnerability (Glautier et al. 2001). Porter's 5 forces model (Porter 1980) aids analysis of the environment based on the following forces: (1) threat of new entrants; (2) threat of substitutes; (3) power of buyers; (4) power of suppliers; and (5) rivalry between existing competitors. In their efforts to gain recognition and to be heard in the market place, new entrants are often aggressive in their pursuit of attracting customers. The threat of substitutes refers to the broader view of products / services that are capable of performing a function outside of their intended industry. Power of buyers and power of suppliers can be viewed as opposing. Buyers may exert power by dominating an organisations order book, through using industry standard parts, and through entailing fewer costs related to switching from one product/service to another. Conversely, suppliers operating in a niche market, supplying differentiated products, and possessing threats of forward integration find themselves in a lucrative position. A supplier's commitment to continuous improvement, ability to adapt, and providing on time deliveries can also increase power. Such influences of buyers and suppliers can constrain an organisation or even an industry in terms of its strategic manoeuvrability.

The recent survey of UK manufacturers (The Manufacturer 2006b) reveals that the most important attributes of a world class manufacturer includes permanently striving for continuous improvement and responding quickly to the changing needs of its customers (Figure 2). This significant understanding has been developed over time partly due to the experiences of globalisation, internationalisation, and competitive businesses and partly due to the wide and successful implementation of different standards and models which are based upon continuous improvement cycles like ISO 9001:1994, ISO 9001:2000, Six Sigma, and Lean Manufacturing to name a few. The emerging manufacturing paradigms share experiences of successful manufacturing philosophies deployed at a given point in time.

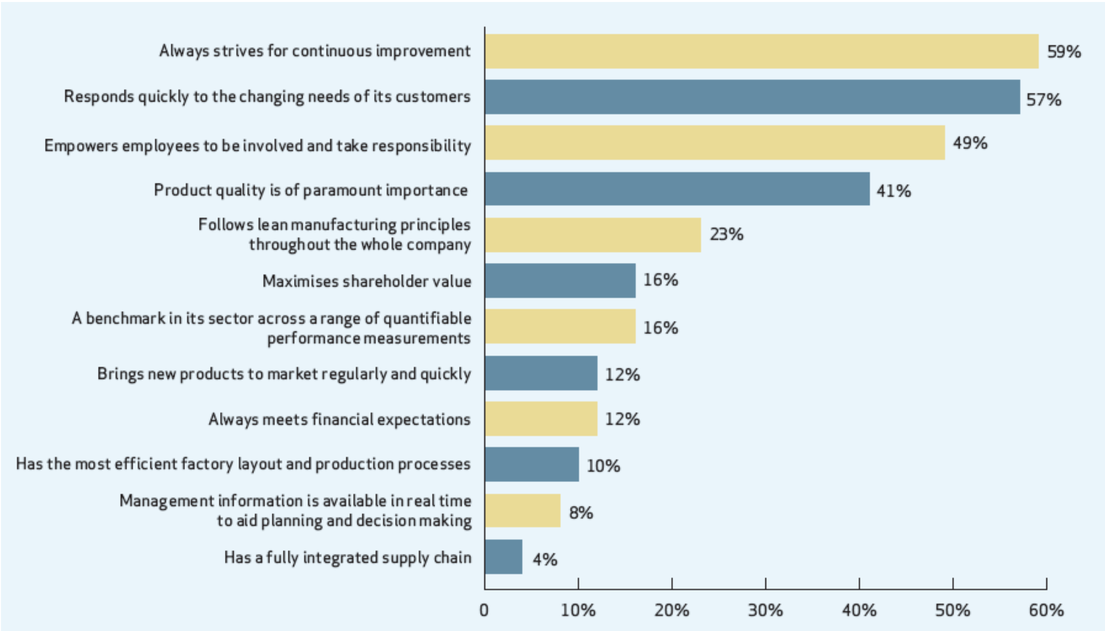

Figure 2: Most important attributes of a world class manufacturer (The Manufacturer 2006b)

2.3 Manufacturing philosophies and emerging paradigms

Manufacturing philosophies evolve with changes in the environment within which MEs operates. This section aims to address established manufacturing philosophies and emerging paradigms that have either been adopted by industry or are receiving increasing attention.

Before reviewing manufacturing philosophies, it is necessary to briefly review types of manufacturing systems. There is a variety of definitions available for types of manufacturing systems. According to a broad definition, there are following types of manufacturing systems:

- *Custom manufacturing systems:* These are the oldest production systems used to produce a smaller number of products to fulfil customer orders. These normally require highly skilled worker machines to produce individual parts.

- *Dedicated manufacturing lines (DMLs)/continuous manufacturing systems:* "A machining system designed for production of specific part type at high volume" (ElMaraghy 2006). The objective of this type is cost-effectiveness achieved through pre-planning and optimization. This is also known as continuous manufacturing where products have limited variations and uniform parts flow from station to station and semiskilled workers operate the stations;

- *Intermittent or job-lot manufacturing systems:* This system is used where continuous manufacturing is not practical and production is run in lots of products. The parts in a particular lot are processed together through a station;

- *Flexible manufacturing systems (FMSs):* "An integrated system of machine modules and material handling equipment under computer control for the automatic random processing of palletized parts" (ElMaraghy 2006). The objective is cost-effectiveness for manufacture of several types of parts within pre-defined part families;

- *Just in time (JIT) manufacturing systems:* These are computer based monitoring systems developed in Japan and stresses on effective use of resources. The focus is on eliminating tasks, such as transportation, inspection, and storage which are wasteful. JIT philosophy is used for raw materials, parts and products.

- *Reconfigurable manufacturing systems (RMSs):* "A system designed for rapid change in structure in order to quickly adjust production capacity and functionality, within a part family, in response to changes in market requirements" (ElMaraghy 2006). The objective is to provide functionality and capacity when it is needed and exactly what is needed. RMS may lie between DML and FMS in terms of capacity and functionality (ElMaraghy 2006; Mehrabi et al. 2000).

Having had a brief overview, this chapter will now look into manufacturing philosophies and emerging paradigms.

2.3.1 Lean manufacturing

Lean production was a term first used to describe production techniques used by the Japanese automotive industry, lean because it used less of everything as compared to mass production (Radnor et al. 2004; Womack et al. 1990). The first realisation that lean imposes is that only a few steps that an organisation carries out actually create value the customer is paying for (The Manufacturer 2003). Initially targeted towards achieving operational efficiency through elimination of non-value adding activities or *muda* (the Japanese word for waste) lean is now having repercussions across enterprise functions. Toyota is still claimed to be the benchmark for lean against which all other companies are measured. Using the lessons learnt from Toyota, lean requires leadership vision, and a step-by-step approach which sticks to the plan. But where do UK firms stand in terms of world class lean practice? Most are still early on the lean journey (Davis 2006). Though lean tools like Kanban, kaizen, value stream mapping and 5S are common, methods of delivery and emphasis vary. Doing more with less is the main theme within lean systems. The five principles of lean are (Womack et al. 1990): (1) specify value as perceived by the customer; (2) map the whole value stream; (3) maintain a continuous flow of value adding activities; (4) produce only what is pulled by the customer; and (5) strive towards perfection (continuous improvement).

According to the Lean Manufacturing Survey (The Manufacturer 2006a) completed by more than 300 UK manufacturers, the practice of lean manufacturing has proven invaluable to them with six out of ten describing it as essential to the prosperity of their organisation, and four in ten describing it as important. There were only 0.02% respondents who said it was “not very important”. The benefits of lean are reported in the this Lean Manufacturing Survey of UK manufacturers (The Manufacturer 2006a). According to this survey, UK manufacturers found lean manufacturing beneficial in: (1) improving efficiency and processes; (2) removing waste; (3) reducing costs; (4) reducing lead times; (5) reducing inventory; and (6) reducing workforce. The results of the survey are shown in Figure 3.

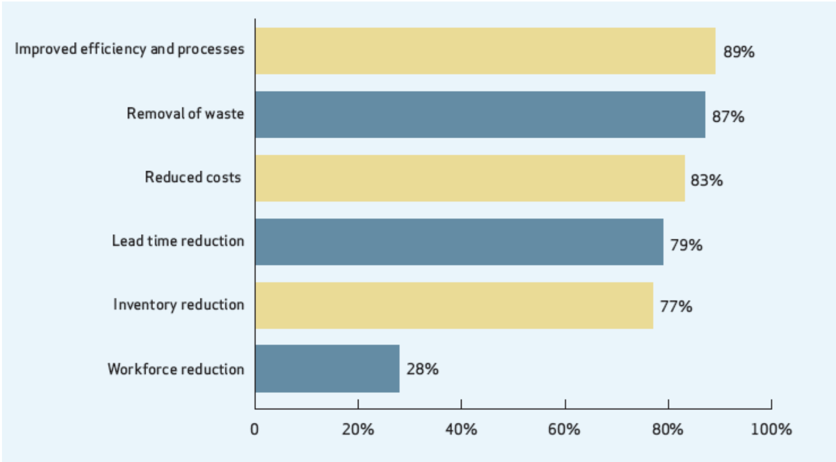

Figure 3: Benefits of lean manufacturing (The Manufacturer 2006b)

Analogies referencing Hooke's law, a journey, and the human body have been used to describe lean in the organisational context (Radnor et al. 2004). Radnor and Boaden (2004) draw parallels between training regimes to develop agility, fitness, stamina, and muscles of a sportsperson and appropriate pursuit of leanness within an organisation (Radnor et al. 2004). A sportsperson must develop appropriate to their discipline / sport and thus an organisation must use lean as is strategically and tactically viable. An organisation may reach a state of corporate anorexia if they pursue leanness beyond their limit i.e. undernourished processes, going beyond elastic limit (permanent deformation), going past their destination and becoming ineffective (Radnor et al. 2004). Table 1 summarizes key literature on lean manufacturing.

Table 1: Review of key literature on lean manufacturing

Key References	Institution	Key Work/Findings
(Womack et al. 2003; Womack et al. 1990)	Lean Enterprise Institute, Cambridge, MA, USA	Lean thinking
(The Manufacturer 2003)	The Manufacturer	Beginners guide and champions of lean
(Radnor et al. 2004)	Warwick University, UK	Developing and understanding of 'corporate anorexia'
(Davis 2006)	The Manufacturer	Beginners guide and champions of lean

2.3.2 Agile manufacturing

Change is the greatest constant of modern times (Sterman 2000). This is evermore evident in manufacturing as the industry is becoming increasingly customer lead/oriented. Agile manufacturing has been defined variably by different authors since its introduction in the report titled "21st century manufacturing enterprise strategy" which was published by the Iacocca Institute of Lehigh University, USA (Goldman et al. 1991). Some definitions of agility are given below:

- *"Agility is the ability to thrive and prosper in a competitive environment of continuous and unanticipated change, to respond quickly to rapidly changing markets driven by customer-based valuing of products and services. It is the coming business system that will replace the mass production businesses of today (US Agility Forum Literature) (Kidd 1995)";*

- *"Being Agile means being proficient at change - and allows an organization to do anything it wants to do whenever it wants to (Dove 1994)";*

- *"Agility is dynamic, context specific, aggressively change embracing, and growth oriented. It is not about improving efficiency, cutting costs, or battening down the business hatches to ride out fearsome competitive storms. It is about succeeding and about winning profits, market share and customers in the very centre of competitive storms that many companies now fear (Goldman et al. 1995)";*

- *"An Agile corporation is a fast moving, adaptable and robust business enterprise capable of rapid reconfiguration in response to market opportunities. Such a corporation is founded on appropriate processes and structures and the integration of technology, organization and people into a coordinated system in order to achieve a quantum leap forward in competitive performance by delivering capabilities that surpass those obtained from current enterprise practices (Kidd 1995);*

- *"Agility is the capability of surviving and prospering in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services" (Gunasekaran 2001);*

The agile manufacturing philosophy is aimed at addressing the responsiveness dimension that is not evident in lean. *Thus an agile enterprise is defined by many as one that is easily reconfigurable, innovative, and able to respond quickly to changing customer and market requirements (Cheng et al. 1998; Gunasekaran 1998; Kidd 1994; Kusiak et al. 1998; Monker 1994).* Therefore, agility demands simplified BPs, high scalability, secure networks, streamlined applications, centralized data management, layered, reusable architecture, common, standard interfaces that enable dissimilar systems to work together, virtualizes management services and above-all rapid response to changing market conditions.

To stay competitive in ever-changing environments, every factory must have agility to meet the diverse demands of every customer (Cook 1999). It is important to know when to start agility and being flexible in an enterprise. Agility and flexibility can only be accomplished when factories include these aspects in the design process from the start (Cook 1999). If these concepts are not included from the outset, it is simply too expensive, and thus cost-prohibitive from a competitive view, to add these features later on. How to apply these features in manufacturing plants, plant machines, and plant processes are discussed (Cook 1999). It follows that the enterprises should be change-capable from the initial design structures. However, there is an indistinct difference between flexibility and agility. Backhouse and Burns (1999) elaborate this point, making the distinction that agility is the ability of an enterprise to adapt to unpredicted changes in the external environment and flexibility is the ability of companies to respond to a variety of customer requirements which exist within defined constraints (Backhouse et al. 1999). Therefore agility and flexibility differ by the degree of predictability. Agility shares lean's concept of focusing on core activities but introduces; temporary strategic alliances with suppliers and competitors in fulfilling customer requirements (virtual companies), flexibility in human resources, and flexibility in manufacturing systems. The underlying structure of an agile enterprise is depicted in Figure 4 (Hooper et al. 2001). In this respect agility and lean are conflicting, the main issue is that of an enterprise maintaining flexibility and whether it does so by introducing waste in to the system (going against the principles of lean).

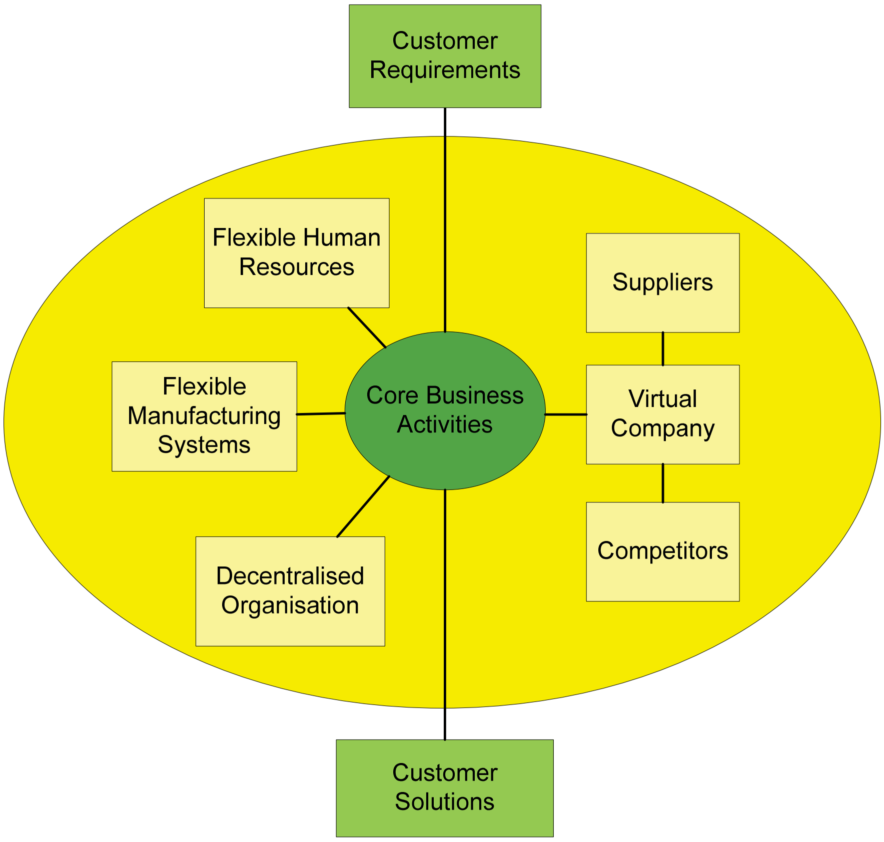

Figure 4: The structure of agile enterprise (adopted from (Hooper et al. 2001))

In the literature, there are different views about comparing lean and agile; some think these are opposite concepts while others think these are complementary to each others. Adopting a more constructive way, agile and lean could be related by two opposing criteria; productivity and effectiveness respectively where (Riis et al. 2001):

- productivity is the ability to utilize and optimize resources of the company; while
- effectiveness is the ability to select and implement strategies and market opportunities with interesting future perspectives of the enterprise where capability of the enterprise to reconfigure and change the business on a continuing basis is important.

It implies that each enterprise needs both manufacturing paradigms, lean and agile, to be adopted for better results but the enterprise needs to keep a balance between them to achieve business objectives. The concepts of leanness and agility are deeply interconnected. For example, reducing a process time will contribute to both leanness and agility as reduced time is improving productivity as well as effective reorganisation and reconfiguration of the enterprise (Riis et al. 2001). Reconfiguration is important among other aspects of enterprise dynamism which contribute towards achieving agility. Dove (2006) categorized enterprise responses into reactive and proactive dynamics categories which includes reconfiguration, among others, as a reactive dynamics to reorganise resource or process relationship (Dove 2006). Reorganisation of process-resource couples may lead to reconfigure MEs hence enhancing their agility.

During recent application of agile manufacturing concepts in four multinational companies Opel, 3M, John Deere and Airbus, the in-depth analysis revealed that the lean manufacturing, or at least many of its principles formed the basis of agile manufacturing (Vázquez-Bustelo et al. 2006). These recent case study results apparently reinforce the idea expressed by (Kidd 1994) that agile manufacturing has achieved evolutionary form of manufacturing system due to inclusion of prior paradigms. The results of these four case studies also highlighted that agile manufacturing promotes customer orientation in factories by adoption of make-to-order (MTO) production based upon pull system and process management (Kidd 1994). In automotive industry, agile manufacturing is considered as enabler of cost effective responses to unpredictable and ever changing product demand and rapid product launches (Elkins et al. 2004). In order to achieve such responsiveness in different industries, structured model driven approaches are required to design and induce change capability (Masood et al. 2010a). Table 2 summarizes key literature on agile manufacturing.

Table 2: Review of key literature on agile manufacturing

Key References	**Institution**	**Key Work/Findings**
(Kidd 1994; Kidd 1995)	Cheshire Henbury Research and Consultancy, Macclesfield, UK	Agile manufacturing: forging new frontiers and a strategy for the 21^{st} century
(Monker 1994)	---	Search for agile manufacturing
(Goldman et al. 1995)	Lehigh University, Bethlehem, USA	Agile competitors and virtual organizations: strategies for enriching the customer
(Gray et al. 1996)	Computational Centre for Industrial Innovation, Oak Ridge National Laboratory, USA	Review of the Technologies Enabling Agile Manufacturing (TEAM) program in collaboration with US Department of Defense (DoD), National Institute of Science and Technology (NIST) and National Science Foundation (NSF)
(Cheng et al. 1998)	Glasgow Caledonian University, Glasgow, UK	Implementation of agile manufacturing – an AI and internet based approach
(Gunasekaran 1998; Gunasekaran 2001)	Department of Manufacturing and Engineering Systems, Brunel University, UK	❑ Agile manufacturing: enablers and an implementation framework; ❑ Agile manufacturing: the 21^{st} century competitive strategy
(Kusiak et al. 1998)	Intelligent System Laboratory, University of Iowa, USA	Design for agility: a scheduling perspective
(Sterman 2000)	MIT Sloan School of Management, MIT System Dynamics Group, USA	Business dynamics: system thinking and modelling for a complex world
(Riis et al. 2001)	Centre for Industrial Production, Aalborg University, Aalborg, Denmark	A strategic approach to develop agile manufacturing
(Elkins et al. 2004)	Stevens Institute of Technology, Hoboken, USA and Paradigm Shift International, USA	Agile manufacturing systems in the automotive industry
(Dove 2006)	Stevens Institute of Technology, Hoboken, USA	Engineering agile systems: creative-guidance frameworks for requirements and design
(Vázquez-Bustelo et al. 2006)	Universidad de Oviedo, Spain	Agile manufacturing: industrial case studies in Spain (Opel, 3M, John Deere and Airbus)
(Masood et al. 2010a)	MSI Research Institute, Loughborough University, UK	Model driven approach to responsive manufacturing

2.3.3 Mass customisation

Today's customer is much more aware of its needs and wants these to be fulfilled according to the required specifications. This leads to more and more customisation of products. The customer orientation of today's manufacturers gives way to very unique and thus diverse portfolio of products. Even with limits imposed on product specifications it can be difficult to manufacture in an efficient manner, both with respect to cost and manufacturing processes i.e. machine setups. Toffler (1970) introduced mass customisation as a visionary concept (Toffler 1970), although Davis (1987) later termed it mass customisation (Davis 1987). Mass customisation draws on the ability to reap the benefits of producing in quantity but maintaining customisation, hence producing customised products at mass production prices (Browne et al. 1995; Duray et al. 2000). Although the vision of mass customisation is old, industry interest and research in to the dimensions surrounding the vision are receiving increasing attention (Duray et al. 2000).

Organisations, or departments within an organisation, can operate to produce customised products and benefit from cost reductions through volume across a range of products, as illustrated in Figure 5 (Weston et al. 2004). The vertical dashed lines represent all sub-processes n=1 to n=15. Products are produced for varying applications by following an appropriate set of sub-processes (represented by green nodes). Thus there are a number of end-to-end process streams depending on the end product sought (horizontal black arrows labelled product application 1 to m). The organisation stream represents the specialism evident within an organisation or department. The organisational or departmental divisions (highlighted in yellow) have the responsibility of improving and operating efficiently within their defined boundaries. Hence by grouping and producing in volume across products, the net benefit of volume is achieved. This grouping or mix produces economies of scope. This is what differentiates mass customisation from mass production; mass production seeks to achieve economies of scale through producing in volume along the process stream i.e. producing in volume according to product application.

A key to being a successful mass-customizer is postponing the task of differentiating a product or service for a specific customer until the latest possible moment (Krajewski et al. 2002). Krajewski and Ritzman (2002) give example of paint retailers stocking only pigments and base colours, mixing as required to meet unlimited customer needs. This is a prime example whereby holding a suitable quantity of every variant would be impractical, as would be requesting special orders from producers/stockists.

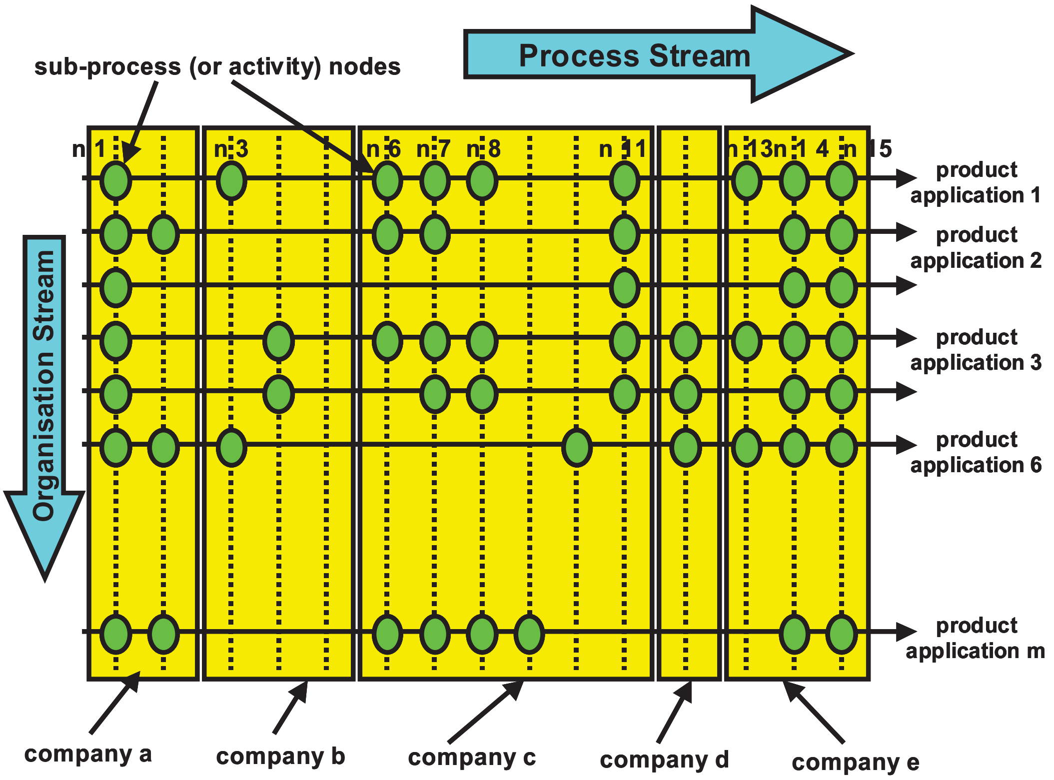

Figure 5: The significance of process and organisation streams in mass customisation (adapted from (Weston et al. 2004))

Duray, Ward et al. (2000) suggested a framework for the classification of mass-customizers according to the point in the production cycle where the customer is involved in specifying the product (customer involvement) and the type of modularity used in the product (modularity type). The classification matrix developed suggests the following archetypal mass-customizers; fabricators, involvers, modularises, and assemblers. Mass customisation also requires that information be available for both the customer and manufacturer in order to match capabilities to requirements. Frutos and Borenstein (2004) discussed the information requirements at length and suggested a framework that; increases the level of customer satisfaction by turning him/her into a co-designer rather than a simple purchaser, increases the knowledge about customer’s preferences, provides companies with valuable information about their needs and preferences to offer more customer oriented products (Frutos et al. 2004). Table 3 summarizes key literature on mass customisation.

Table 3: Review of key literature on mass customisation

Key References	Institution	Key Work/Findings
(Toffler 1970)	Cornell University; Russell Sage Foundation, USA	Mass customisation as a visionary concept of change (‘mass future shock’ or ‘disease of change’ are used by Toffler in socialist and futurist terms)
(Davis 1987)	Massachusetts, USA	Mass customisation (termed by Davis as a future perfect)
(Browne et al. 1995)	Computer Integrated Manufacturing Research Unit (CIMRU), National University of Ireland, Galway, Ireland	Industry requirements and research issues
(Duray et al. 2000)	University of Colorado at Colorado Springs, USA	Approaches to mass customization: configurations and empirical validation
(Frutos et al. 2004)	Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil	Mass customisation framework with customer-company interaction
(Weston et al. 2004)	MSI Research Institute, Loughborough University, UK	Process thinking in support of system specification and selection The significance of process and organisation streams in mass customisation

2.3.4 Reconfigurable manufacturing

The reconfigurable manufacturing paradigm started getting international recognition from a keynote paper presented at the CIRP General Assembly. The work included authors from the US NSF Engineering Research Centre for Reconfigurable Manufacturing Systems, Italy, Germany, Japan and Belgium (Koren et al. 1999). The need and rationale for such a new manufacturing paradigm was driven from the challenging market changes viz: high frequency introduction of new products, changes in existing products, rising changes in product volume and mix, technology changes and changes in government regulations (Koren et al. 1999). The US NSF

ERC/RMS researchers presented review of manufacturing techniques and introduced *reconfigurable manufacturing system as a new paradigm the aim of which was to enhance responsiveness to market changes by rapidly and cost-effectively adjusting production capacity and functionality* (Koren et al. 1999; Mehrabi et al. 2000). This new paradigm stressed the importance of increasing manufacturing process responsiveness while using main attributes of mass (i.e., reducing product cost), lean (i.e., improve product quality) and flexible manufacturing approaches (i.e., increase product variety) in order to achieve competitive market advantages. Figure 6 shows economic goals of various manufacturing paradigms including mass, lean, flexible and reconfigurable manufacturing (Mehrabi et al. 2000). The components of reconfigurable manufacturing systems as defined by (Koren et al. 1999) included reconfigurable machines, processes, software and reconfigurable controllers, as well as methodologies for their systematic design and rapid ramp-up (Koren et al. 1999; Mehrabi et al. 2000). Figure 7 shows aspects related to reconfigurable manufacturing systems (Mehrabi et al. 2000).

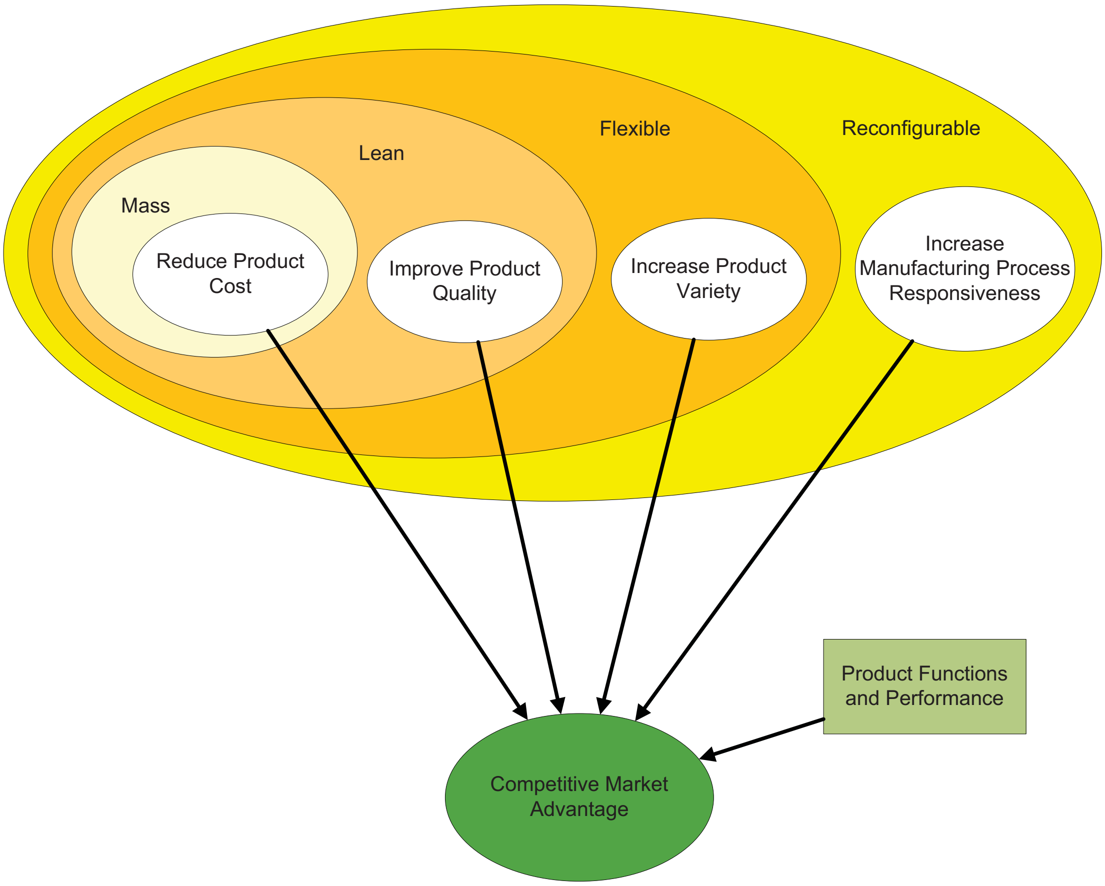

Figure 6: Economic goals of various manufacturing paradigms (Mehrabi et al. 2000)

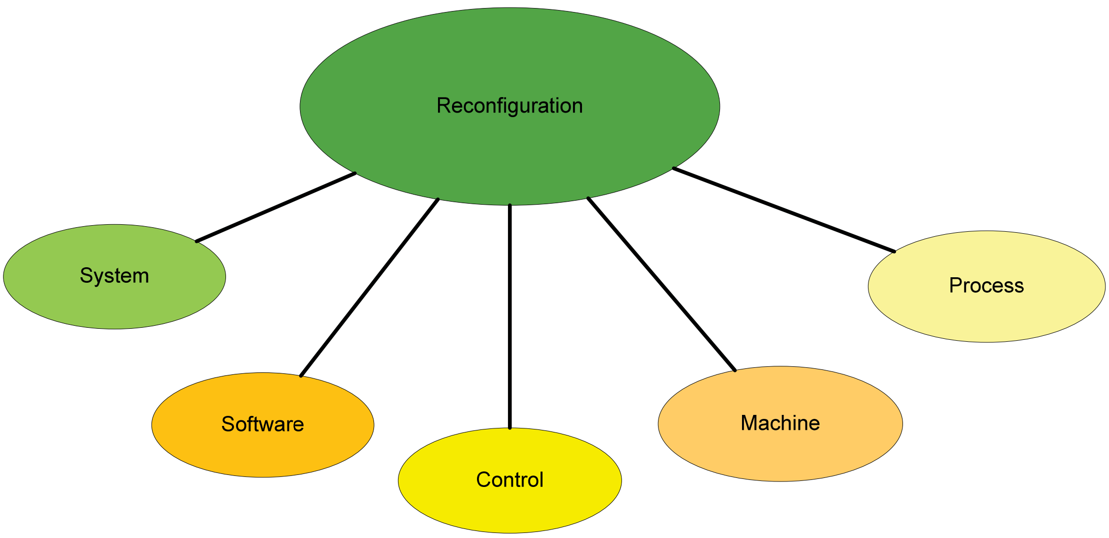

Figure 7: Aspects of reconfigurable manufacturing systems (Mehrabi et al. 2000)

Alongside, long standing research at the MSI Research Institute led to the development of new approaches to reconfigurable, component based modular system design (Harrison et al. 2004; Harrison et al. 2001; Monfared et al. 1997; Monfared et al. 1999; Weston 1999; Weston et al. 2004). (Weston 1999) classified business process oriented classification of enterprise systems and highlighted the need of migration from current generation enterprise systems to future generation. Such new generation of holistic systems will be reconfigurable and will be required to rapidly and readily reengineered (Weston 1999).To achieve such systems, the relationships between system components need to be flexibly configured and structured. It has been argued that manufacturing systems suitable for the future manufacturing businesses will have to incorporate more flexibility and intelligence, evolving towards reconfigurable manufacturing paradigms (Molina et al. 2005).

Progress towards the development of reconfigurable and changeable manufacturing has been reported in (Dashchenko 2006; ElMaraghy 2006; ElMaraghy 2009; Heisel et al. 2006; Mehrabi et al. 2002; Ohashi et al. 2001). Since the reconfigurable manufacturing concept is not a complete solution for an ME to meet all of its challenges, it is also promising to make use of other technologies like lean, agile and mass customisation to supplement and optimize its use (Bi et al. 2008). Reconfiguration of multi-product manufacturing system is an essential part of analysis and planning activities as a product life cycle dynamics (Hon et al. 2007). Hence, effective production planning and control (PPC) can play an important role in making a manufacturing system reconfigurable and responsive. Such PPC problems exist in the industry and their effective solution may lead to achieving project milestones effectively. The classification, design and operation of changeable manufacturing including PPC systems was recently presented in (Wiendahl et al. 2007).

The scope of this thesis is limited to system level reconfigurability. In order to induce reconfigurability into MEs, structured model driven approaches are required to be adopted for their design (Masood et al. 2010b). Hence, *reconfigurable manufacturing enterprises (RMEs) will share principles of lean, mass, flexible and reconfigurable paradigms and will be able to rapidly and cost-effectively change according to the market requirements*. Table 4 summarizes key literature on reconfigurable manufacturing.

Table 4: Review of key literature on reconfigurable manufacturing

Key References	Institution	Key Work/Findings
(Monfared et al. 1997)	MSI Research Institute, Loughborough University, UK	Reengineering and reconfiguration of manufacturing cell control systems and reuse of their components
(Koren 2006; Koren et al. 1999; Koren et al. 1998)	National Science Foundation Engineering Research Centre for Reconfigurable Manufacturing Systems (NSF ERC/RMS), University of Michigan, USA	❑ The papers from 1998 and 1999 presented impacts of manufacturing configurations on performance and reconfigurable manufacturing systems respectively during CIRP General Assembly; ❑ General RMS characteristics: comparison with dedicated and flexible systems
(Weston 1999; Weston et al. 2004)	MSI Research Institute, Loughborough University, UK	❑ Reconfigurable, component based systems and role of enterprise engineering; ❑ Process thinking in support of system specification and selection.
(Monfared et al. 1999)	MSI Research Institute, Loughborough University, UK	Reengineering and reconfiguration of manufacturing cell control systems and reuse of their components
(Mehrabi et al. 2000; Mehrabi et al. 2002)	NSF ERC/RMS, University of Michigan, USA	Flexible and reconfigurable manufacturing systems: trends, perspectives and key to future manufacturing
(Harrison et al. 2004; Harrison et al. 2001)	MSI Research Institute, Loughborough University, UK	❑ Distributed engineering of manufacturing machines; ❑ Life cycle engineering of modular automated machines.
(Ohashi et al. 2001)	Industrial Electronics and Systems Laboratory, Hyogo, Japan	Model based reconfigurable manufacturing systems using state transition diagrams and general graph descriptions
(ElMaraghy 2006; ElMaraghy 2009)	Intelligent Manufacturing Systems (IMS) Centre, University of Windsor, Ontario, Canada	Changeable and reconfigurable manufacturing systems paradigms
(Dashchenko 2006)	Moscow State Technical University, MAMI,	Reconfigurable manufacturing systems and transformable factories

Key References	**Institution**	**Key Work/Findings**
	Moskva Russian Federation	
(Molina et al. 2005)	Instituto Tecnolo´ gico y de Estudios Superiores de Monterrey, Mexico	Next-generation manufacturing systems: Key research issues in developing and integrating reconfigurable and intelligent machines
(Heisel et al. 2006)	Institute of Machine Tool, University of Stuttgart, Germany	Progress in reconfigurable manufacturing systems
(Hon et al. 2007)	Liverpool University, UK	Impact of product life cycle in manufacturing systems reconfiguration
(Wiendahl et al. 2007)	IFA Institute for Production Systems and Logistics, Leibniz University, Hannover, Germany	Changeable manufacturing: classification, design and operation
(Bi et al. 2008)	Integrated Manufacturing Technologies Institute, National Research Council, London, Ontario, Canada	Reconfigurable manufacturing systems: state of the art
(Masood et al. 2010b)	MSI Research Institute, Loughborough University, UK	Model driven design of reconfigurable manufacturing systems

2.3.5 Key PPC strategies

The PPC system is the central logistic mechanism that matches the company's output and logistic performance with customer demands (Wiendahl et al. 2007). This domain is quite rich in terms of literature on its definitions and traditional methods (Beamon et al. 2000; Bonney et al. 1999; Ladet et al. 1995; Stevenson et al. 2005; Tabe et al. 1980). This section will only briefly look into key PPC strategies. In Make-To-Order (MTO) manufacturing, products are made to meet the customer's specification, and are often processed in small batches. Different PPC approaches applied to MTO companies are referred to in the literature: as aggregate planning; master production planning; and production planning and scheduling. These approaches can be based on the use of 'tools' like material requirement planning (MRP) and just in time (JIT) (Stevenson et al. 2005). Production planning in case of uncertain individual demand in relation to MRP II concept was presented in (Zäpfel 1996).

Determining the right choice of PPC strategy is complex because of the increasing number of alternative variants of these approaches and because the scenarios of production that may occur can be various and can change over time. MEs that need to cope with uncertainties in demand commonly require responsive manufacturing systems which can readily be reconfigured to maintain alignment with changing production plans. Choosing and implementing a PPC strategy and system may prove costly to most of MTO companies. But adopting the wrong PPC strategy may prove even more costly. Hence MEs need a systematic approach which helps them choose a suitable way of achieving PPC. Table 5 reviews key literature on PPC.

Table 5: Review of key literature on PPC

Key References	Institution	Key Work/Findings/Recommendations
(Tabe et al. 1980)	Aoyama-Gakuin University, Tokyo, Japan	Analysis of production ordering quantities and inventory variations in a multi-stage production ordering system
(Ladet et al. 1995)	MACSI-INRIA & LGIPM, ENIM/University of Metz, France	Integrated systems engineering
(Zäpfel 1996)	Institute of Production Management, University of Linz, Austria	Production planning in the case of uncertain individual demand: extension for an MRP II concept
(Bonney et al. 1999)	Department of Manufacturing Engineering and Operations Management, University of Nottingham, Nottingham, UK	Differentiating push and pull systems
(Beamon et al. 2000)	University of Washington, Industrial Engineering, Seattle, USA	Hybrid push-pull control algorithm for multi-stage, multi-line production systems
(Zhao et al. 2001)	The Chinese University of Hong Kong, Shatin, Hong Kong	Evaluation of safety stock methods in multilevel MRP systems
(Kirchner et al. 2002)	Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Stuttgart, Germany	Towards self-adaptive production systems: modular generic simulation models for continuous re-planning and reconfiguration
(Stevenson et al. 2005)	Lancaster University, UK	Review of production planning and control: the applicability of key concepts to make-to-order industry
(Lima et al. 2006)	Department of Production and Systems, School of Engineering of University of Minho, Campus de Azurém, Guimarães, Portugal	Distributed production planning and control agent based system
(Walton et al. 2008)	Goizueta Business School, Emory University, Atlanta, GA, USA	Production planning by spreadsheet for a start-up firm
(Oduoza et al. 2009)	University of Wolverhampton, Wolverhampton, UK	A decision support system framework to process customer order enquiries in SMEs

2.3.6 Critical review of the manufacturing philosophies and emerging paradigms

Modern day manufacturing philosophies and their typical environment was considered in this chapter. Tables 1-5 presented summaries of key literature review on lean, agile, mass customisation, reconfigurable manufacturing systems and PPC. Unless an enterprise is in the fortunate position of producing a truly unique product, they will almost certainly be faced with competition (Lee 2004). A monopolistic fortunate position is not shared by most enterprises, commonly exposing them to a highly competitive business environment. In order to achieve a sustained or outstanding position in the face of open business competition, it is necessary for a manufacturing enterprise to keep changing and improving its BPs. Adopting a manufacturing philosophy is a strategic decision for an enterprise. It is important that whatever philosophy is adopted the company concerned takes a holistic view of the organisation including production and non-production related activities and their interoperation. It is also noted that most successful initiatives are bottom-up, especially lean initiatives.

Mass customisation is getting more popular while many manufacturers undertake agile and lean strategies to drive their businesses. The main focus of these philosophies is to produce quality products as well as reducing inefficiencies. These inefficiencies may be any type of waste (*muda*), any inability to respond to the industrial requirements, or the inability to conform to the customer specifications. There may be a scope to manufacture in volume in the advent of mass customisation. However, the diversity of customers and their needs coupled with ever shortening product lifecycles and lead-times introduces further constraints upon manufacturers and their approaches to the reconfiguration and interoperation of their systems.

With agility's focus on reconfigurability, the frequency of change in the manufacturing environment, and lean's focus on doing more with less, it is evident that manufacturing systems must be thoroughly understood and should exhibit a capability to respond to changes in a timely manner. This must also be true for the reconfiguration and interoperation of future manufacturing systems within an enterprise.

2.4 Requirement for reconfiguration of MEs

2.4.1 Motivation

Present day organisations cannot sustain if they concentrate only on a current set of products and services. Due to the shorter life spans of products they may very soon become obsolete in markets. Hence the long-term success of companies lies not only in their products but also in the processes they use to make products (Hammer et al. 1993). Key priorities of UK manufacturers are depicted in a recent survey (The Manufacturer 2006b) where it is evident that many are leading to change their systems (Figure 8). For instance, 57% of the manufacturers think that new product development is key priority to their business which may lead to changes in production lines, raw materials and / or supply chains which is another strategic area to 58% of those manufacturers.

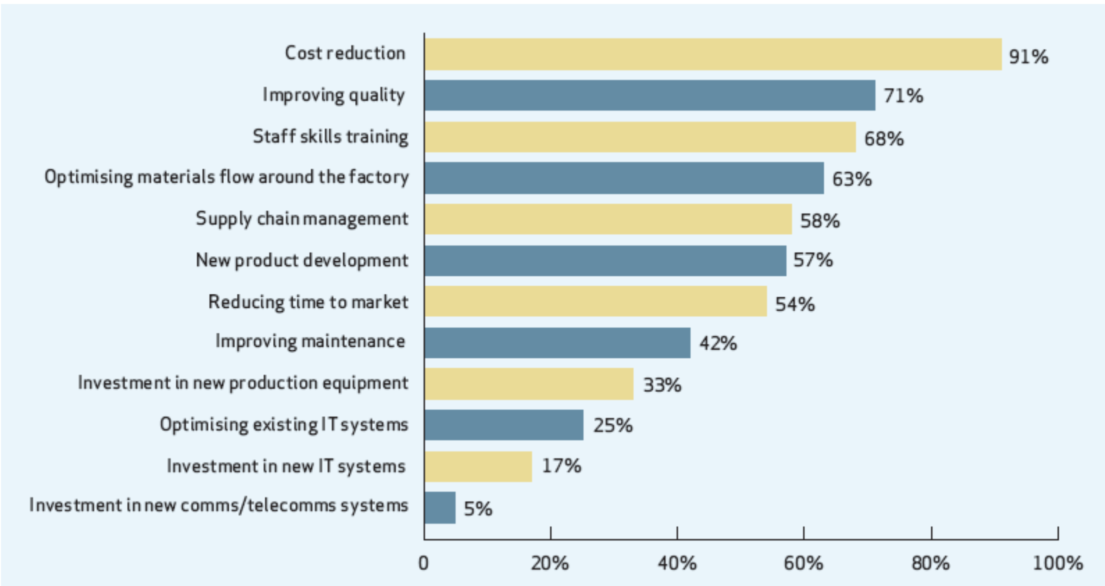

Figure 8: Key priorities in business strategy (The Manufacturer 2006b)

There are many other challenges to present day organisations like business competition, conscience, complexity of products and processes, rapid changes, and off course the changing requirements of customers. Although organisations are supported by different resources, information systems and organisation structures, their non-responsiveness to change will expose them to threats that may end their existence. Thus where responsiveness demands reconfigurable and interoperable systems should be in place. This is explained in Figure 9. Present day markets require MEs to be designed and run in a flexibly structured yet optimised way. However, modern approaches to ME engineering do not enable this requirement to capture ME attributes such that suitable processes, resource systems and support services can be readily implemented and changed (Chatha 2004).

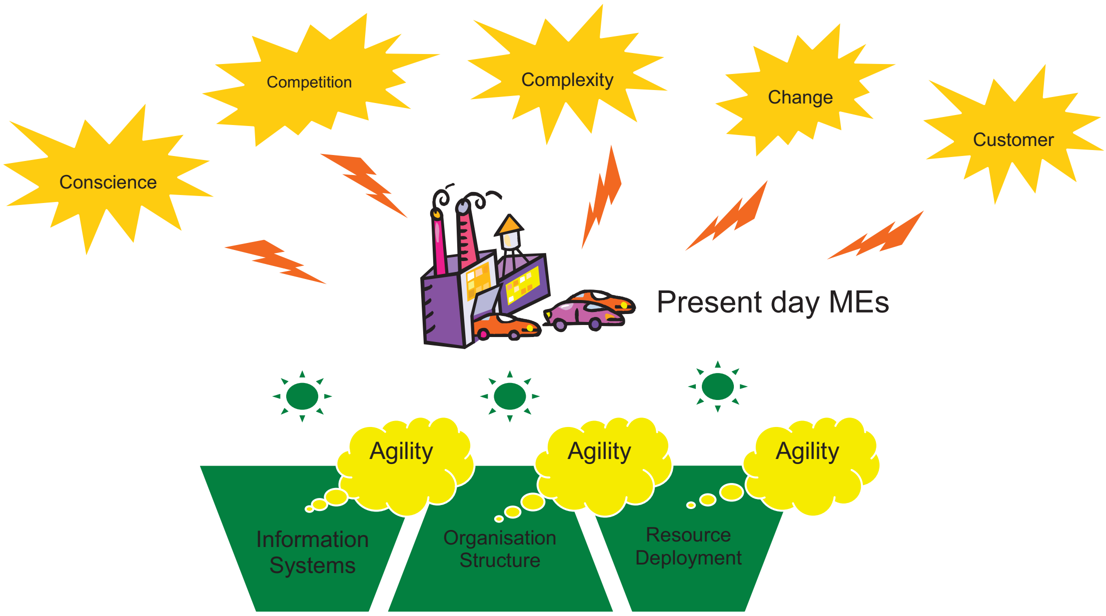

Figure 9: Present day MEs and impacting influences (Adopted from (Chatha 2004))

2.4.2 Complexity

Typically present day enterprises have organised sets of activities ranging from engineering, to production, to customer interaction which are supported by related human, software and machine systems (as shown in Figure 10) (Weston et al. 2004). Also commonly organisations have multiple product types flowing through those sets of activities in differing quantities and at different rates often dictated largely by customer needs. Different groups of products flowing through activities (or sub processes) can be considered to comprise process (or value) streams. Normally also, especially in medium and large sized companies, various different departments or organisational sub units, with their particular human and technical resource systems (that possess specific functional competencies) must support the realisation of these process streams. It follows that organisations need to attribute responsibility for realising segments of the process streams to systems of resources with appropriate competencies and levels of performance (See Figure 5). As product life-times reduce, resulting in greater rates of new product introduction, product variety and variance in processing requirements, and as customer needs become less certain, this impacts in terms of needing to cope with increased levels of complexity. This complexity means that modelling related product, process and resource systems becomes more difficult; but on the other hand the need for modelling grows so that new, improved and competitive organisational behaviours can be conceptualised and implemented at a rate that can match ongoing requirements change.

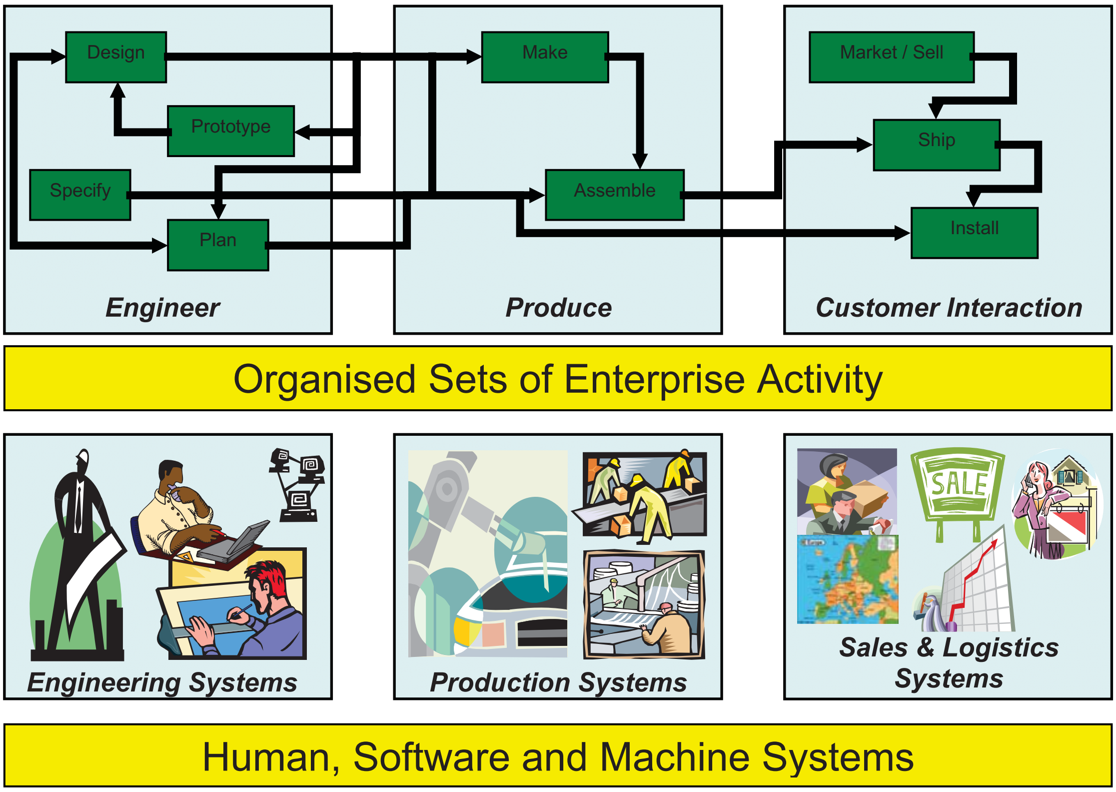

Figure 10: Enterprise activities (Adopted from (Weston et al. 2004))

2.4.3 *Decomposition requirement*

To handle complexity in MEs it is necessary to decompose its product, process and resource systems to enable modelling and better understanding in support of organisation change and development. Some rational basis is needed to decompose general ME requirements into classes of ME system that can readily be selected, tailored to specific ME needs and thereby implemented: so as to satisfy functional, process integration, change and distribution requirements (Weston et al. 2004). It is necessary to develop and agree upon appropriate problem decompositions to handle the complexity involved (Weston et al. 1998). This leads to identifying the reusable fragments, systems and BPs. While decomposing the system into fragments the ways should be considered how to recompose these fragments afterwards. Underpinning each EM approach is a technique for decomposing processes into sub-processes and unitary activities (Rahimifard et al. 2007). By formally decomposing a complex process network into descriptions of its elemental parts and dependencies between parts, subsequent systems integration aspects of organisation design and change can be enabled.

2.4.4 Requirement for change and change capability

ME systems should be inherently change capable, so that needed changes in system composition and system behaviours can be programmed to handle anticipated changes or reactively modified in response to unanticipated changes in business requirements and environmental conditions (Weston et al. 2004). The changes may be due to current market situations, change in resources and change in technical instructions. In any case, the system should be able to respond rapidly. Monfared's model of change (See Figure 11) depicts that the change may also be initiated from the bottom-up (Monfared 2009).

Monfared's model of formalising change in a manufacturing organisation highlights and classifies changes with respect to different aspects of organisations i.e. change in market, change in resources, change in technical instructions, business requirements change, production (services) requirements change and change in operational details (Chatha 2004). A number of benefits can be achieved if necessary changes and their impacts are formally documented and articulated. As illustrated the business requirements of an organisation can be linked to, and articulated in terms of, a conceptual model of systems whereas service requirements and operational details of a system can naturally be linked to detailed design and operation descriptions of these systems. There may be a number of types through which a change can occur. A change process may be initiated from operational change, resource change, policy change, or change in market configuration, to name a few.

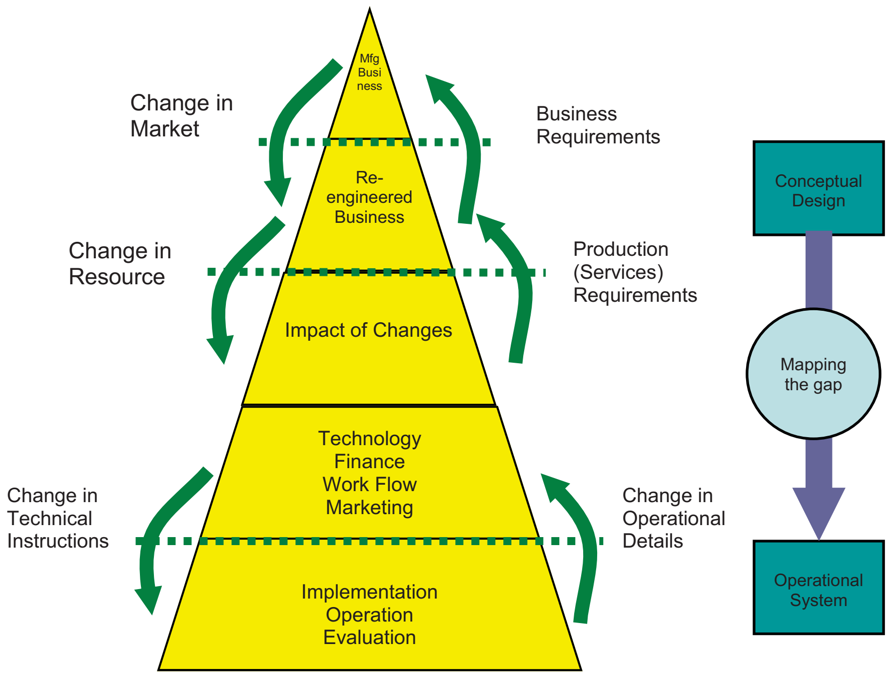

Figure 11: Model of change (Monfared 2009)

2.4.5 Requirement for reconfiguration of MEs

The complexity matrix of a variety of products, processes and related set of organisation needs may be resolved into decomposed entities. This decomposition leads to change capability and reconfigurability which is the need of the hour in order to better manage rapidly changing systems. The emergence of an agile manufacturing paradigm is driven by the need of manufacturing enterprises to respond rapidly and flexibly to unpredictable market demands (Gunasekaran et al. 2002). In response to requirements for agile manufacturing, there is a need for a manufacturing system that can (Lee et al. 2004): (a) provide the means and capabilities to support flexibility, re-configurability, and reusability; such system characteristics are important to enable the launch of new product models to be undertaken quickly, and to support the rapid adjustment of manufacturing system capacity to meet changes in market demands; and (b) enable new functions and process technology that needs to be rapidly integrated into existing manufacturing systems. This demands reconfigurability in future MEs that can accommodate most changes in the processes, resources and products according to the market changes. It also emphasizes the reuse of knowledge and core competencies by suitable alliances to reduce cost and improve efficiency (Gunasekaran 1998).

Based on the results derived from the international Delphi survey, a specially formed Committee on Visionary Manufacturing Challenges in USA identified six "grand" challenges for manufacturers that represent gaps between current practices and the vision of manufacturing in 2020. The committee, that worked under Commission on Engineering and Technical Systems, identified following 'grand' challenges for manufacturing (US National Research Council 1998):

1) Achieve concurrency in all operations;
2) Integrate human and technical resources to enhance workforce performance and satisfaction;
3) "Instantaneously" transform information gathered from a vast array of diverse sources into useful knowledge for making effective decisions;
4) Reduce production waste and product environmental impact to "near zero";
5) Reconfigure manufacturing enterprises rapidly in response to changing needs and opportunities; and
6) Develop innovative manufacturing processes and products with a focus on decreasing dimensional scale.

The committee recommended among others the following key strategic technology and research areas as the most important requirement for meeting the grand challenges (US National Research Council 1998):

1) Adaptable, integrated systems, processes and integrated equipment that can be readily reconfigured;
2) System synthesis, modelling and simulation for all manufacturing processes; and
3) Technologies to convert information into knowledge for effective decision making.

The committee recommendations classified enterprise modelling and simulation as one of the two breakthrough technologies that would accelerate progress in addressing the aforementioned grand challenges (US National Research Council 1998). In addition, the committee recommended that the most effective research would be multidisciplinary and grounded in knowledge of manufacturing strategies, planning and operations because manufacturing is inherently multidisciplinary and involves a complicated mix of people, systems, processes and equipment (US National Research Council 1998). The recommendations for the industry and government included adaptation and reconfiguration of manufacturing processes rapidly for the production of diverse and customized products. It also included adaptation and reconfiguration of manufacturing enterprises to enable the formation of complex alliances with other organisations.

More than 2,500 manufacturers across the United States responded to a recently conducted national survey under Next Generation Manufacturing project (ASMC et al. 2009). The survey was developed to better define the strategies and business actions necessary for world-class performance and success into the next generation of manufacturing (ASMC et al. 2009). The survey identified that systematic continuous improvement will be a key competitive differentiator through 2015 and beyond. The survey results showed barriers to future manufacturing as 86.3% companies were aware of the superior process / improvement focus strategy but could only achieve 43.8%. Approximately two-thirds of manufacturers (65.9%) are using measurement metrics that are furthest from world class standards to measure the return from process improvement in their companies; even 16.8% have no measurement system at all. Fifty-eight percent of manufacturers reported that they were at or near world class performance in making on-time deliveries according to customer specifications, while 42 percent indicated they were furthest away from the world class performance in this benchmark. In the post recession era the companies that do not recognise or continuously improve are at serious risk of losing their competitive edge. Continuous improvement to reduce lead times and cost and to raise productivity and quality is inevitable in such hostile environments of today's intense global market.

In another report developed in 2008 by an Interagency Working Group on Manufacturing R&D Committee on Technology, National Science and Technology Council of USA outlined federal priorities for future manufacturing research and development including key priority for development of flexible and reconfigurable distributed enterprise operations (US National Science and Technology Council

2008). Table 6 summarises key projects undertaken for grand manufacturing challenges around the world.

Table 6: Summary of key projects on grand manufacturing challenges

Key References	Institution	Key Work/Findings/Recommendations
(US National Research Council 1998)	Committee on Visionary Manufacturing Challenges, Commission on Engineering and Technical Systems, National Research Council, Washington, D.C., USA	Key grand challenges to manufacturing included rapidly reconfiguring manufacturing enterprises in response to changing needs and opportunities. The committee recommendations included further research into enterprise modelling and simulation as one of the two breakthrough technologies.
(Molina et al. 2005)	Instituto Tecnolo´ gico y de Estudios Superiores de Monterrey, N.L., Mexico	Next generation manufacturing systems: key research issues in developing and integrating reconfigurable and intelligent machines.
(Gausemeier et al. 2006)	Institute of Production Management, Technology and Machine Tools Darmstadt University of Technology, Germany	Future scenarios, describing consistent networks of influence from markets, technologies and business environment with a time horizon of 2020.
(Heisel et al. 2006)	Institute of Machine Tool, University of Stuttgart, Germany	Progress in reconfigurable manufacturing systems.
(NSTC 2008)	Interagency Working Group on Manufacturing R&D Committee on Technology, National Science and Technology Council, USA	Manufacturing the Future: Federal Priorities for Manufacturing Research and Development. Flexible, reconfigurable distributed enterprise operations.
(ASMC et al. 2009)	American Small Manufacturers Coalition (ASMC) and Manufacturing Performance Institute (MPI), USA	Study to measure progress on adopting world-class performance strategies as a first Step in initiative to help U.S. manufacturers survive recession.
(Engineers Australia 2009)	Institution of Engineers Australia	Engineering the Future of Australian Manufacturing.

2.4.6 Requirement for responsive PPC in reconfiguration of MEs

The present author holds the view that adopting and maintaining an efficient PPC system is crucial due to the increasing dynamic in customer demands and expectations in present, highly competitive, manufacturing environments (Stevenson et al. 2005). In general, adoption of a production planning and control strategy covers the following issues: management of customer demand, planning and meeting material requirements, and capacity planning, scheduling and sequencing of jobs. Use of a suitable PPC strategy helps a business to: minimize throughput and lead time; reduce work in progress; keep inventory costs at a minimum; improve the organisations responsiveness to change in demand (resulting in changes in product and process some times); and improve delivery date adherence. These are important objectives, and choosing the right production planning and control approach and system is hence a crucial strategic decision (Stevenson et al. 2005). It has been observed that modern manufacturing systems must be; flexible/agile, reactive, integrated, and cost efficient (Ladet et al. 1995). It also follows that ME personnel must have (individual and collective) in-depth understandings about specific processes and resource systems and that these processes must be flexible enough to change whenever the need rises. Such requirements place further emphasis on selecting an appropriate PPC system, which should be dynamically adaptable to both the local and distributed utilization of production resources and materials (Lima et al. 2006). Thus the design and re-design of such systems requires the adoption of systematic approaches which deploy various types of system model to understand current and possible future behaviours and to help inform ongoing decision making as environmental and organisational changes occur. PPC in support of future MEs inherently requires 'change capability' characteristics; suitable distribution of production resources; and some degree of autonomy of production resources (Rahimifard et al. 2007).

The production of finished items or components to meet an existing order is called Make-To-Order (MTO). In a MTO Company, products are made to the customer's specification, and are often processed in small batches. Different PPC approaches applied to MTO companies are referred to in the literature: as aggregate planning; master production planning; production planning and scheduling, push, pull, CONWIP and postponement approaches (Berkley 1992; Bonvik et al. 1997; Spearman et al. 1990; Tabe et al. 1980; Zäpfel 1996). These approaches can be based on the use of 'tools' like Material Requirement Planning (MRP) and Just In Time (JIT) (Monden 1993; Ohno 1988; Stevenson et al. 2005). Determining the right choice of PPC strategy is complex because of the increasing number of alternative variants of these approaches. MEs that need to cope with uncertainties in demand commonly require responsive manufacturing systems which can readily be reconfigured to maintain alignment with changing production plans (Masood et al. 2010a). Choosing and implementing a PPC strategy and system may prove costly to most of MTO companies. Hence MEs need a systematic approach which helps them choose a suitable way of achieving PPC. Thus the present author concludes that the design and re-design of PPC systems for MEs requires adoption of a systematic approach which enables enterprise engineering teams to understand current and possible future behaviours and support ongoing decision making as environmental and organisational changes occur. Table 7 summarises key literature on responsive PPC requirements in future reconfigurable manufacturing.

Table 7: Summary of key literature on responsive PPC requirement in reconfigurable manufacturing

Key References	**Institution**	**Key Work/Findings/Recommendations**
(Tabe et al. 1980)	Aoyama-Gakuin University, Tokyo, Japan	Analysis of production ordering quantities and inventory variations in a multi-stage production ordering system.
(Ohno 1988)	Toyota Motors, Japan	Toyota Production System.
(Spearman et al. 1990)	Department of Industrial Engineering and Management Sciences, Northwestern University, Evanston, Illinois, USA	CONWIP: a pull alternative to Kanban.
(Berkley 1992)	School of Business, University of Wisconsin-Madison, Madison, Wisconsin, USA	A review of the Kanban production control research literature.
(Monden 1993)	Toyota Motors, Japan	Toyota production system: an integrated approach to just-in-time.
(Ladet et al. 1995)	MACSI-INRIA & LGIPM, ENIM/University of Metz, France	Integrated systems engineering.
(Zäpfel 1996)	Institute of Production Management, University of Linz, Austria	Production planning in the case of uncertain individual demand Extension for an MRP II concept.
(Bonvik et al. 1997)	Operations Research Centre, MIT, Cambridge, MA, USA	A comparison of production-line control mechanisms.
(Stevenson et al. 2005)	Lancaster University, UK	Review of production planning and control: the applicability of key concepts to make-to-order industry.
(Lima et al. 2006)	Department of Production and Systems, School of Engineering of University of Minho, Campus de Azurém, Guimarães, Portugal	Distributed production planning and control agent based system.
(Wiendahl et al. 2007)	IFA Institute for Production Systems and Logistics, Leibniz University, Hannover, Germany	Classification, design and operation in changeable manufacturing.

Key References	Institution	Key Work/Findings/Recommendations
(Rahimifard et al. 2007)	MSI Research Institute, Loughborough University, UK	Factory changeability and responsiveness.
(Zhen et al. 2009)	MSI Research Institute, Loughborough University, UK	Factory changeability and responsiveness.

2.4.7 Requirement for structured enterprise modelling and integration methods

In order to better understand and design complex organisations, structured modelling methods are the need of the hour. It is widely accepted that modelling methods are helpful in abstracting the complex scenarios of the present day organisations; so as to further support decision making processes (Berio et al. 2001; Chatha 2004; Chatha et al. 2005; Chen et al. 2008; Monfared 2009; Rahimifard et al. 2007; Vernadat 2002; Weston et al. 2004). The conception of this abstraction is dependent upon the quality of data collection being carried out at the premises of organisation. Also important maybe the context in which data is collected and in what context this data will be subsequently used. Broadly speaking, the aim of EM is to provide: (a) understanding of a subject MEs organisation structure and operations; (b) analysis, simulation, and decision-making for the organisation; and (c) controlling and monitoring enterprise operations. The main motivations for enterprise modelling are: (1) managing system complexity by understanding how the enterprise works; (2) capitalization of enterprise knowledge and know-how; (3) enterprise engineering (EE) and continuous process improvement; (4) better management of all types of processes; and (5) enterprise integration (EI) itself.

One emerging trend in global markets is increasing collaboration among enterprises during the entire product life cycle. Constant changes in inter and intra organisational environments will persist in the future (Chen et al. 2003). MEs have to flexibly react to changes in markets and trading partners. In addition, they have to cope with internal changes from both technical (e.g. new software versions, new software and hardware technologies) and organisational points of view (e.g. merging, re-organisation). Indeed, interoperability is not only a problem of software and IT technologies (Chen et al. 2003). It implies support for communication and transactions between different organisations that must be based on shared business references. To be shared among organisations, these references must be agreed upon and respond to the co-operation needs of the organisation. To gain time and efficiency, and to avoid re-defining co-operation rules and software supporting it each time, these references must be based on business standards or norms. The business standards must be independent and weakly coupled with IT solutions and IT standards to avoid proprietary solutions and to support openness and evolution.

In order to represent complex configurations of MEs using modelling methods, it is important to make the models alive. A part of keeping models alive is to update models and structures binding models, regarding with suitably processed plant data – as well as to support model interoperation.

Enterprise modelling was main subject area for many European led projects during last decade for example OPAL, GLOBE, IBIS, INSTRUMENTS, PROMOTER-2, AIT-IMPLANT, IIMB, UEML and INTEROP-NoE (CIMOSA Association 2009b). Kosanke and Vernadat et al (1999) discussed the problems, initiatives and benefits of enterprise engineering and integration based upon CIMOSA (Kosanke et al. 1999). Zelm et al. (1995) presented CIMSOA business process modelling and its pilot implementation at FIAT (Zelm et al. 1995). Table 8 summarises key literature on requirements of enterprise modelling and integration methods.

Table 8: Summary of key literature on requirements of enterprise modelling and integration methods

Key References	Institution	Key Work/Findings/Recommendations
(Zelm et al. 1995)	CIMOSA Association, Germany	Problems, initiatives, pilot application at FIAT and benefits of enterprise engineering and integration based on CIMOSA.
(Kosanke et al. 1999)	CIMOSA Association, Germany	Problems, initiatives, pilot application at FIAT and benefits of enterprise engineering and integration based on CIMOSA.
(Berio et al. 2001)	LGIPM, University of Metz, France European Commission, Unit for e-Commission, Interoperability, Architecture and Methods, Luxembourg	Enterprise modelling and state of the art.
(Vernadat 2002)	LGIPM, University of Metz, France European Commission, Unit for e-Commission, Interoperability, Architecture and Methods, Luxembourg	Enterprise modelling and state of the art.
(Chatha 2004)	MSI Research Institute, Loughborough University, UK	Enterprise modelling .
(Chen et al. 2004)	IMS-LAPS, University of Bordeaux, France	Definition and clarification of basic concepts of enterprise integration. Overview of standards and architectures for enterprise integration.
(Weston et al. 2004)	MSI Research Institute, Loughborough University, UK	Enterprise modelling .
(Chatha et al. 2005)	MSI Research Institute, Loughborough University, UK	Enterprise modelling.
(Rahimifard et al. 2007)	MSI Research Institute, Loughborough University, UK	Enterprise modelling.
(Chen et al. 2008)	IMS-LAPS, University of	Definition and clarification of basic concepts

Key References	Institution	Key Work/Findings/Recommendations
	Bordeaux, France	of enterprise integration. Overview of standards and architectures for enterprise integration.
(Monfared 2009)	MSI Research Institute, Loughborough University, UK	Enterprise modelling.
(CIMOSA Association 2009b)	EU Projects	European led enterprise modelling projects during 1998-2007 viz: OPAL, GLOBE, IBIS, INSTRUMENTS, PROMOTER-2, AIT-IMPLANT, IIMB, UEML and INTEROP-NoE.

2.4.8 Critical review of the literature on reconfigurable manufacturing

Tables 1-8 presented summaries of manufacturing system philosophies and emerging paradigms and finally requirements for reconfigurable manufacturing. Understanding the processes involved in realising products has been an area of interest to the practitioners. The roles people play and how they must interact with other roles to realise quality products, in time, at the right place and at competitive cost are also amongst the highest considerations. Due to partial ME understandings, people may not know the purpose and causal impacts of the parts of the products they are realising. It follows that they likely have limited know-how of the information flows among different elements of an ME. The importance of the information in relation to the operations carried out at different steps in an ME is also an area of limited knowledge to people (Mintzberg et al. 1999). Hence, there is a need to develop new approaches that can answer such questions by providing much improved organisational understandings.

Secondly, it is observed that today's information systems should map onto the working of an organisation because if the working of an organisation is a mess, automating it will yield an automated mess. Often off-the-shelf information systems cannot satisfactorily support the overall working of an organisation because (Weston 1999): (1) they impose an implicit (typically ill-defined) structure on the organisation rather than reinforcing a structure that is well matched to changing enterprise needs, (2) they will not be able to communicate/interact with each other properly if different off-the-shelf systems (based on different architectural styles) are implemented in different parts of the organisation. In order for systems to work together they must conform to a common architecture, and organisation design practice should define or refine such an architecture. Hence a true picture of the design and working of an organisation should specify requirements of the systems that will be built to support the working of the organisation. These requirements should also be interoperable for the case of reconfiguration over the time.

Even though organisations are typically the result of sound working knowledge and practical experiences, it is very tedious to operationally change because of the settling and learning time the organisation must pass through. However, organisation design for most companies is neither a science nor an art; it is an oxymoron (Goold et al. 2002). Organisations are rarely built upon sound systematic and methodological planning (Goold et al. 2002). This is a natural consequence of such socio-technical systems. Consequently, the structures that evolve often neither meet the goals and objectives of the (re)design nor have adequate information systems to support them. Hence, there is a requirement to develop such means in which roles and systems can interoperate their specifications during (re)design phases and during the (re)configuration of systems.

Chapter 3

Research Focus and Design

3.1 Motivation and introduction

Following the critical review of literature on modern manufacturing system philosophies and emerging paradigms, this chapter will present the chosen area and design of this research. The research focus, aim, objectives and methodology adopted during this research are presented in the following sections.

3.2 Requirement for the reconfiguration in ME Design

The critical review of the literature on reconfigurable manufacturing revealed that during recent times technological innovation has induced very significant changes in industry. It has also impacted significantly on the way that MEs operate and compete with each other. In general MEs are very complex entities: designed, managed and changed by people and their designed systems; to realise people and system requirements; by deploying technological resources in systematic, timely and innovative ways that generate competitive behaviours. Because typically MEs have multi purposes and stakeholders it is difficult to decide how best to develop the technological systems they deploy and it is difficult to change them rapidly and in ways that enhance overall ME competitive behaviours (Weston et al. 2004). Whereas comparatively it will be simpler, easier and faster to design and realise change in some systems with a well defined purpose and small set of owners. Hence there is a need to seek to deploy decomposition principles aimed at creating understandable and reusable human and technical building blocks; which can be used as 'components' or "modules" of wider scope and complex MEs that can be reconfigured readily, so as to respond quickly.

Globalisation is but one outcome of technological innovation. With sufficient resources, many entrepreneurs now physically or virtually relocate themselves and their products (knowledge, experience, ideas and artefacts) to various locations around the globe. This has enabled knowledge sharing on a worldwide basis and globalisation of technical systems. As a result it is natural that many MEs have become entities with a global reach. Some key impacts on MEs of technological innovation and globalisation are illustrated through the cause and effect diagram shown in Figure 12 (Weston et al. 2009). These causal effects illustrate a chain of events that have increased the need for flexibly integrated and reusable MEs: comprising actual flexible ME components, models of ME components and models of flexible configurations of (real and virtual) components, which can facilitate model driven ME decision making for future MEs.

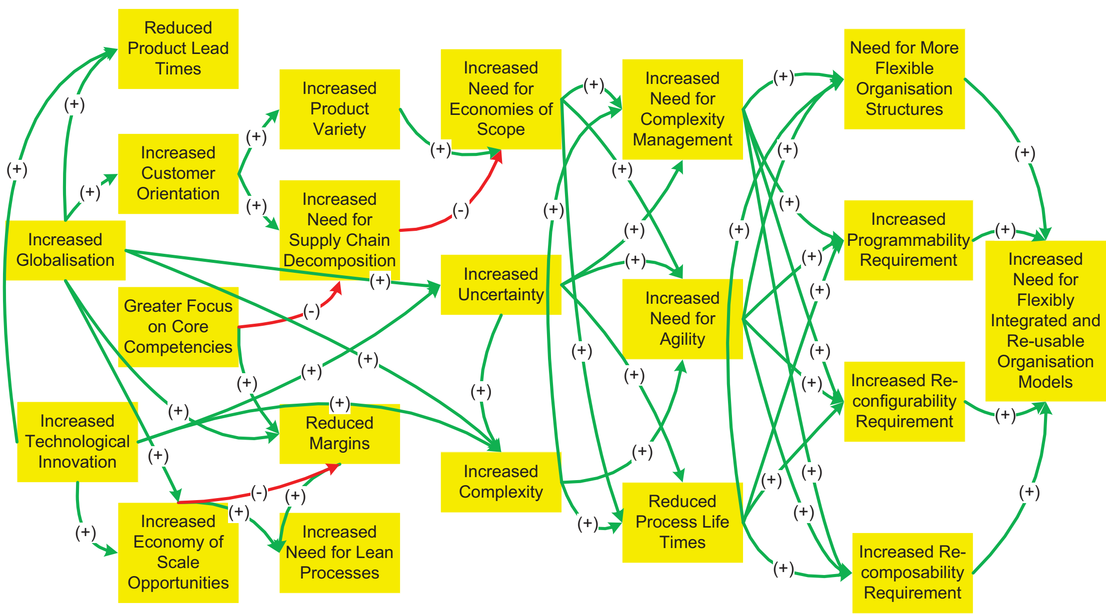

Figure 12: Causal effect – need for model-driven ME decision making (Adopted from (Weston et al. 2009))

Key issues that needs to be considered in any possible ME design are:

A) how to realise flexible ME design;

B) how to reconfigure for customisation;

C) complexity and change management; and

D) responsive deployment of finite resources;

In Chapter 2 it was observed that to address these issues successfully it is necessary to adopt a structured approach to the design of future MEs that can simplify design and take into account concerns of all stakeholders. There are a number of paradigm concepts that have emerged which potentially provide different ways of structuring resources into systems that realise products and services. It was also observed in Chapter 2 that emerging ME design technologies that could be utilised include:

a) ME design paradigms and concepts

b) enterprise engineering architectures and methods

c) systems engineering methodologies

d) infrastructural designs and services

e) process and system engineering tools

In order to achieve the research goals it is important to focus this study and define its aim and objectives.

3.3 Research focus

Keeping in mind the aforementioned ME design requirements and current and emerging design practices and solutions, the focus of this research will be to develop a new modelling approach to the design of MEs. The following section elaborates the aim and primary objectives of the research.

3.4 Research aim and objectives

The research reported in this thesis aims to ***"develop and prototype a new integrated modelling approach to conceptually designing and computer executing behaviours of reconfiguration of manufacturing enterprises"***. The following research objectives are set in order to achieve the above stated research aim.

Objective 1: Identification of the research gap in literature on manufacturing philosophies and emerging paradigms including lean, agile, mass customisation, reconfigurable manufacturing, PPC, and enterprise modelling and integration (EMI);

Objective 2: Development of a new integrated modelling approach to the reconfiguration of MEs using ISO standardised EMI approaches;

Objective 3: Industrial application and carrying out proof of concept testing of the new integrated modelling approach to reconfiguring MEs;

Objective 4: Enhancement of the integrated modelling approach proposed in objective 2 on the basis of lessons learnt from industrial application as proposed in objective 3;

Objective 5: Industrial application of the enhanced integrated modelling approach in two different SMEs;

Objective 6: Evaluation of the proposed enhanced integrated modelling approach as proposed in objective 4 and on the basis of industrially tests in objective 5;

In order to achieve the stated research aim and objectives, a structured research design is necessary.

3.5 Research design

Table 9 presents methodology that will be adopted in this research. The table shows a plan of major activities that needed to be carried during this research. It also shows, for each major activity, the choice of generic research methods adopted and the type of data involved during implementation of the methods.

Table 9: Research methodology to be adopted

Activity No.	**Major Activities in Research**	**Adopted Generic Research Method(s)**	**Data Type Involved**	**Mapping onto Research Objective No.**
1.	General review of literature on manufacturing system philosophies and emerging paradigms including lean, agile, mass customisation, reconfigurable manufacturing and PPC.	Exploratory	Qualitative	1
2.	Identify and document published approaches to EMI through detailed and specific literature review.	Exploratory	Qualitative	1
3.	Propose a new modelling approach based upon detailed literature findings; along with methods and toolsets to realise it.	Grounded Theory	---	2
4.	Exploratory case study work with industrial collaborators to model their systems. Early modelling was partly based upon data captured from an exploratory case from automotive sector. An enhanced CIMOSA modelling framework and public domain process modelling tools were deployed .	Exploratory, Descriptive, Explanatory	Qualitative, Quantitative	3
5.	Structure enhancements to earlier modelling activities and propose and create components of a newly proposed modelling approach which was a developed extension of (3). Prototype simulator used for the integrated models. Enrichment of concepts for earlier modelling concepts and proposal of an enhanced modelling approach.	Grounded Theory, Explanatory	Qualitative	4

Activity No.	Major Activities in Research	Adopted Generic Research Method(s)	Data Type Involved	Mapping onto Research Objective No.
6.	Partial testing of the enhanced modelling approach using two different SME cases with industrial collaborators.	Case-study, Explanatory	Qualitative, Quantitative	5
7.	Evaluation of the developed enhanced modelling approach based upon their partial case testing in the industry.	Explanatory	---	6

In general two main research strategies were chosen for this research, namely: "case-study" and "grounded theory". A number of industrial cases were studied during this research. The first of these was chosen with a view to specifying and initially testing partially enhanced EM concepts and principles, and to prepare groundwork for the development of a new modelling approach. This approach was to be further enhanced and partially tested in a number of distinctive other industrial cases. The selection of these cases was to be dependent largely upon ease of data accessibility and upon MSI Research Institute's previous contacts and experience with the companies.

A brief overview of the selected research methods is considered necessary, in order to explain why these methods were chosen, and the steps that needed to be taken to achieve data elicitation and analysis.

Case-study strategy

Case-study research as a strategy considers an object (whether a situation, individual, event, group, organisation or whatever) and develops a detailed understanding of it (Wisker 2007). During this research, as stated earlier, the selection of the case was dependent upon data accessibility and MSI Research Institute's previous experience and knowledge of a complex engineering process. This implied a need for previous or new interactivity between the Loughborough University and selected companies and their respective relevant groupings and assigned teams of personnel. The main sources of data for capturing process descriptions was expected to be company records, documentation and discussions with colleagues in the case study companies and other concerned MSI persons, who have an in-depth knowledge from working in or with those companies. The data was to be analysed using a strategy of developing case descriptions in an embedded way.

Grounded theory

As the intent of a grounded theory is to generate or discover theory (Creswell 2007), such a research strategy was employed to develop concepts and make propositions based on current literature about EMI. Understandings were developed during case studies, from using public domain software tools that were available to this researcher for modelling purposes. In the entirety of this research general concepts were developed and their applicability tested with respect to different case-study configurations. By testing the applicability of these concepts in different cases it was shown that the developed concepts were general enough to be applied in different domains. The concepts developed during this research were also evaluated with reference to state-of-the art modelling frameworks and methodologies e.g., CIMOSA.

Descriptive method

"Descriptive research aims to find out more about a phenomenon and to capture it with detailed information" (Wisker 2007). It asks 'what' questions and does not capture reasons of happenings within the phenomenon. When descriptive research is applied to a case it brings about a method that allows the capture of an in-depth understanding of the case. The descriptive method was expected to be used during early modelling as part of the exploratory case study.

Exploratory method

Exploratory methods are used if more detailed reasons are required than is possible from 'what' questions of a descriptive method. Exploratory research asks both 'what' and 'why' questions (Wisker 2007). While asking 'why' questions the exploratory research method deals with complex issues of a phenomenon as well. When applied in conjunction with a case-study strategy it explores those situations in which the intervention being evaluated has no clear, single set of outcomes (Yin 1994). Exploratory methods were expected to be used during the literature review and initial case study work during this research.

Explanatory method

This research method asks 'why' questions in addition to the 'what' questions as is the case for the exploratory method (Wisker 2007). During this research study an explanatory method was expected to be utilised in order to explain the application and impact of concepts, developed through descriptive and exploratory case study, and grounded theory strategies, in respect to the modelling and design of future ME.

Evaluation

During this study, three out of eight strategies described by (Maxwell 2004) namely: rich data, comparison, and generalisation are selected to evaluate the research findings. The first criterion rich data is self-evident and requires research findings to have structured and organised semantically rich descriptions of reality. Secondly, the generic modelling structure and concepts (framework) developed in this research are compared against state-of-the-art modelling frameworks and architectures e.g., CIMOSA. The applicability of the developed modelling structure and concepts is tested in different configurations, hence making use of the third strategy.

3.6 Research process

The research process to be followed during this research study is shown in Figure 13. The process is documented using the IDEF0 modelling formalism. The main activities to be carried out during this research are represented, as a sequence of activities, showing interactions amongst them. This process does not show the actual sequence of research activities followed, as the actual sequence of activities was in part circumstantial, so during the actual study there were minor variations from the sequence shown in Figure 13. The research activities were divided into phases as shown in Figure 13. The first phase of research was to be focused on reviewing literature, defining aims and objectives and structuring the modelling activities needed to carry out whilst modelling an enterprise. The distinctive output of this phase was to be a new modelling approach. The second phase was to be focused on enhancing a number of modelling concepts based upon experiences gained from an exploratory case study, resulting in the development of an enhanced modelling approach. The third phase was to be focussed on application and evaluation of the enhanced modelling approach.

The rest of the thesis follows based on a structure inherited from the sequence of activities highlighted in the research process. Chapter 4 presents a detailed analysis of candidate EMI approaches that will conclude by identifying gaps in the state of the art, academic and industrially applied, process modelling frameworks and languages.

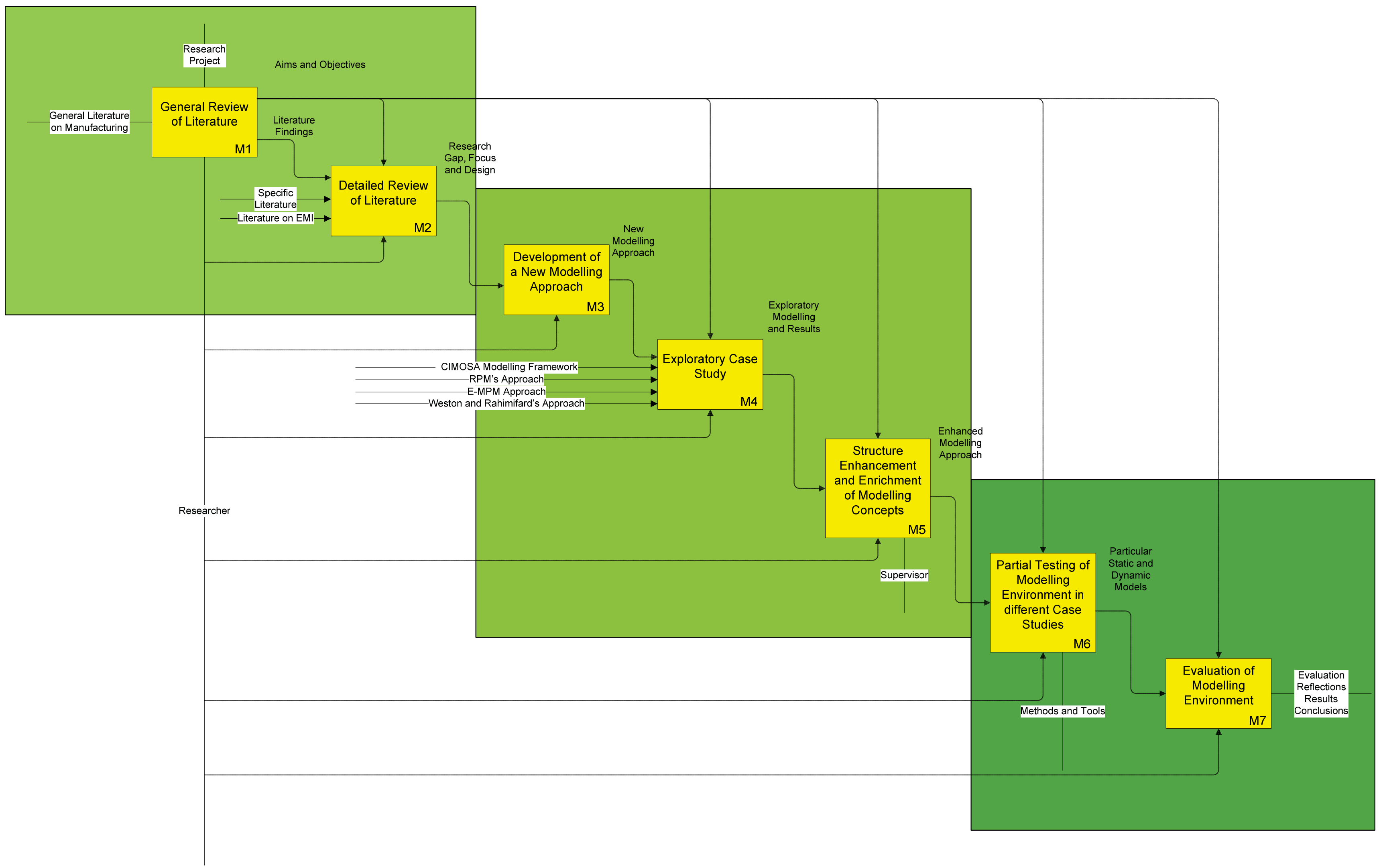

Figure 13: The research process

Chapter 4

Analysis of Candidate Enterprise Modelling and Integration Approaches

4.1 Motivation and introduction

This chapter will present and analyse candidate enterprise modelling and integration (EMI) approaches. The topics of enterprise integration (EI), enterprise engineering (EE), enterprise modelling (EM) and simulation modelling (SM) are discussed in the following sections. Studying the literature in these areas will highlight relationships between these areas and also aid understanding of present state of the art coverage of enterprise modelling approaches.

4.2 Enterprise integration

EI consists of breaking down organizational barriers to improve synergy within the enterprise so that business goals are achieved in a more productive and efficient way (Vernadat 2002). It is defined as: 'a state of enterprise operation in which all necessary things, processes and infrastructure, are in place that enable the communication of correct information, at the correct time, every time' (Nell 1996). In essence, EI enables complex interactions needed in an organisation to be managed (Patankar et al. 1995; Petrie 1992). Integration allows the creation of a synergistic whole built on the capability of its constituent components (Ladet et al. 1995). The primary aim of EI is to increase the responsiveness and efficiency of the whole system compared to its components. Integration has evolved from computer systems integration to EI (Kosanke et al. 1999). Kosanke (1996) adds to this definition and includes aspects of integrating machines, computers and people. There are other definitions which exist in the literature (ISO14258 1998; Kosanke et al. 1999; Thacker 1989). However all include the common theme of validity and timeliness of information.

In order to accelerate and make a free flow of the decisions, processes, and materials possible, it is necessary to remove the barriers which limit these activities. Integration of business processes (BPs) facilitates information, material and decisions flows, avoiding the sequential 'over the wall' approach thus breaking barriers to free flow (Ladet et al. 1995).

EI has two principle types; *inter*-EI, which is concerned with local business units, and *intra*-EI concerned with internetworking of suppliers and customers i.e. other enterprises and related supply chains. The latter form of integration is sometimes termed the *virtual enterprise* or *extended enterprise*, dependant upon the duration of the joint venture (short and long term respectively). Putting this in the context of the enterprise, integration concerns highly non-deterministic and heterogeneous systems (Kosanke et al. 1999). Thus EE aims to bring together disciplines to aid integration activities.

4.3 Enterprise engineering

Enterprise engineering (EE) has been discussed in the literature as both a taught and distinct discipline (Liles et al. 1996) and as a large scale team effort (Berio et al. 1999; Vernadat 1996), i.e. a combination of engineering disciplines. Vernadat's definition holds true in both instances: "the art of understanding, defining, specifying, analysing, and implementing BPs for the entire enterprise life cycle, so that the enterprise can achieve its objectives, be cost-effective, and be more competitive in its market environment" (Vernadat 1996). Although this definition is widely accepted (Chatha 2004; Lim et al. 1997; Monfared 2009; Szegheo 2000) there is an implicit bias towards business process reengineering and a limitation to BPs. As integration needs go beyond system, application, and process to now consider EI, the following definition becomes more applicable: "define, structure, design and implement enterprise operations as communication networks of BPs, which comprise all their related business knowledge, operational information, resources and organisation relations" (Kosanke et al. 1999). This more recent definition lays emphasis on the migration of Computer Integrated Manufacturing (CIM) systems and the involvement of EE in designing and conceiving an enterprise network as opposed to re-engineering its constituent BPs.

The EE paradigm views the enterprise as a complex system that can be engineered to accomplish specific organisational objectives. The fundamental question the enterprise engineer is posed with is how to improve the total enterprise to better achieve goals and objectives (Liles et al. 1996). EE has evolved from an emerging discipline covering concepts from industrial and systems engineering, to a discipline now covering a diverse range of traditionally discrete yet complementary disciplines. Engineering disciplines are still dominant, e.g. systems, industrial, manufacturing, information systems, and software engineering, however the role, place, and involvement of people must also be acknowledged fully during integration and thus EE (Kosanke et al. 1999). EE calls upon tools, methods and theories from various reference disciplines however, distinction from other disciplines is imperative to recognition (Liles et al. 1996). It is this aspect that has led the industry not to adopt this discipline formally. However there is increasing interest in this area both from industry and research groups; examples include formation of Society for Enterprise Engineers (SEE), Enterprise Engineering Group at The University of Texas Arlington, and Enterprise Engineering program at Brunel University, UK. A major deliverable of EE is an integrated enterprise (Lim et al. 1997). Having introduced EE and discussed its increasing significance and logical progression from CIM, EM "a central role in EE" (Vernadat 1996) will now be introduced and discussed.

4.4 Enterprise modelling

New advances in EE methods as well as strong requirements for progressing towards EI call for efficient EM languages and advanced computer-based tools (Berio et al. 1999). EM is defined as: 'an art of externalizing enterprise knowledge which adds value to the enterprise or needs to be shared. It consists of making models of the structure, behaviour and organization of the enterprise' (Vernadat 2002). The main motivations for EM are (Vernadat 2002): (1) managing system complexity by understanding how the enterprise works; (2) capitalization of enterprise knowledge and know-how; (3) EE and continuous process improvement; (4) better management of all types of processes; and (5) EI.

To cope with fast-changing manufacturing markets, a modelling support system and the systems used to design and construct these systems should be easy, fast and cost effective to change (Monfared 2009). All things to be integrated and coordinated need to be modelled to some extent. EI in any complex system can not be achieved without EM. EM is clearly a pre-requisite to EI while EI is first of all a matter of BP coordination and cooperative decision-making (Kosanke 1997; Ladet et al. 1995; Petrie 1992; Vernadat 2002). BPs to be integrated or computer-controlled need to be formalized in some way as well as objects they use, handle or process, information accessed or generated, resources required to execute them, and responsibilities and authorities required for their control. For instance, if an agent called 'system A' executing a given BP needs to 'talk', i.e. interact in the form of a dialogue, with an agent called 'system B' executing another BP, there is the need for two fundamental components (Vernadat 2002) (see Figure 14):

1) An integration platform and its integrating infra structure (IIS), i.e. hardware and software support to allow communication between 'system A' and 'system B' in the form of a flow of information objects; and

2) An enterprise model, or common semantic referential, used to ensure that when 'system A' refers to 'concept C', 'system B' has the same understanding of 'concept C' than 'system A' has. In other words, 'system A' and 'system B' share the same knowledge about 'concept C'.

Hence, the enterprise model is used as a semantic unification mechanism, or knowledge mapping mechanism, built by applying principles and tools of a given EM method.

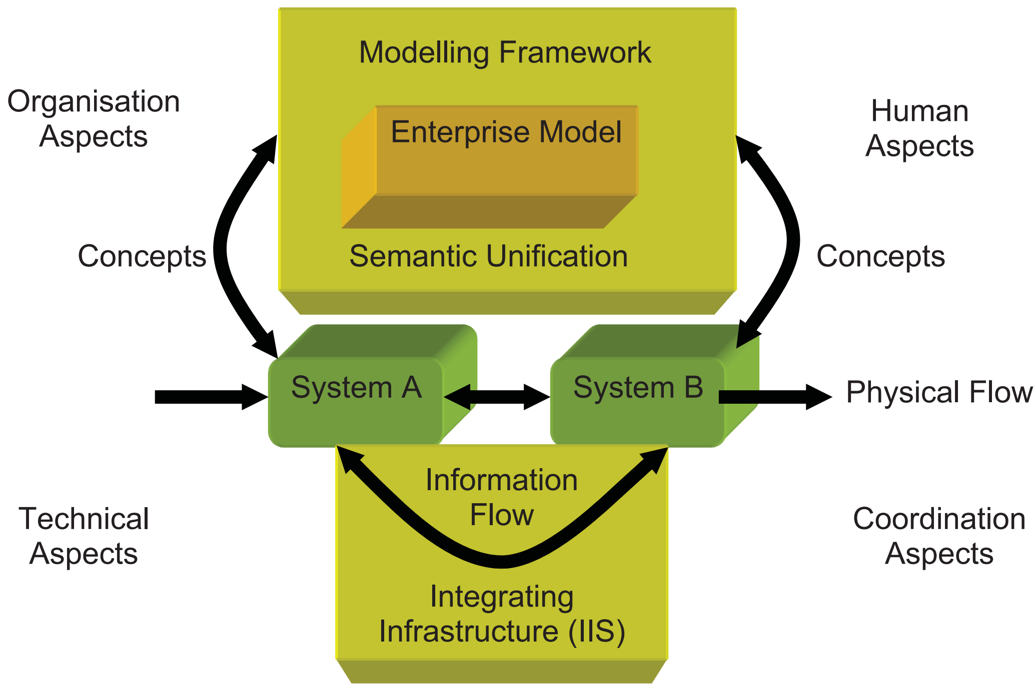

Figure 14: Enterprise modelling: why? (Adopted from (Vernadat 2002))

To appreciate the significance of EM and its importance within today's MEs, an appreciation of the aims of EM must be ascertained. The EM approach does not aim at modelling the entire enterprise in full details, although various levels of abstraction might allow this to be possibly done. The term enterprise means here a part of a company which needs to be represented (Vernadat 2002). The scope of the activity must be decided by the business users. After requirements being captured, it is the prime goal of EM to support the analysis of an enterprise. Modelling relevant BPs and enterprise objects are among the other aims of the EM. An object may be modelled if it has to interoperate with at least two components of the integrated system. If this is not the case, the same may be a local case and does not need to be modelled. Vernadat (2002, 1996) summarises that EM aims to provide (Vernadat 1996; Vernadat 2002):

1) A better understanding of the enterprise structure and operations (i.e. to visualize enterprise knowledge);

2) Support for EE of existing or new parts of the enterprise both in terms of analysis, simulation, and decision-making; and

3) A model used to control and monitor enterprise operations.

Timely execution of BPs is always vital to the existence of an enterprise. The problem in manufacturing enterprise integration and control is to ensure timely execution of BPs on the functional entities of the enterprise (i.e. human and technical agents) to process enterprise objects (Vernadat 2002). The process of EM starts from the analysis phase of the existing system. It then leads to the conceptual model of the existing system (AS-IS). At the conceptual level, reengineering a design transforms into conceptual model of future system (TO-BE). It then leads to the re-engineered system during the implementation phase (Vernadat 2002) (See Figure 15).

A uniform representation of the enterprise enables an understanding that will traverse functional and organisational boundaries; uniformity is aided by the interdisciplinary nature of EM. It is not merely one person attempting to model the entire enterprise rather a team with members focussing on modelling particular aspects for particular purposes. Uniformity also gives rise to standardisation, within the organisation and across industry.

Designing of new enterprise components and appraising current practice is tied up with a continuous improvement culture in the case of a lean philosophy and a drive to increase responsiveness in the case of an agile philosophy. Whereas once BPs are merely duplicates of previous designs, designs that were proven to work through their operation and predominately based on qualitative data, the present environment warrants that this solid foundation be built upon to gain advantages over competitors.

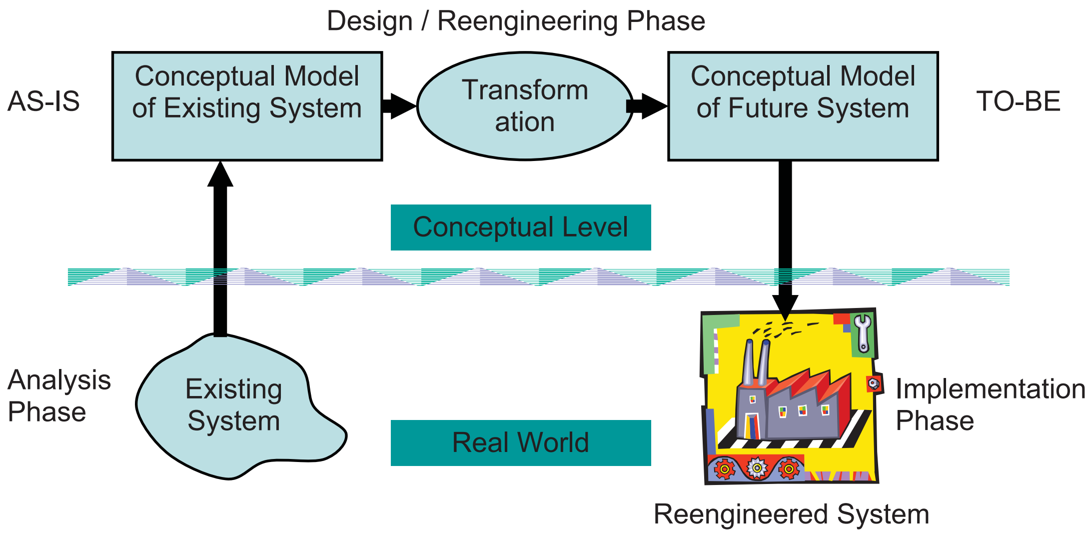

Figure 15: Enterprise modelling: how? (Adopted from (Vernadat 2002))

Employing a systematic approach as opposed to an ad-hoc approach yields better overall performance (Bernus et al. 1994), provides formalised methods and techniques for enterprise improvements and design, and enables capturing knowledge of the individual (Kalpic et al. 2002), and is termed capitalisation of knowledge (Vernadat 1996). Timescales for implementing design changes to parts of the enterprise are reduced through using common templates or calling from a library of representative generic or partial models which can interoperate. It may take time to develop initial enterprise models but this is reduced for future iterations of the modelling process and the effort required to integrate future enterprise modifications is vastly reduced.

EM also supports process management activities. Effective monitoring and control of processes ensures that models remain current and conversely that processes follow the prescribed model(s). An improved vision of the process being managed implies a better and more appropriate assigning of measures of performance. Avoiding the use of arbitrary measures and implementing more specific metrics yields a realistic view of performance. A similar argument can be formed for the enterprise management function, although it must be acknowledged that models tend towards a higher aggregation as they proceed up the functional hierarchy (Vernadat 1996). The aims listed and elaborated above give sufficient insight in to the purpose of modelling an enterprise. Support for change management, systems integration, system design and analysis, and knowledge capture are exemplar applications of EM (Vernadat 1996). The essence of modelling an enterprise will now be discussed.

EM stems from the need to understand the causal implications of pursuing certain actions over others without affecting real-time processes. By creating a model, whether it is dynamic or static, complexity can be minimised. The definition of a model supports this view: "A simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions" (Oxford English Dictionary 2009). Any type of model, whether it is mathematical, graphical, or physical, provides an abstraction of reality for the purposes of creating a comprehendible and consensual depiction of a given real world scenario. Enterprises are systems that can be analysed and modelled using systems theory (ISO14258 1998). An enterprise model is defined as: "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).

It is important to acknowledge the fact that enterprises are becoming evermore complex and are now analogous to natural systems (Ladet et al. 1995). The models of different functions or entities link up to give entirety to the whole system model and there is no high usefulness of the individual models. In reality, constituent models exist that collectively represent the required aspects of the enterprise, to the level of abstraction that is required (Vernadat 1996). Thus EM does not provide a turnkey solution for users wishing to represent an enterprise rather it provides an iterative approach.

Whilst Vernadat's definition is rather generalised, the following elaborates on the purpose of business users and intentions sought through modelling an enterprise: "A representation of what an enterprise intends to accomplish, how it operates and possibly how it is organized, which is used to improve the effectiveness and efficiency of the enterprise" (ISO14258 1998; TC184 SC5 WG1 1997). Vernadat's definition relates the purpose for modelling to the end user of the model. The ISO[13] stance is that models have a more discrete purpose, that being to serve the enterprise in pursuit of improvements. The ISO definition gives an indication of the development of a future (TO-BE) model that addresses the inefficiencies highlighted through modelling the

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[13] ISO: International Organisation for Standardisation

current (AS-IS) situation. Anomalies aside, the consensus view is that EM enables a systematic approach to understanding an enterprise and that this understanding will facilitate improvements to the way in which an enterprise performs (Lim et al. 1997; Szegheo 2000; Vernadat 1996). Frameworks in support of EM shall be discussed in the following section.

4.5 Frameworks in support of EM

To address EM problems, several methods or reference architectures have been proposed during the last two decades as a result of world leading consortia and multi-regional research team work for computer integrated manufacturing viz: Integrated DEFinition (IDEF) methods (Mayer 1991), Purdue Enterprise Reference Architecture (PERA) (Williams 1992; Williams 1996), Architecture of Integrated Information Systems (ARIS) (Scheer 1992; Scheer et al. 1994), GRAI Integrated Methodology (GRAI-GIM) (Chen et al. 1996), Computer Integrated Manufacturing Open System Architecture (CIMOSA) (ESPRIT Consortium AMICE 1993; Vernadat 1996), Integrated Enterprise Modelling (IEM) (Bernus et al. 2006), and Generalised Enterprise Reference Architecture and Methodology (GERAM) (Bernus et al. 1996a; IFIP - IFAC Task Force 1999).

IDEF is a structured set of modelling methods comprising (Knowledge Based Systems Inc 2009a; Mayer 1991):

- IDEF0 for function modelling which was derived from Structured Analysis and Design Technique (SADT). It was also released by the Computer Systems Laboratory of the National Institute of Standards and Technology (NIST) as a standard for function modelling in FIPS Publication 183 published in December 1993. IDEF0 models decisions, actions and activities of an organisation and system and are often created as one of the first tasks of a project;
- IDEF1x/EXPRESS for information modelling;
- IDEF3 for business process modelling;
- IDEF4 for object modelling; and
- IDEF5 for ontology modelling.

PERA is a methodology for enterprise engineering of industrial plants (Williams 1996). It provides a generic model for full life cycle of enterprises. It provides a formal way to identify optimum levels of automation and addresses continuous processes and discrete parts manufacturing (Williams et al. 1998). ARIS is a process oriented EM approach that aims to integrate functions through modelling and monitoring the action flow (Chen et al. 2008). It supports mapping to system descriptions developed using the Unified Modelling Language (Monfared 2009). However, undue simplifications in the business process analysis and integration phase are a substantial risk for the implementation of integrated systems (Williams 2009). GRAI-GIM provides systematic approach for modelling the ME decision systems (Vernadat 1996). GRAI grid is introduced as a tool for organizational analysis (Vernadat 1996). The methodology was experimented in a number of industrial case studies as a support for analysis and preliminary design of automated manufacturing systems (Vernadat 1996). It is a methodology for design and analysis of production systems based on the GRAI method (Chen et al. 1996). It comprises of modelling methods; GRAI Grid for organisational analysis; GRAI Nets for functional aspects; IDEFØ; and MERISE. The following are the practical limitations to this GRAI-GIM (Vernadat 1996):

- Same concepts are modelled twice (e.g., activities are modelled in GRAI nets and in IDEF0 diagrams);
- No resource view available;
- Produces static models, hence of limited value to support dynamism or change management;
- Does not support detailed system design and implementation description at an engineering level.

CIMOSA Covers both functional and behavioural aspects of CIM systems (Vernadat 1996). It supports system design specification and implementation description issues developed according to user requirements (derivation process) (Vernadat 1996). It limits the range of available building blocks, forcing vendors to provide standard components (Vernadat 1996). Inline with emerging international standards for CIM (Vernadat 1996). CIMOSA is the only EM modelling method which satisfies the principles of separation/decoupling of concern, genericity, reusability, functional decomposition, separation/decoupling of functionality and behaviour, separation/decoupling of processes and resources; and conformity all together (Vernadat 1996). CIMOSA adds the principles of economy of design effort, standardized modules, enterprise-wide modelling; and model-based integration (Vernadat 1996). CIMOSA provides guidelines, architecture, and an advanced modelling language for EM that covers function, information, resource and organisation aspects of an enterprise (ESPRIT Consortium AMICE 1993; Vernadat 1996). CIMOSA methodologies and framework can help capture process oriented elements in MEs (Chatha et al. 2005; Kosanke 1995; Kosanke et al. 1999; Zelm et al. 1995). CIMOSA was developed and validated during several European projects of the ESPRIT program (ESPRIT Consortium AMICE 1993). However, CIMOSA is limited due to its inherent complexity and lack of computer tools supporting the whole methodology (Vernadat 1996). It only gives static views and hence can not be used for decision making in changing or dynamic environments on its own. CIMOSA and ARIS both are process oriented approaches that aim to integrate functions through modelling and monitoring the action flow (Chen et al. 2008).

IEM is an EM method which is used for process reengineering (Bernus et al. 2006). It uses function and data in a single model. Its basic constructs include product, order and resource. GERAM is a generalisation of CIMOSA, GIM, and PERA (Bernus et al. 1996b; IFIP - IFAC Task Force 1999). GERAM v1.6.3 is also included in ISO WD 15704 as an appendix. It provides guidelines for EE (from PERA and GIM), a system life cycle (from PERA) and modelling constructs (from CIMOSA).

Table 10 summarises key EM frameworks and their key strengths and weaknesses.

Table 10: Key strengths and weaknesses of EM frameworks

Key References	**Key EM Frameworks**	**Research Institutions**	**Key Strengths**	**Key Weaknesses**
(Knowledge Based Systems Inc 2009a; Mayer 1991)	IDEF	Computer Systems Laboratory of the National Institute of Standards and Technology (NIST), USA US Air Force	IDEF suite and methods provides structured design and analysis for: ❑ function modelling; ❑ information modelling; ❑ business process modelling; ❑ object modelling; and ❑ ontology modelling.	❑ Lacks organisation modelling; ❑ Lacks dynamic analysis capabilities.
(Williams 1992; Williams 1996; Williams et al. 1998)	PERA	Purdue University, USA	PERA provides a generic model for full life cycle of enterprises. It provides a formal way to identify optimum levels of automation and addresses continuous processes and discrete parts manufacturing (Williams et al. 1998).	❑ Only provides reference models but no modelling constructs; ❑ Lacks dynamic analysis capabilities.
(Scheer 1992; Scheer et al. 1994)	ARIS		❑ ARIS is a process oriented approach that aims to integrate functions through modelling and monitoring the action flow (Chen et al. 2008). ❑ ARIS supports mapping to system descriptions developed using the Unified Modelling Language (Monfared 2009).	Undue simplifications in the business process analysis and integration phase are a substantial risk for the implementation of integrated systems (Williams 2009).
(Chen et al. 1996; Vernadat 1996)	GRAI-GIM	University of Bordeaux, France	❑ GRAI-GIM provides systematic approach for modelling the ME decision systems (Vernadat 1996). ❑ GRAI grid is introduced as a tool for organizational analysis (Vernadat 1996). ❑ The methodology was experimented in a number of industrial case studies as a support for analysis and preliminary design of automated manufacturing systems (Vernadat 1996). ❑ It is a methodology for design and analysis of production systems based on the GRAI method (Chen et al. 1996). It comprises of modelling methods: ○ GRAI Grid for organisational analysis; ○ GRAI Nets for functional aspects; ○ IDEF0; and	❑ Same concepts are modelled twice (e.g., activities are modelled in GRAI nets and in IDEF0 diagrams); ❑ No resource view available; ❑ Produces static models, hence of limited value to support dynamism or change management; ❑ Does not support detailed system design and implementation description at an engineering level.

Key References	Key EM Frameworks	Research Institutions	Key Strengths	Key Weaknesses
			○ MERISE	
(Chatha et al. 2005; ESPRIT Consortium AMICE 1993; Kosanke 1995; Kosanke et al. 1999; Vernadat 1996; Zelm et al. 1995)	CIMOSA	ESPRIT Consortium AMICE	❑ CIMOSA covers both functional and behavioural aspects of CIM systems (Vernadat 1996). ❑ It supports system design specification and implementation description issues developed according to user requirements (derivation process) (Vernadat 1996). ❑ It limits the range of available building blocks, forcing vendors to provide standard components (Vernadat 1996). ❑ Inline with emerging international standards for CIM (Vernadat 1996). ❑ CIMOSA is the only EM modelling method which satisfies the following principles (Vernadat 1996): ○ Separation/decoupling of concern; ○ Genericity; ○ Reusability; ○ Functional decomposition; ○ Separation/decoupling of functionality and behaviour; ○ Separation/decoupling of processes and resources; and ○ Conformity all together. ❑ CIMOSA adds the principles of (Vernadat 1996): ○ Economy of design effort; ○ Standardized modules; ○ Enterprise-wide modelling; and ○ Model-based integration. ❑ CIMOSA provides guidelines, architecture, and an advanced modelling language for EM that covers function, information, resource and organisation aspects of an enterprise (ESPRIT Consortium AMICE 1993; Vernadat 1996). CIMOSA methodologies and framework can help capture process oriented elements in MEs (Chatha et al. 2005; Kosanke 1995; Kosanke et al. 1999; Zelm et al.	❑ Inherent complexity (Vernadat 1996). ❑ Lack of computer tools supporting the whole methodology (Vernadat 1996). ❑ Only gives static views and hence can not be used for decision making in changing or dynamic environments on its own.

Key References	Key EM Frameworks	Research Institutions	Key Strengths	Key Weaknesses
			1995). ❑ CIMOSA was developed and validated in several European projects of the ESPRIT program (ESPRIT Consortium AMICE 1993). ❑ CIMOSA is a process oriented approach that aims to integrate functions through modelling and monitoring the action flow (Chen et al. 2008). ❑ Most of the other architectures aim at representing business user's concerns with no direct link to IT implementation, except CIMOSA where the IIS (integrating infrastructure) has been proposed to implement enterprise model for enterprise operations monitoring and control (Chen et al. 2008).	
(Bernus et al. 2006)	IEM	Fraunhofer Institute for Production Systems and Design Technology (German: IPK) Berlin, Germany	IEM is an EM method which is used for process reengineering (Bernus et al. 2006). It uses function and data in a single model. Its basic constructs include product, order and resource.	❑ Basic constructs lack function and organisation aspects; ❑ Lacks on detailed formalism side.
(Bernus et al. 1996b; Bernus et al. 1996a; IFIP - IFAC Task Force 1999)	GERAM	IFIP – IFAC Task Force	GERAM is a generalisation of CIMOSA, GIM, and PERA (Bernus et al. 1996b; IFIP - IFAC Task Force 1999). GERAM v1.6.3 is also included in ISO WD 15704 as an appendix. It provides guidelines for EE (from PERA and GIM), a system life cycle (from PERA) and modelling constructs (from CIMOSA).	❑ Does not include detailed formalisms/constructs as CIMOSA does in the form of Fes, FOs, etc. ❑ Inherent complexity. ❑ Lack of computer tools supporting the whole methodology. ❑ Only gives static views and hence can not be used for decision making in changing or dynamic environments on its own.

After an appraisal of the capabilities of various EMI approaches, it was decided to build this research on CIMOSA. The rationale for this decision is explained below. CIMOSA has been central in the development of most of the aforementioned EM architectures, languages and tools (Vernadat 2002). A multi-criterion analysis of reference architectures and modelling languages used in production systems modelling revealed that CIMOSA was identified as the most suitable to use in the modelling process as compared to other assessed modelling languages namely GRAI/GIM, Petri Networks, OOA/OMT, CIMOSA, IDEF0, IDEF1X, IDEF3, IEM, ARIS, EXPRESS and UML assessed upon the most comprehensive reference material (CIOCA et al. 2005). The results of the assessment are shown in Figure 16 (CIOCA et al. 2005).

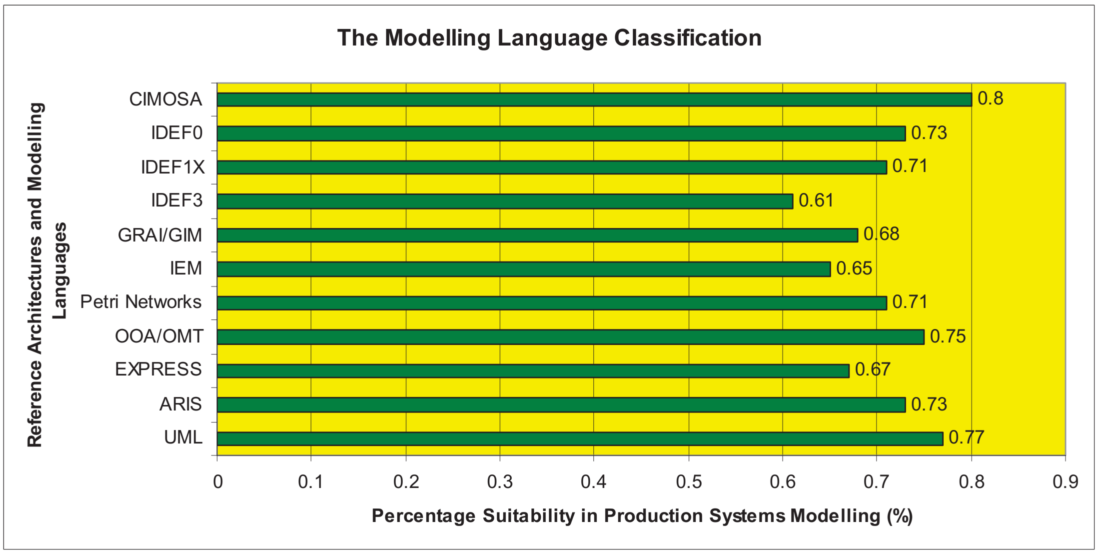


Figure 16: The modelling language classification based upon multi-criterion analysis of reference architectures and modelling languages (CIOCA et al. 2005)

The multi-criterion analysis of reference architectures and modelling languages used in production systems modelling revealed that GERAM and CIMOSA were on the top as compared to other assessed architectures namely ARIS, GRAI/GIM, IEM and PERA (CIOCA et al. 2005). It is worth noting that CIMOSA is one of the major constituents of GERAM in terms of its subdivision of genericity: reference architecture (generic and partial) and particular architecture (instantiation) and in terms of its sub division of model content views: resource, organisation, information and function. The results of the assessment are shown in Figure 17 (CIOCA et al. 2005).

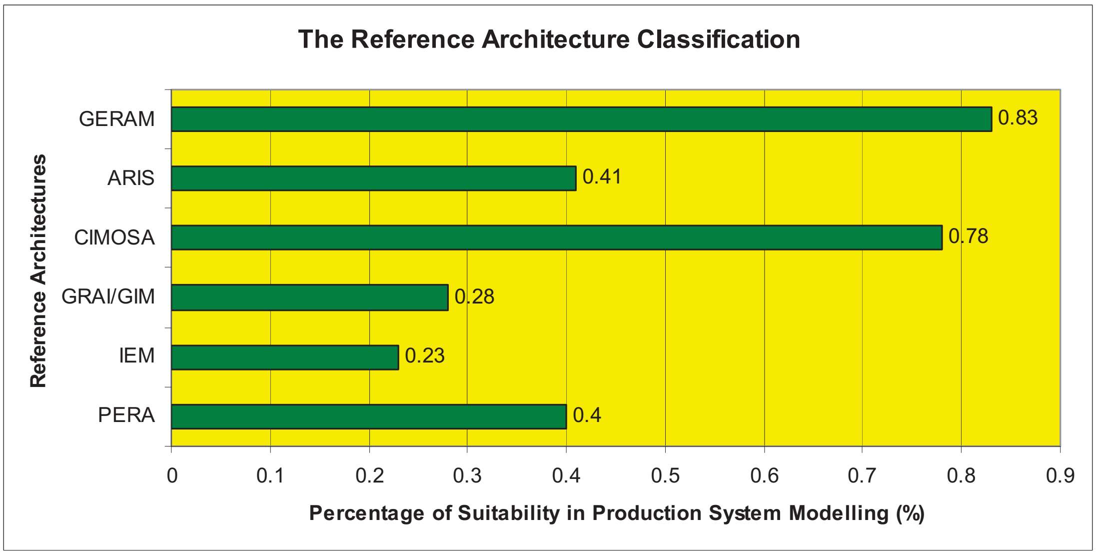


Figure 17: The reference architecture classification based upon multi-criterion analysis of reference architectures and modelling languages (CIOCA et al. 2005)

CIMOSA has also been central to many European led enterprise modelling projects viz (CIMOSA Association 2009a):

1. Integrated information and process management in manufacturing engineering (OPAL, 1998);
2. Global approach to business re-engineering (GLOBE, 1999);
3. Integrated business information systems (IBIS, 1999);
4. Tools and techniques for integration of workflow with GroupWare and BP re-engineering (INSTRUMENTS, 1999);
5. Process modelling techniques research working group (PROMOTER-2, 1999);
6. Implanting CCSW and CAD innovations into the user enterprises (AIT-IMPLANT, 1999);
7. Integration in manufacturing and beyond (IIMB, 2000);
8. Unified EM language (UEML, 2002);
9. Interoperability research for networked enterprises application and software (INTEROP-NoE, 2007).

Recent research work also ascertain that CIMOSA has been central to most of the state of the art approaches and is widely accepted and used by viz: Monfared (Monfared 2000; Monfared 2009), Chatha et al (Chatha 2004; Chatha et al. 2005; Chatha et al. 2003), Weston et al (Weston 1996; Weston et al. 2004; Weston et al. 2006; Weston et al. 2007), Rahimifard and Weston (Rahimifard et al. 2007), Ajaefobi et al (Ajaefobi 2004; Ajaefobi et al. 2006) and Masood et al (Masood et al. 2007; Masood et al. 2010b; Masood et al. 2010a; Masood et al. 2008a; Masood et al. 2008b). Previous model driven approaches also demonstrated a combined use of either IDEF or CIMOSA with Petri nets to model workflows based upon processes and resources (Dong et al. 2005; Kim et al. 2001). On the basis of University-Industrial research work of the MSI Research Institute, at Loughborough University, spread over approximately two decades, MSI researchers have developed and used CIMOSA concepts and have contributed strongly to EM developments. The PhD research of Aguiar (Aguiar et al. 1999; Aguiar 1995), Singh (Singh 1994), Coutts (Coutts 2003) and Monfared (Monfared 2000) conceived and deployed EM methods and tools. Their approaches to modelling: (1) built upon concepts originally developed as part of IDEF (Kim et al. 2001), CIMOSA (Vernadat 1992), GRAI/GIM (Chen et al. 1996) and the Purdue (Williams 1992; Williams 1994) reference architectures; and (2) have contributed towards GERAM standardisation (Bernus et al. 1996b). Since then Weston (Weston 1998), Harrison et al (Harrison et al. 2001), Derks et al (Derks 2002; Derks et al. 2003), West et al (West et al. 2003), Chatha (Chatha 2004; Chatha et al. 2007), Byer (Byer 2004; Byer et al. 2005), Ajaefobi (Ajaefobi 2004), Moreira (Moreira 2005), Rahimifard and Weston (Rahimifard et al. 2007), Zhen and Masood et al (Zhen et al. 2009), Masood et al (Masood et al. 2010b; Masood et al. 2010a), Wahid et al (Wahid et al. 2008) and Weston et al (Weston et al. 2009) have significantly enhanced CIMOSA modelling by building upon its key process oriented decomposition and modelling strengths and by addressing some of its previous weaknesses; such as by enabling more effective resource and organisation modelling and by unifying the use of EM and (discrete event and continuous) SM tools. The research reported in this thesis was built upon a unified set of EMI concepts researched within MSI Research Institute that originally were based upon the use of CIMOSA requirements modelling templates that naturally decompose (and explicitly describe) specific process networks used by MEs to realise products and services. Table 11 shows the development of the state of the art in EMI.

Table 11: Key developments in EMI

Key References	**Research Group**	**Key Work/Findings**
(Vernadat 1992; Vernadat 1994a; Vernadat 1994b; Vernadat 1996; Vernadat 2002)	MACSI-INRIA & LGIPM, ENIM/University of Metz, France	❑ CIMOSA: EM and EI using a process-based approach; ❑ CIMOSA: Current status and perspectives.
(Singh 1994)	MSI Research Institute, Loughborough University, UK	Distributed manufacturing control systems with particular reference to hierarchical scheduling
(Kosanke 1995; Kosanke 1996a; Kosanke 1996b; Kosanke 1997; Kosanke 2007; Kosanke et al. 1995; Kosanke et al. 1999; Kosanke et al. 1996)	CIMOSA Association, Germany	❑ EI: issues, why and how; ❑ Comparison of EM methodologies; ❑ Process oriented presentation of modelling methodologies; ❑ CIMOSA – overview, status and application; ❑ CIMOSA: open architecture for CIM – an example for specification and statement of requirements for GERAM; ❑ CIMOSA: EE and integration
(Aguiar 1995)	MSI Research Institute, Loughborough University, UK	Business process models in support of integrated manufacturing systems
(Zelm et al. 1997; Zelm et al. 1995)	CIMOSA Association, Germany	CIMOSA and its applications in an ISO 9000 process model
(CIMOSA Association 1996; CIMOSA Association 1997)	CIMOSA Association, Germany	❑ A primer on key concepts, purpose and business value;. ❑ CIMOSA applications 1994-97
(Reithofer 1997; Reithofer et al. 1997)	Institute for Real-Time Computer Systems and Robotics, University of Karlsruhe, Germany	❑ Bottom-up modelling with CIMOSA; ❑ Bottom-up planning approaches in EM – the need and the state of the art.
(Weston 1998; Weston 1999)	MSI Research Institute, Loughborough University, UK	❑ Comparison of the capabilities of software tools designed to support the rapid prototyping of flexible and extendible manufacturing systems; ❑ Reconfigurable, component-based systems and the role of enterprise engineering concepts
(Ortiz et al. 1999)	GIP, University of Valencia, Spain	Building a production planning process with an approach based on CIMOSA and workflow management systems.
(Wilson et al. 1999)	MSI Research Institute, Loughborough University, UK	Achieving manufacturing business integration through the combined formalism of CIMOSA and Petri nets

Key References	Research Group	Key Work/Findings
(Monfared 2000; Monfared 2009)	MSI Research Institute, Loughborough University, UK	Design and construction of change capable manufacturing cell control systems using CIMOSA based enterprise modelling.
(Santos et al. 2000)	University of Aveiro / Department of Mechanics	A modelling language for the design and execution of enterprise models in manufacturing
(Berio et al. 2001)	MACSI-INRIA & LGIPM, ENIM/University of Metz	EM with CIMOSA: functional and organisational aspects
(Kim et al. 2001)	Taejon University Information System Engineering	Integrated use of $IDEF_0$, $IDEF_3$ and Petri Net methods in support of BP Modelling
(Derks 2002; Derks et al. 2003)	MSI Research Institute, Loughborough University, UK	❑ Enhanced exception handling in sales order processing workflows; ❑ Role of workflow management system in product engineering.
(Coutts 2003)	MSI Research Institute, Loughborough University, UK	Easing the creation and maintenance of software systems through the use of domain machines
(Chen et al. 2004)	IMS-LAPS, University Bordeaux	Standards on EI and engineering – state of the art
(Chatha 2004; Chatha et al. 2007; Chatha et al. 2005; Chatha et al. 2006; Chatha et al. 2003)	MSI Research Institute, Loughborough University, UK	Enriched multi process modelling approach
(Rahimifard et al. 2007)	MSI Research Institute, Loughborough University, UK	Enterprise and simulation modelling techniques
(Chen et al. 2008)	IMS-LAPS, University Bordeaux	Architectures for enterprise integration and interoperability: Past, present and future
(Zhen et al. 2009)	MSI Research Institute, Loughborough University, UK	A structured modelling approach to simulating dynamic behaviours in complex organisations

The CIMOSA framework and its constructs will be discussed in the following section.

4.6 CIMOSA framework

The ESPRIT Consortium AMICE developed CIMOSA which aims to facilitate change and integration of facilities and operations (ESPRIT Consortium AMICE 1993; Vernadat 1992). This is achieved via providing a framework for analysing the evolving requirements of an enterprise and translating these into a system that enables and integrates ME functions. Figure 18 shows the CIMOSA modelling framework. There are three orthogonal dimensions of the framework termed generation (of views), instantiation (of building blocks) and derivation (of models). Within the generation principle there are four viewpoints: (1) function; (2) information; (3) resource; and (4) organisation. CIMOSA encompasses these four different views of an ME within reference and particular architectures. The generation dimension recommends that the ME be modelled using these complementary viewpoints (Vernadat 1996). The instantiation dimension is based on three generic layers. This describes the level of detail of building blocks used when constructing a model. Building blocks may be generic blocks (generic layer), taken from industry sector specific libraries (partial layer), or company specific (particular layer). The derivation dimension models enterprises according to the three levels shown in Figure 18. This covers perceived business needs, executable model building, and details regarding implementation.

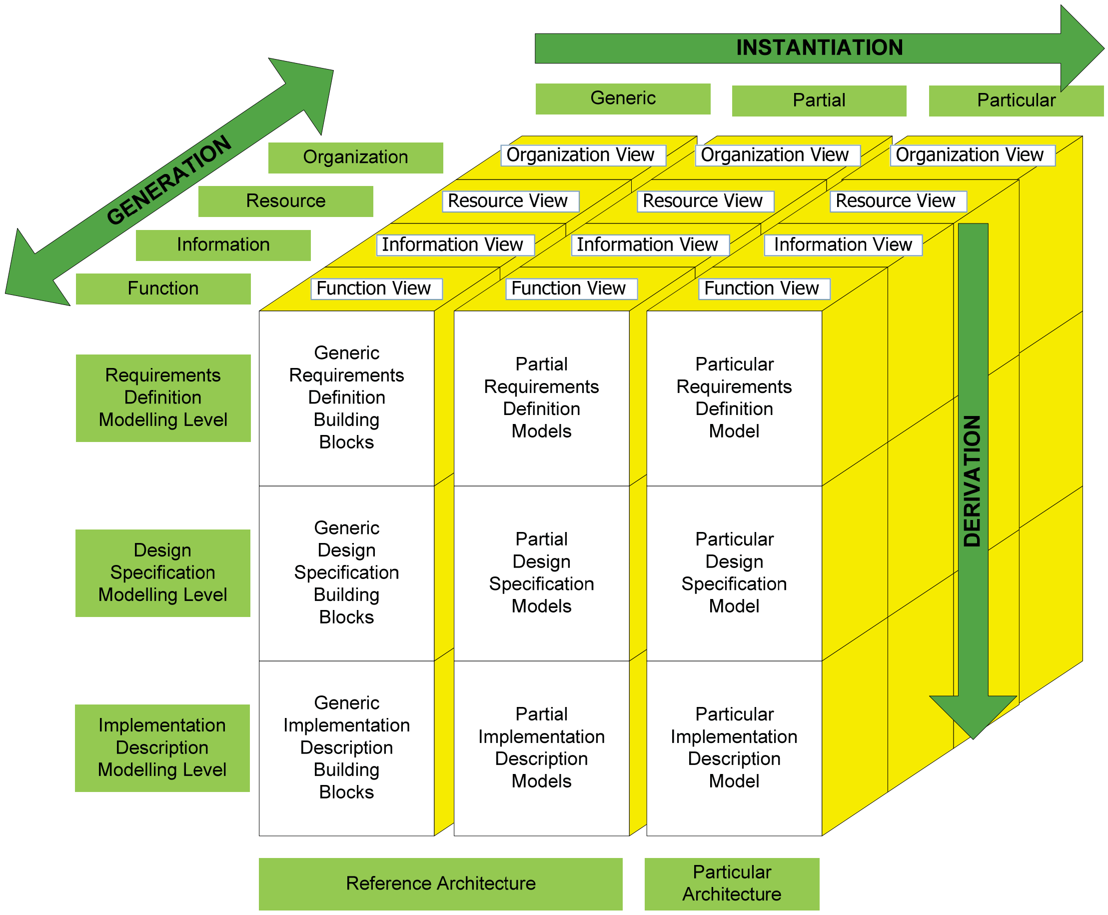


Figure 18: CIMOSA modelling framework (Vernadat 1996)

CIMOSA allows the *as-is* situation within an enterprise to be modelled as well as any suggested *to-be* configurations. A *bottom-up* approach can be taken when concerned with existing implementations and a *top-down* approach with planned implementations. CIMOSA is principally based on the concept of isolation in the following contexts: (1) isolation between the user representation and the system representation; (2) isolation between control and functions; and (3) isolation between functions and information. Through isolation, as outlined above, organisational flexibility can be modelled as the market changes and the ME reacts to changes. The isolation between functions and information facilitates integration. Constructs related to CIMOSA are detailed in the following section.

4.6.1 CIMOSA constructs

There are a number of key definitions that must be understood prior to using CIMOSA modelling constructs that includes: (1) Domains (DMs); (2) Domain Processes (DPs); (3) BPs; (4) Enterprise Activities (EAs); (5) Functional Operators (FOs); and (6) Functional Entities (FEs). A *DM* specifies the overall scope and content of the particular model of the enterprise (Monfared *et al,* 2002). That is to say that a *DM* establishes the boundaries for the part of the enterprise that is to be represented and analysed using CIMOSA. A *DP* defines which enterprise functions influence the achievement of the related domain objectives (Monfared et al. 2002). DPs are triggered by events and produce a defined end result (CIMOSA Association 1996). CIMOSA can be used to represent several domains interacting via their constituent DPs (Figure 19).

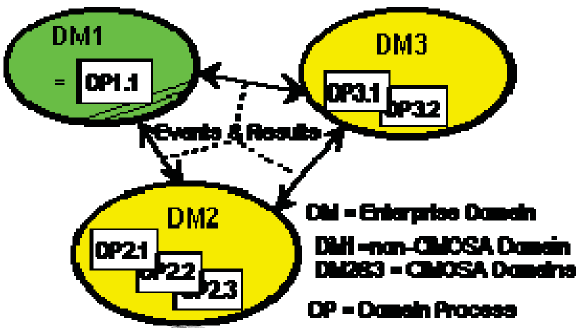


Figure 19: Inter and intra domain relationships (CIMOSA Association 1996)

BPs are special types of enterprise functions (Monfared et al. 2002). They aggregate lower level threads / sequences of *EAs* in to a recognised process (Monfared et al. 2002). *EAs* are the lowest level of activities that can be defined i.e. they cannot be decomposed further. However, they may be decomposed in to *FOs* at the design modelling level (Monfared et al. 2002). FOs are basic units of work at the lowest level of granularity, in the function view (CIMOSA Association 1996). A *FE* is an active resource able to perform *FOs* completely on its own e.g. humans, machines and applications (CIMOSA Association 1996). CIMOSA domains are broken down in to atomic functional elements of BPs and EAs. Figure 20 shows the relationships between DM, DP, BP, and EA and their further breakdown into FOs and FEs and how they relate to an EA.

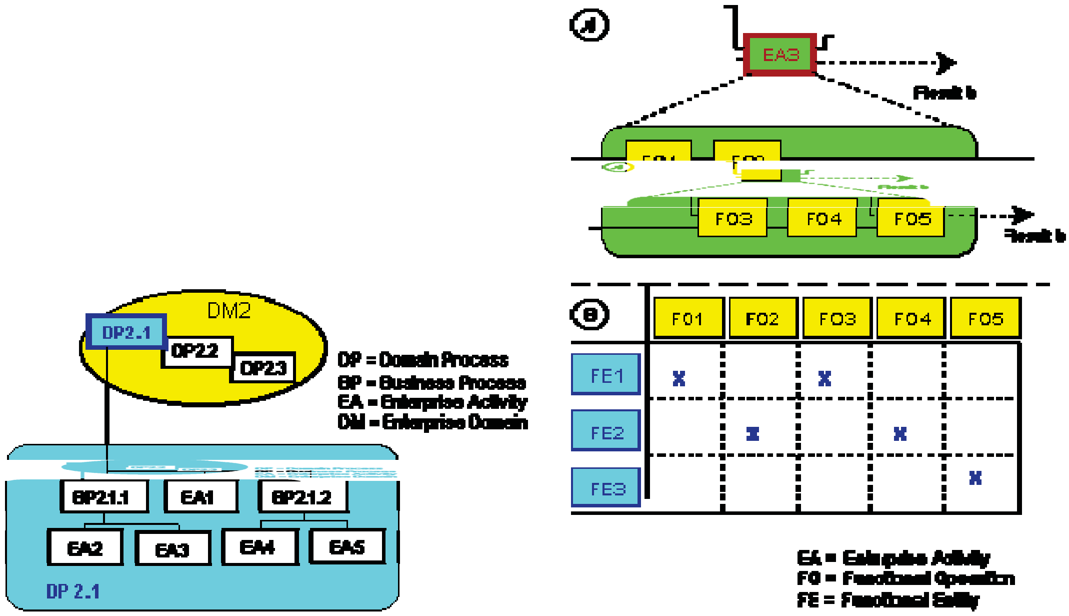


Figure 20: Domain process decomposition up to FOs and FEs (CIMOSA Association 1996)

Apart from its advantages, CIMOSA is limited due to non-availability of a prescriptive approach to producing models while using it. The following section will discuss requirements of a new integrated modelling approach to reconfiguring MEs.

4.7 Requirement of a new integrated modelling approach to reconfiguring MEs

During the previous two decades, a number of research institutes mostly in the UK, Europe and USA have presented active research in the field of EM including (but not limited to): (1) IFIP Task Force; (2) ISO / WGs; (3) MSI Research Institute at Loughborough University; and (4) NIST. A detailed list of key work related to EM is presented in Table 11. There have also been recent advancements to extend the coverage of public domain open system architectures either to advance EM or to bridge the gap between enterprise modelling and simulation modelling. Such enhancements include Monfared's approach (Monfared 2000; Monfared 2009), Chatha's E-MPM (Chatha 2004; Chatha et al. 2007), and Rahimifard and Weston's enhanced use of EM and SM techniques (Rahimifard et al. 2007). Apart from its benefits, CIMOSA is limited due to non-availability of a prescriptive approach to producing models while using it. This area has been addressed in part by Monfared's work at the MSI Research Institute. This major development has been the specified use of a graphical static diagramming approach to realising CIMOSA models. Monfared's approach utilises four graphical modelling templates; context diagram, interaction diagram, structure diagram, and activity diagram. The context diagram is used to define domains to be modelled. The interaction diagram shows interactions between dependant DPs. The structure diagram identifies, structures, and organises BPs and EAs that collectively comprise a DP. The activity diagram represents flows associated with EAs and BPs (Chatha et al. 2003). Collectively these diagrams support the decomposition of domains in to their constituent EAs. Table 12 shows a comparison of different EM approaches against an organisation design requirements set as outlined by Chatha (2004).

Table 12: Comparison of different EM approaches against enterprise design requirements set (Chatha 2004)

Organisation Design Requirements		**CIMOSA**	**Monfared's Process Modelling Approach**	**IDEF3**	**IEM**
Process Lifecycle		**	**	**	***
Multi-process oriented organisation structure enforcing decomposition principle	Multi-process oriented structure	*	---	---	---
	Decomposition principle	***	***	**	**
Generic process modelling language for generating semantically rich process specifications		**	***	**	**
Process modelling method to support process lifecycle		***	***	---	***
Modelling concept framework		****	---	---	---
Exception handling		**	---	---	---
Resource coordination		---	---	*	---
Coverage	*******Very High**	******High**	*****Medium**	****Low**	***Very Low**

Chatha (2004) developed the enriched multi-process modelling (E-MPM) method, at the MSI Research Institute. E-MPM built on Monfared's approach by enriching static models in order to close the static-simulation modelling gap. Monfared's approach provided a rich static representation of sequences of activities and allowed decomposition of domains in accordance with CIMOSA principles. It did not however support any real time interactivity with the process and its related information being modelled and encoded in a computer executable format. An appreciation of time was given in activity diagram but no mechanism was specified for change in state of activities, change in activity relationships and so forth. The elaborated behaviour of activity threads over time i.e. dynamics, were not therefore supported or represented in Monfared's approach. This led to the development of the E-MPM method (Chatha 2004). The aim of this approach was to extend Monfared's diagramming technique to encompass simulation and workflow aspects.

Rahimifard and Weston (2007) presented their initial work on transforming process segments coded by EMs into equivalent SMs. They observed technical, practical, business and social constraints on the widespread application of EM. They found primarily the technical factors that constrained on the use of current EM approaches had arisen mainly because contemporary public domain EM techniques provided limited capabilities to encode and computer execute temporal aspects of process networks. They also found that it was not practical to encode into a unified enterprise model all relevant (to enterprise organisation and its environment) causal and temporal entities and factors that can influence current and possible future ME behaviours. Even if this were technically feasible the realities of deciding "what such a model needs to encode", "populating given ME model instances with all needed (particular, semi-generic and/or generic) data", and "updating model instances to maintain their currency" could almost certainly not be economically justified (Rahimifard et al. 2007).

Rahimifard and Weston (2007) also found that it could only prove feasible to deploy a unitary simulation model to replicate and predict holistic ME behaviours at a very high level of abstraction. Hence for the foreseeable future it was presumed by Rahimifard and Weston (2007) that enterprise models would continue to major on representing relatively static properties of process networks which lend them to graphical representation, and that primary constraints would exist on the use of such models as shown in Table 13:

Table 13: Primary constraints for enterprise and simulation modelling approaches (Adopted from (Rahimifard et al. 2007)).

Modelling Approach	Primary Modelling Constraints
Enterprise Modelling	❑ Resultant models focused on relatively enduring aspects of MEs and do not encode time dependencies related to product flows, control flows, process instants, exception instances and time dependent causal effects. ❑ Resultant models cannot replicate real ME behaviours, say in support of model validation. ❑ Resultant models do not provide a basis for predicting future ME behaviours.
Simulation Modelling	❑ Because multi-perspective static and dynamic system properties are modelled together (often in an ill-structured way) simulation models have practical constraints if the model scope/detail/complexity grows. ❑ If a simulation model of an isolated ME segment is created, this model cannot readily be interpreted in its context of intended use.

The combined use of EM and SM is being utilised to support organisation design and change decision making. Rahimifard and Weston (2007) believed that further research is needed to investigate the interplay between enterprise models and simulation models. They observed that supported EMs and their embellishments usefully encoded a restricted but coherent set of relatively enduring entities, entity relationships and properties which could be used to facilitate the design and building of coherent SMs. EMs offer significant potential as a repository of reusable model structures, modelled entities and specific ME knowledge and data. These can be reused when creating SMs. Indeed in principle multiple and coherent sets of SMs can be created at required levels of abstraction and used to replicate, analyse and predict activity, process segment and whole process network behaviours. The key is to reuse model structures as opposed to reuse specific enterprise data (Rahimifard et al. 2007). Simulation model builders will still need to capture dynamic properties of enterprises and conduct experiments that test the validity of models before they are used to support ME design decision making. However, the structural knowledge captured by EMs naturally guides needed structuring of SMs, SM experiments and dynamic data capture. A key promised reuse of model structures lies in the potential to realise interoperability between multiple SM, because the EM captures a domain ontology, which SM building and execution can conform to (Rahimifard et al. 2007).

The current state of the art in EM is limited in enabling coherent reusable models during all life cycle stages (Chatha et al. 2007). In order to make manufacturing systems reconfigurable, enterprise models need to be reusable when and where needed. For this purpose, different modelling techniques should be consistent and interoperable. In this agile manufacturing age, MEs need to be reconfigurable and so must the models. The enterprise models need to be transformable into multiple simulation models. It follows that, by enabling the capture and reuse of multiple perspective enterprise models, in principle current generation EM approaches offer significant potential to help groups of ME personnel collectively re-engineer their businesses on an ongoing basis. However in practice where EM has proven beneficial generally its full range of potential benefits have not been achieved (Chatha et al. 2007).

A further practical consideration when creating simulation models is that the models created should be structured so that systematic change of model parameters is enabled. It is of vital importance as it can minimise the complexity and time involved when exercising simulation models built at any given abstraction level. The focus of the modelling and integration should be on systematic reuse of fragments of an enterprise model in such a way that simulation models that are designed to exercise proposed organisation changes or reconfigurations can be (i) generated more rapidly and effectively, (ii) used to analyse and predict the impact of alternative change configurations and recommendations bearing in mind the specific context in which the organisation will need to operate and (iii) help structure decision making about organisation change or reconfiguration and (iv) provide a basis for managing and enacting (small and large scale) change or reconfiguration (Rahimifard et al. 2007). It follows therefore that there is a need to develop an enhanced integrated modelling approach to support the life-cycle reconfiguration of future MEs.

Chapter 5

Integrated Modelling Approach to the Reconfiguration of Manufacturing Enterprises

5.1 Motivation and introduction

Research challenges were identified in the literature review. Some key research challenges identified of concern in this study are listed in the following:

1) How to cope with customer related uncertainties and complexities in a manufacturing business;

2) Lack of structured, explicit and quantitative modelling methods to design and develop planning and control systems that can address research challenge 1 for different types of manufacturing systems;

To address these research challenges, an innovative integrated modelling approach (IMA) to reconfiguring MEs is proposed and presented in this chapter. The chapter comprises six sections. Section 5.2 describes the context and specific need for the IMA. The principles and steps in IMA are described in section 5.3 and formally represented using IDEF0 diagrams in Section 5.4. Section 5.5 considers issues related to the industrial application of the IMA. Reflections and conclusions are presented in section 5.6 followed by a discussion on future research directions in section 5.7.

5.2 Business environment and specific need for the IMA

In a typical business environment, customers request a manufacturer to produce a given quantity of a product (or products) in an agreed or required time frame. Often products requested by different customers vary from one another and this variance forms one source of complexity with which the production system must deal, commonly where customer orders are placed. The variance can also change over time, e.g., when new or customised products come on stream. Another dimension of complexity is the volume or quantities in which products are required to be made. As the number of orders and/or numbers in each order increases it becomes more difficult for the production system to cope with the demand. Therefore, the product dynamics (PD) includes product variance (ΔP), volume variance (ΔV) hence CO variance (ΔCO) which is composite of ΔP and ΔV. It follows that to cope with customer related change in any business environment, any production planning & control system (PPCS) is required to play an important role to attenuate unwanted dynamic impacts on available but limited production resources. The PPCS can be viewed as generating a work dynamic (WD) which is an attenuated form of PD and is used as input to processes (P_r) and resources (R_e). The PPCS can use various control algorithms to seek to optimally deploy P_r and R_e elements so that product outputs can be achieved responsively. Figure 21 shows typical customer related impacts in a conceptualised combined business, engineering and manufacturing environment.

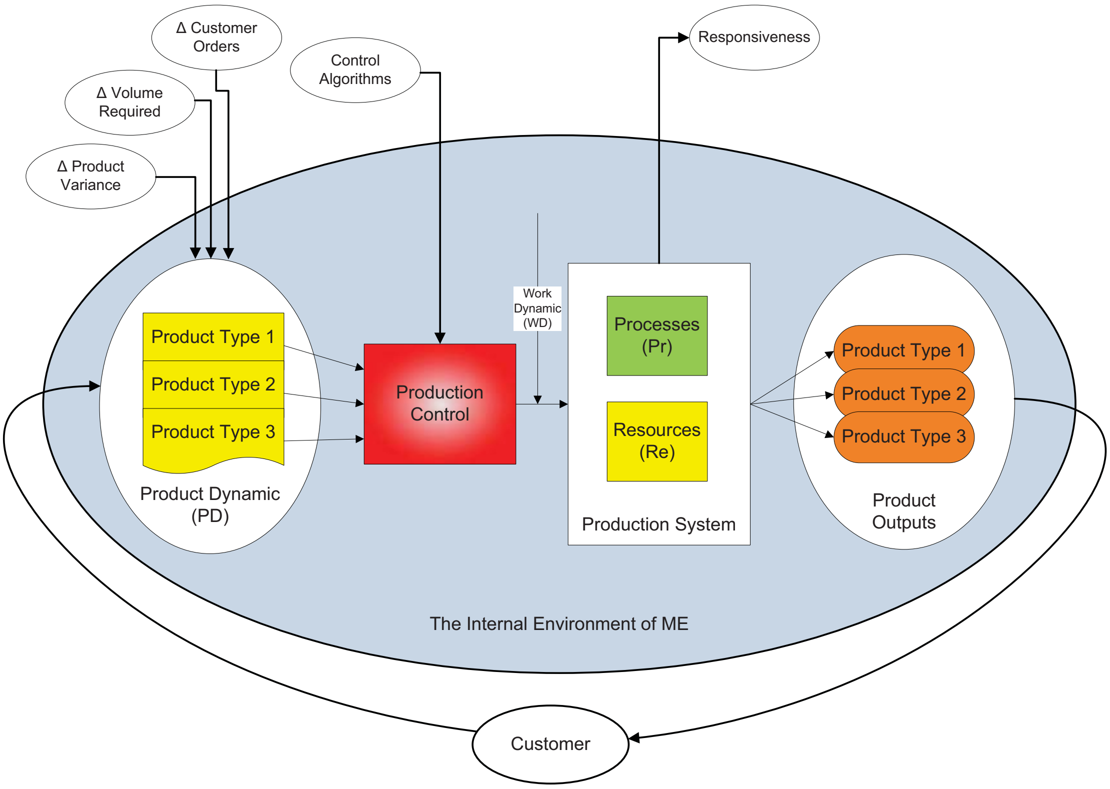


Figure 21: A typical business environment

The design of a production system is typically greatly influenced by the nature of the product and work dynamics as shown in Figure 21. Therefore the PPCS aims to reduce impacts on production systems of the rate of change in product design and demand. The PPCS may be seen as a place where impacts arising from the rate of change in COs, product types and design are relatively fast (i.e., significantly dynamic). Most likely in comparison R_e goes through medium changes while the P_r goes through slow changes. Hence ideally, where possible there is a need to decouple P_r-R_e couples from PPCS, so that it becomes possible to optimize work loads by flexibly distributing those loads. The need also arises to understand the dynamic impacts of changes in customer requirements, such as on (a) the design of production system decisions and (b) production engineering decision making related to process plans, production schedules, and the sequencing and control of work. Ideally any future approach needs to consider such dynamics and their inter-relationship. This mainly concerns understanding, representing, computer executing and virtually experimenting the relations between the WD, P_r and R_e while also considering the impacts of WD on P_r and R_e (Cui et al. 2009). The changes in WD come from the way in which the PPCS attenuates the PD. While the ability of any production system to cope with a generated WD will depend on characteristics of its Pr and Re sub systems and how these are configured and programmed into a production system.

Modelling approaches have a potentially significant role to play in enabling decision making and in supporting systems composition. This can include PPC strategy selection to facilitate responsive manufacturing. BP analysis aided by EMI can reduce risks and improve the chances of implementing successful BPs. It also enables organisations to capitalise knowledge so that they can react by changing operations in an effective, efficient and responsive manner. Systematic decomposition and analysis of complex systems is possible with the aid of supporting architectures and by using complementary modelling techniques which can include EM, CLM, SM and Work Flow Modelling (WfM) (Weston et al. 2006). The models of ME processes, resource systems and workflows so created need themselves to be reconfigurable and interoperable in order to synchronise between virtual and real elements of processes and systems that need to interoperate within dynamic (often uncertain) environments (Weston et al. 2007). In principle, by achieving integration of different modelling approaches, new opportunities will arise to make the models live and responsive to upcoming but 'yet to be determined' rapid changes (Weston et al. 2007).

5.3 The Proposed IMA to reconfiguring MEs

In this section it is explained how PPC problems arising in the context described in Section 5.2 can be addressed via an initial step-wise IMA which is conceived to support the reconfiguration design of MEs. IMA is new process-based, modular approach which is proposed with a view to achieving system composition from reusable systems modules. The proposal is founded on use of ME design and change principles that include the following: (a) the modules can be flexibly (re)configured or (re)composed into higher level modules or systems; (b) the modules are flexible configurations of human and technical (machine + IT) resources that possess abilities to realise defined goals; (c) the modules can be (re)programmable resources, i.e., can possess changeability enabling them to reach various states within their design envelope; (d) processes are decomposed into feasible roles that modules can realise; and (e) modules can be attributed to one or many roles, therefore their actual assignments to roles need to be scheduled and controlled in order to achieve the desired responsiveness.

The following steps are proposed for the IMA to reconfiguring MEs, so as to support design change decision making as illustrated in Figure 22:

Step 1: Use of EM to create and validate visual process maps that provide a 'big picture' of the reality in the organisation and its segments;

Step 2: Use of EM concepts and tables to populate process maps with 'resource' and 'work' data;

Step 3: Use of SMs to replicate existing behaviours and predict potential future behaviours arising from decision making; and

Step 4: Use of SMs to predict potential future (TO-BE) behaviours arising from decision making.

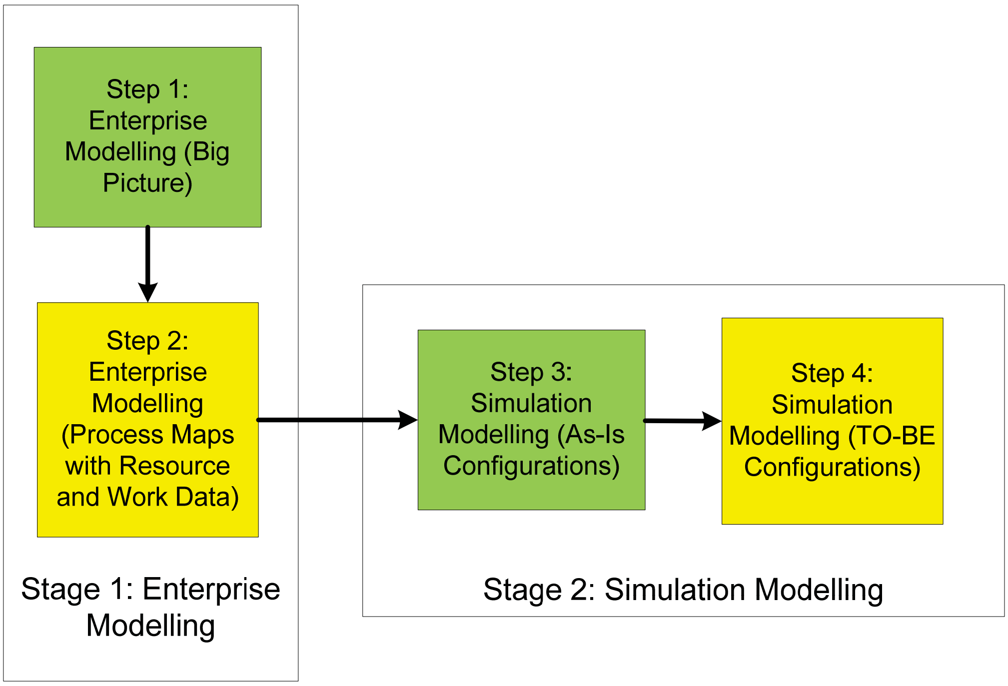


Figure 22: The IMA to reconfiguring MEs

The IMA, in its initial and enhanced versions, has been published by the present author in synonymic forms that are included in Appendix B (Masood 2007; Masood et al. 2010b; Masood et al. 2010a; Masood et al. 2008a; Masood et al. 2008b).

5.4 Design of the IMA to reconfiguring MEs

The proposed IMA to designing the reconfiguration of MEs is explicitly documented in this section by using the well established Integration Definition for Function Modelling (IDEF0) standard. The IDEF0 method is adopted here because: (1) it can usefully model the IMA design steps; and (2) it is a well established function modelling standard issued by NIST, USA. In this standard method a square box is used to denote manufacturing functions along with arrows to show inputs (arrows from left), controls (arrows from top), mechanisms (arrows from bottom) and outputs (arrows stemming outwards right) (NIST 2009). The IDEF0 method is shown in Figure 23.

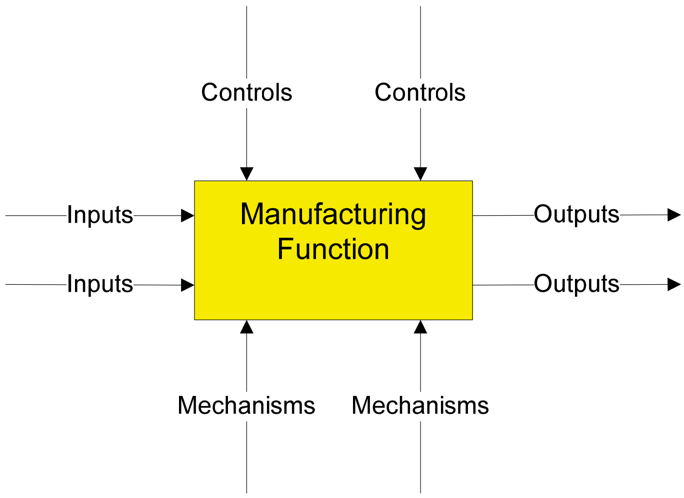


Figure 23: The IDEF0 method (NIST 2009)

Changes in COs, products and work related dynamics impact upon the need to redesign a responsive manufacturing system. The proposed purpose for the IMA is to facilitate the (re)design process of the reconfiguration of the ME by making use of the modelling concepts and the decoupling of Pr-Re couples. This is intended to result in identified ways of improving the reconfigurability and responsiveness of a manufacturing system. Figure 24 shows the main IDEF0 diagram for the proposed IMA in order to facilitate (re)design of the reconfiguration of MEs.

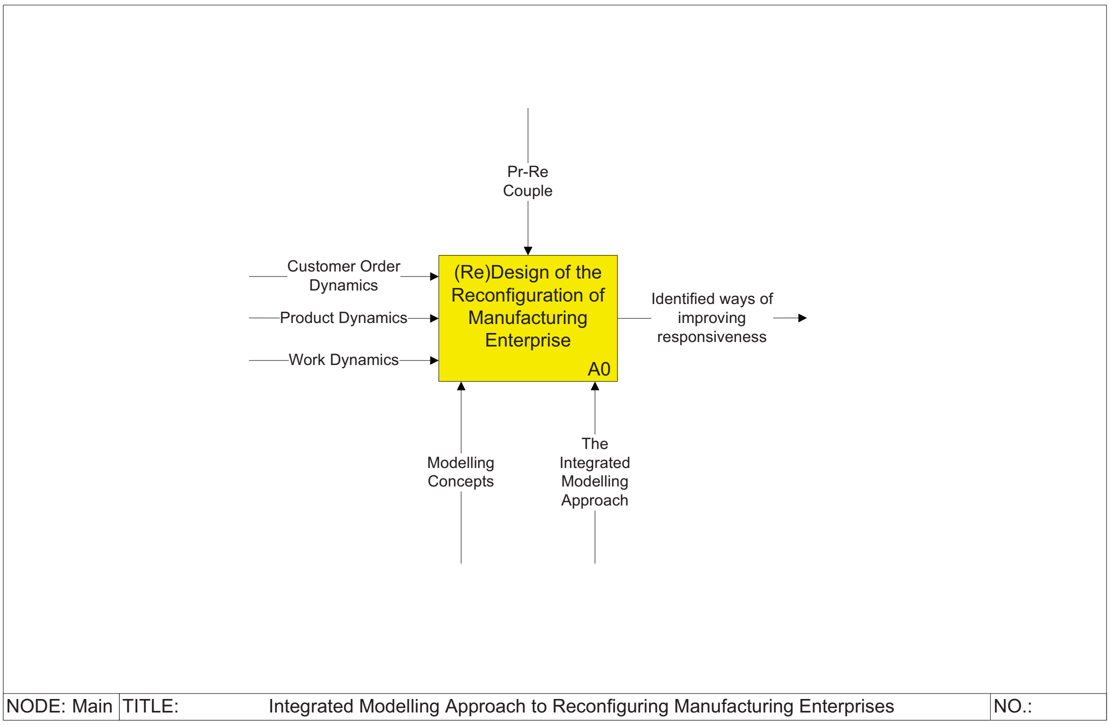


Figure 24: The IMA to reconfiguring MEs (Main)

The following design steps are proposed while undertaking IMA: (a) create enterprise models; and (b) create simulation models. While creating enterprise and simulation models, a specific modelling formalism is followed while keeping in mind overall objectives. Different modelling blocks and identifiers are used to uniquely represent models in terms of CIMOSA and non-CIMOSA domains, activities, events, information, physical and human resources, flow of processes, resources or materials, alternative flows and finances. Key Performance Indicators (KPIs) are used to benchmark designed manufacturing performances with reference to overall objectives. Figure 25 shows the design steps undertaken for the IMA.

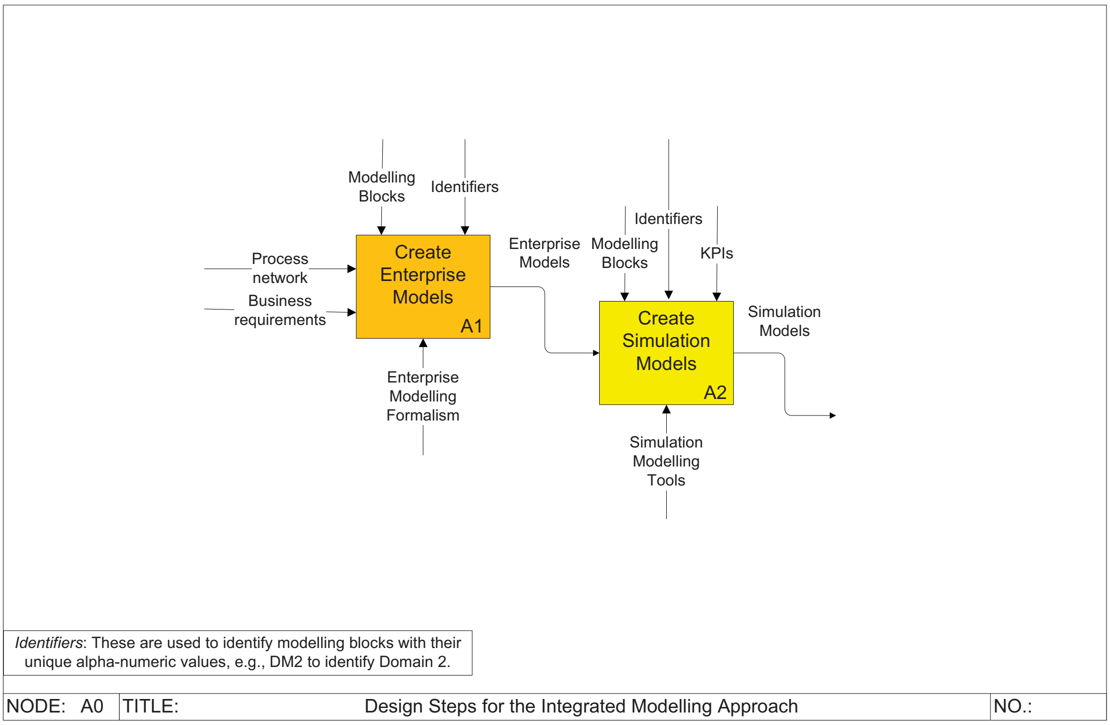


Figure 25: Design steps for the IMA (A0)

5.4.1 Design steps for creating enterprise models (A1)

The following steps are undertaken while creating enterprise models: (1) create context diagram(s); (2) create structure diagram(s); (3) create interaction diagram(s); and (4) create activity diagram(s). While creating enterprise models, related EM formalisms are followed while keeping in mind overall objectives of the exercise and CIMOSA and non-CIMOSA domains. Different modelling blocks and identifiers are used to uniquely document enterprise models. Figure 26 shows the modelling sequence followed while creating enterprise models.

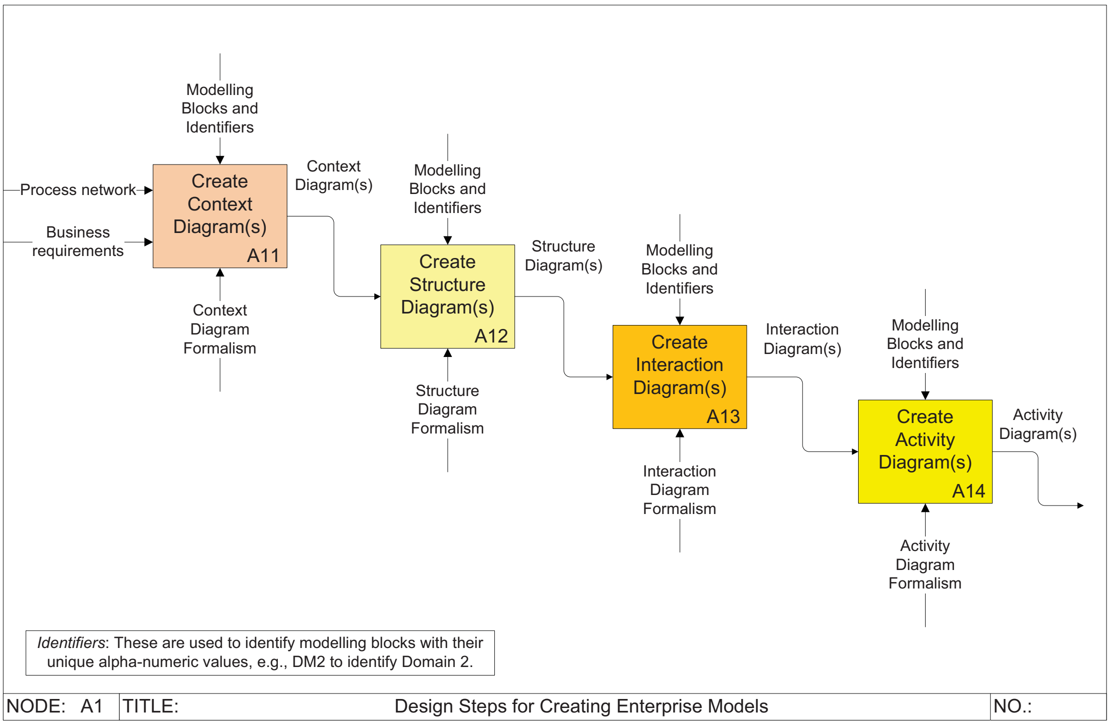


Figure 26: Design steps for creating enterprise models (A1)

5.4.1.1 Design steps for creating context diagram(s) (A11)

The overall objective of creating a context diagram is to determine the scope of involvement from a process-oriented point of view. It is written in the manner "verb + noun", meaning like "something is being done, or going to be done". It represents a process as a central concern not a function. Things involved in realising this objective are domains associated with that objective. CIMOSA domains are represented using oval-shaped modelling blocks, and non-CIMOSA domains with crossed-out oval shaped modelling blocks. Domains are named as "nouns". Identifiers are assigned to domains as (DM + unique number). Figure 27 shows the steps undertaken for creating context diagram(s) as follows: (1) Identify and document related CIMOSA DP(s); (2) Identify and document non-CIMOSA DP(s); and (3) Identify and assign identifiers to DP(s).

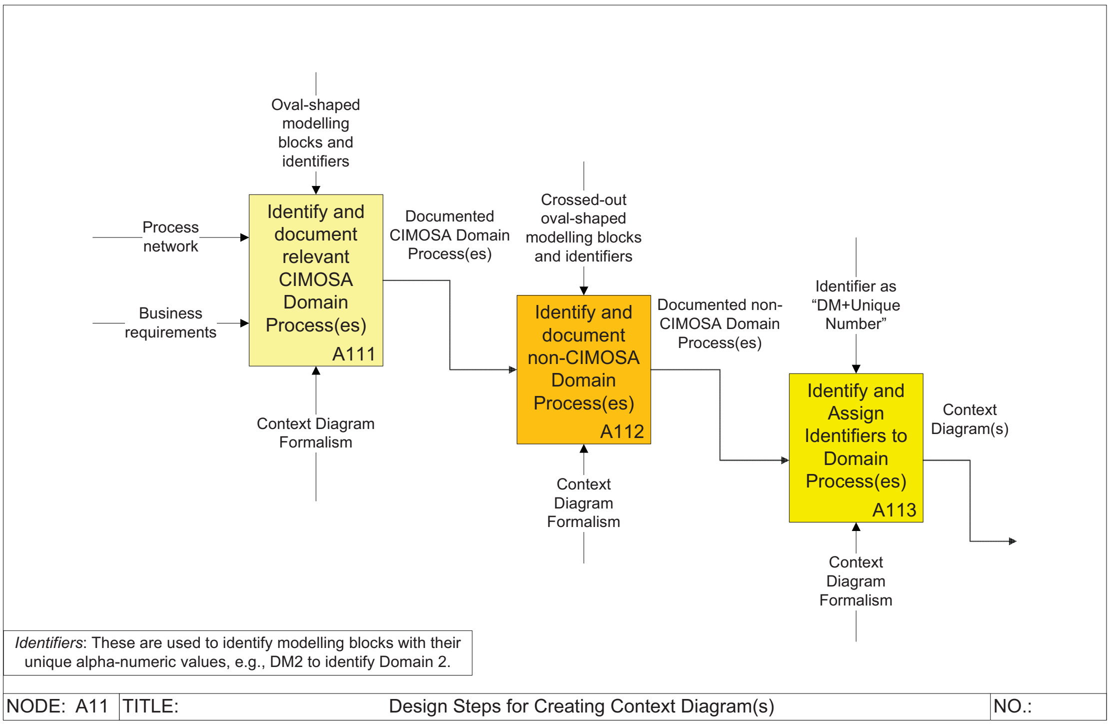


Figure 27: Design steps for creating context diagram(s) (A11)

5.4.1.2 Design steps for creating structure diagram(s) (A12)

Generally, one top level structure diagram may be developed for each domain under consideration. The DP is represented in the centre of the diagram while developing the structure diagram. The BPs involved in a DP are identified and associated with the DP. Identifiers are given to BPs as (BP + domain identifier +unique BP number). Sub-BPs and EAs are identified for each BP. The EAs are represented under each BP. Identifiers are given to sub-BP as (BP + BP number + sub-BP number). Identifiers are given to EAs as (EA + BP or sub-BP or DP number + unique EA number). Figure 28 shows the design steps normally undertaken for creating structure diagram(s) as follows: (1) specify and document structure diagram(s); (2) identify BP(s) involved in this DP and assign identifiers; (3) identify and assign identifiers to sub-BP(s); and (4) identify and assign identifiers to EAs.

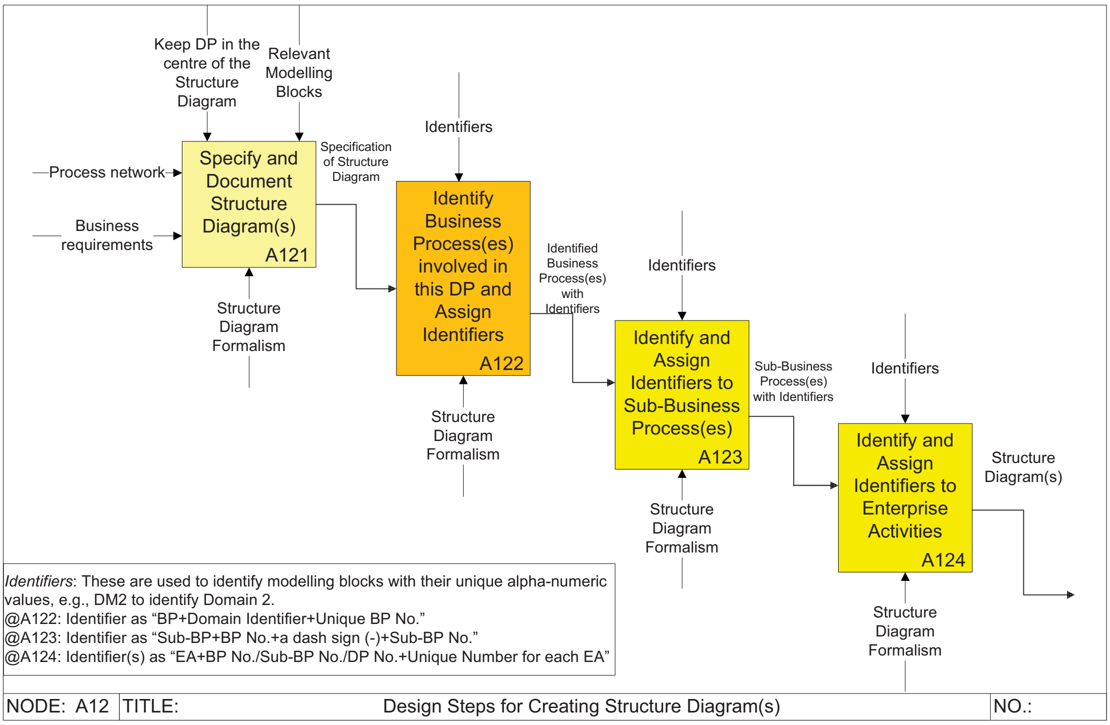


Figure 28: Design steps for creating structure diagram(s) (A12)

5.4.1.3 Design steps for creating interaction diagrams(s) (A13)

One top level interaction diagram can be created for each objective under consideration. The top level interaction diagram is created by considering interactions between domains involved in the context diagram(s). Those interactions are considered to occur between DP(s) owned by the interacting domains. Identifiers are assigned to DP(s) as (DP + domain number). Between any two DPs, only information, human resource(s), physical resource(s), event(s) and finance are represented in interaction diagram(s). One interaction diagram is created for each domain under study. In subsequent interaction diagrams, DPs are decomposed and represented as sub-DPs or BPs. A DP not under consideration is represented as an external link. While creating sub-interaction diagrams, domains under consideration are represented in terms of either their sub-DPs or BPs. Decisions are taken on the basis of ease in the modelling effort, understandings to be developed and subsequent need for development of structure diagrams. Identifiers are assigned to sub-DPs as (DP + parent DP number + unique number of this sub-DP); and to BPs as (BP + parent DP number + unique number of this BP). Figure 29 shows steps undertaken for creating interaction diagram(s) as follows: (1) specify and document interaction diagram(s);

(2) identify BP(s) involved in this DP and assign identifiers; (3) identify and assign identifiers to sub-DP(s); and (4) identify and assign identifiers to BP(s).

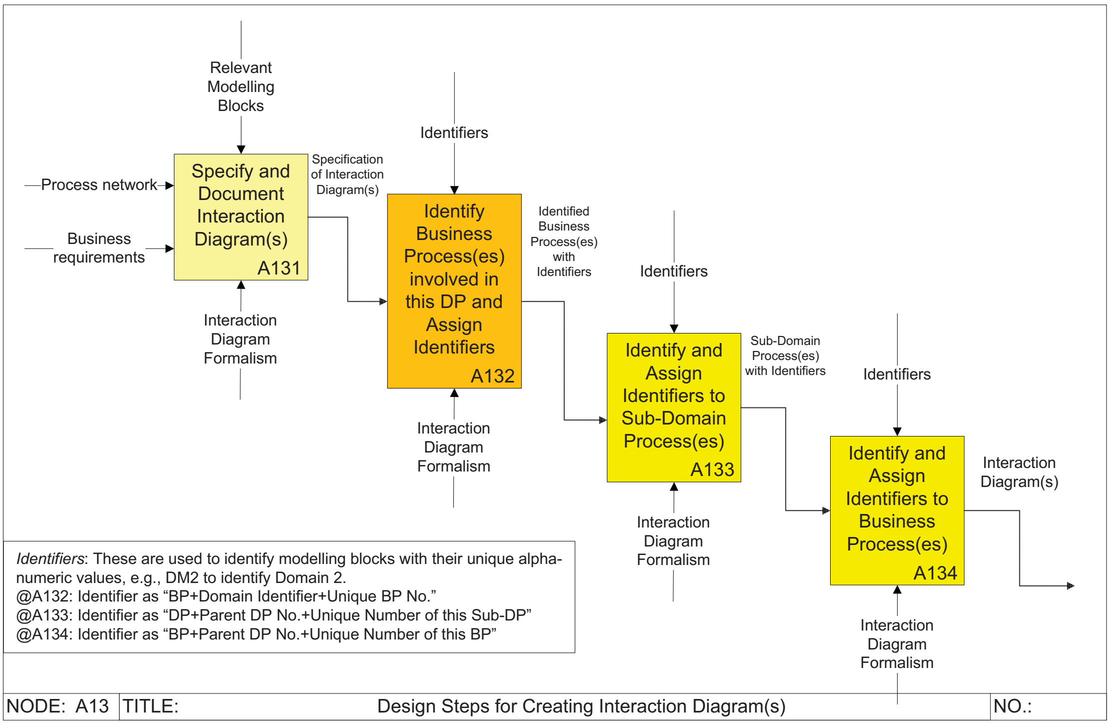


Figure 29: Design steps for creating interaction diagram(s) (A13)

5.4.1.4 Design steps for creating activity diagram(s) (A14)

The activity diagrams are normally developed from structure diagrams, so that their development remains positioned in the context of their parent enterprise. The EAs, BPs and sub-BPs, as identified in structure diagram, are sequenced together using the notations developed for activity diagrams. A complete end-to-end process is represented using activity diagram formalisms with dependencies among EAs/BPs. The flow of process, control, and resources is represented in activity diagrams. If an end-to-end process can not be accommodated using one template then further templates may be added with dependencies shown between any two templates. It is important to place EAs/BPs on activity diagrams with respect to a time line at the bottom of the activity diagram. Figure 30 shows steps undertaken for creating activity diagram(s) as follows: (1) specify and document activity diagram(s); (2) represent complete end-to-end process with dependencies among EAs/BPs; (3) represent the flow of process, control and resources; and (4) carefully check that the EAs/BPs are appropriately placed with respect to the time line.

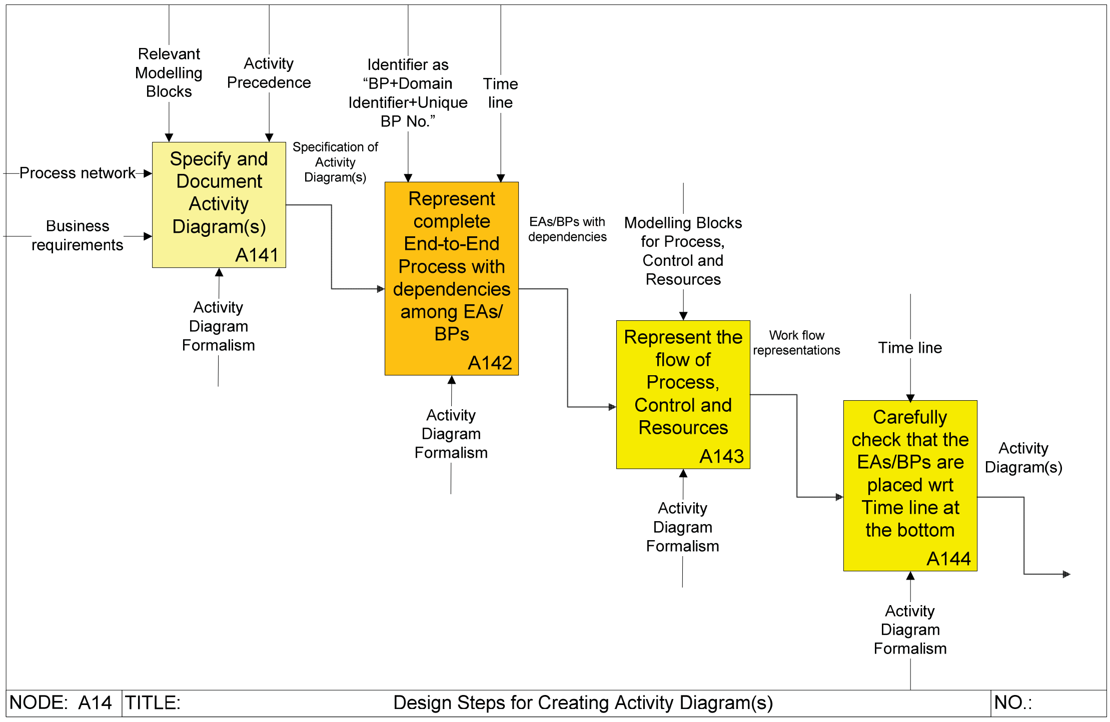


Figure 30: Design steps for creating activity diagram(s) (A14)

5.4.1.5 Analysis of EM tool set

The EM templates facilitate the process of IMA application in an enterprise. These EM templates basically provide a base for EM. Following which SM can be conducted based upon knowledge and data previously coded using enterprise models. The EM templates make use of the following formalisms:

1) General blocks – that includes CIMOSA domain, non-CIMOSA domain, activity, external link and event;

2) Resources – that includes information (resource), human (resources), physical (resources) and finance (related resources);

3) Flow control logic – that includes conditional (logic), OR (logic), AND (logic), sub-process, chained process and delay;

4) Flow types – that includes flow of resource, flow of process and alternative flow; and

5) Operation types – that includes direct generation, direct supportive and indirect supportive (operation types).

Figure 31 shows the EM template that can be used as a basis for creating enterprise models.

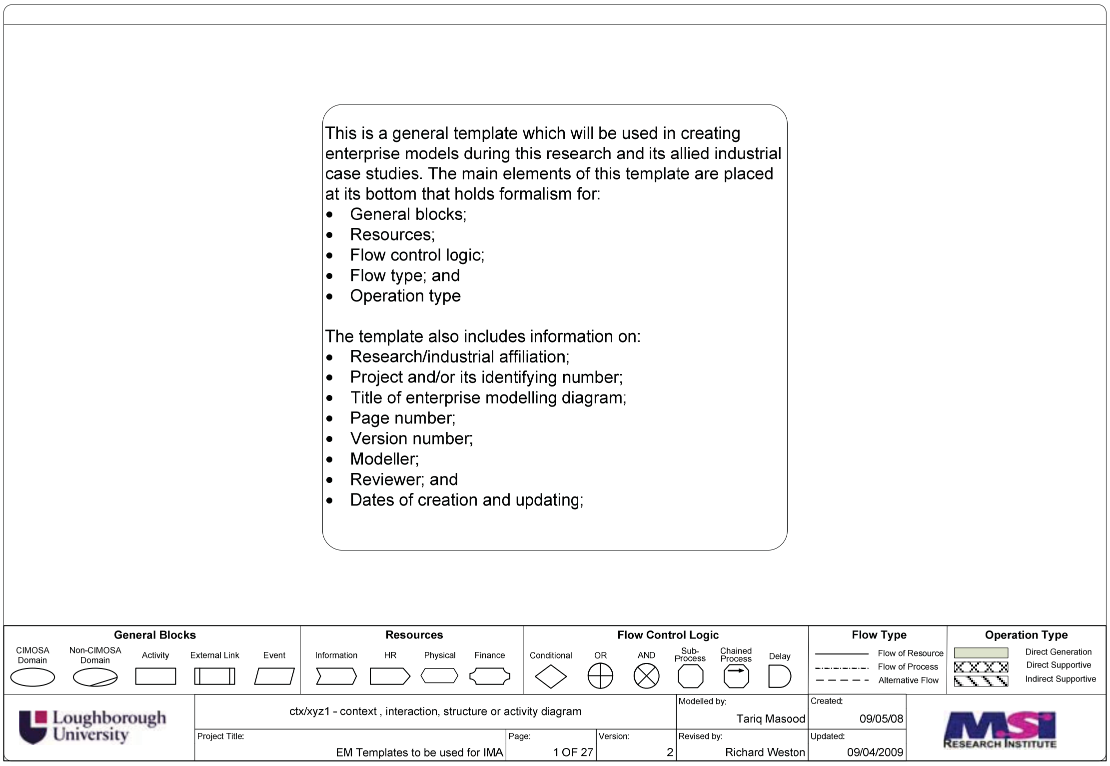


Figure 31: EM template for creating enterprise models

Figure 32, Figure 33, Figure 34 and Figure 35 show an example use of context diagram, interaction diagram, structure diagram and activity diagram respectively.

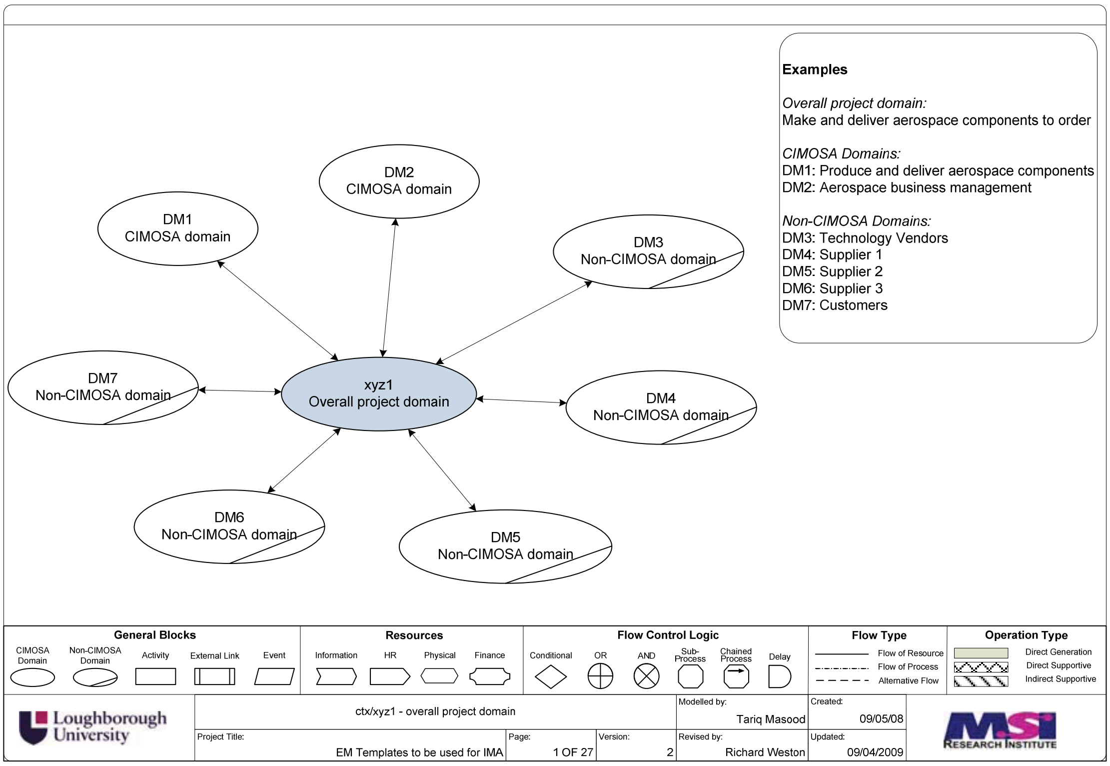


Figure 32: Example use of EM template for 'context diagram'

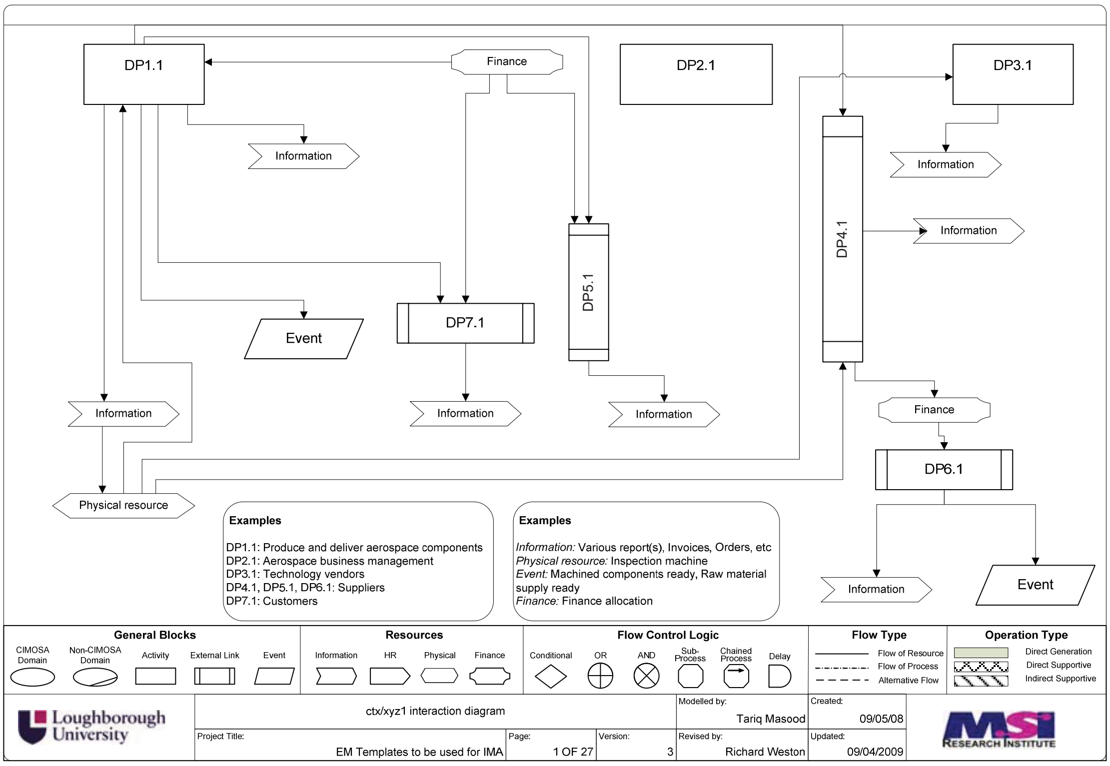


Figure 33: Example use of EM template for 'interaction diagram'

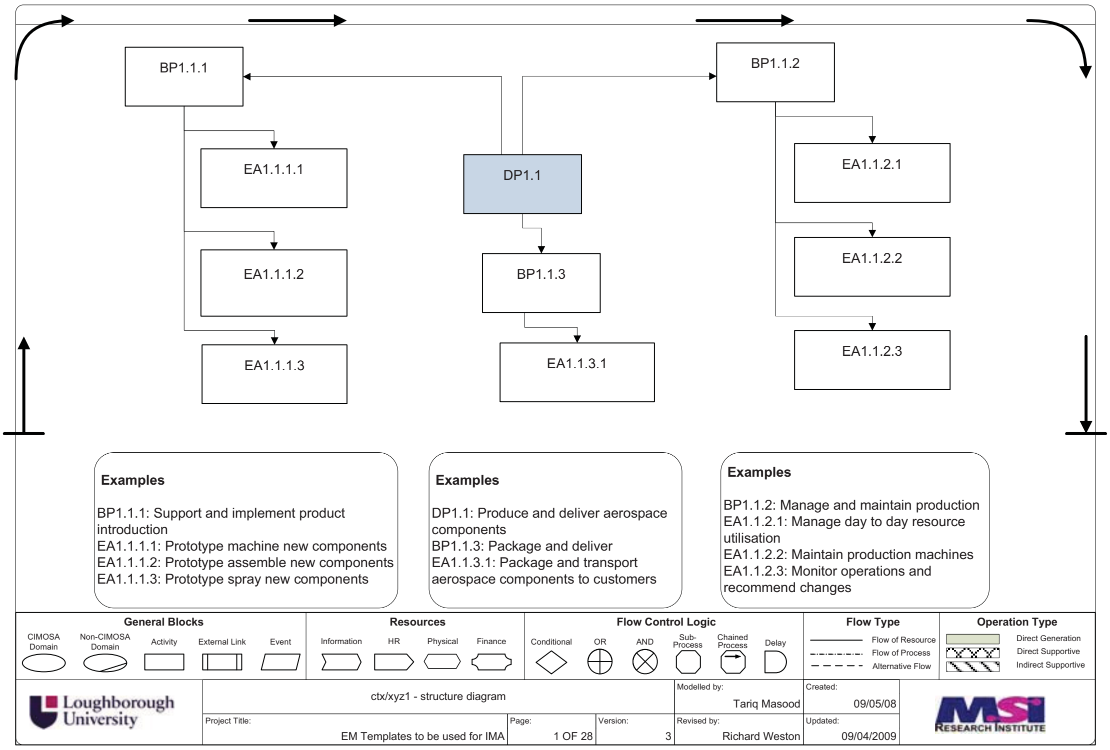


Figure 34: Example use of EM template for 'structure diagram'

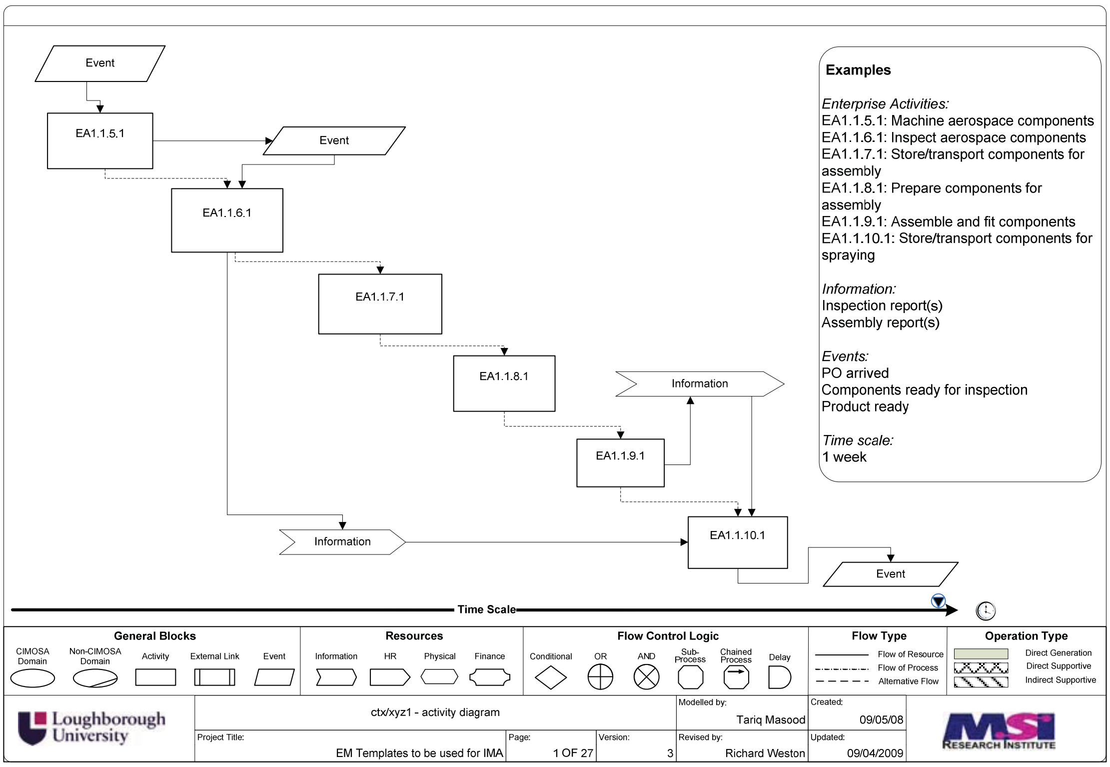


Figure 35: Example use of EM template for 'activity diagram'

5.4.2 Design steps for creating simulation models (A2-1 and A2-2)

The design steps for creating simulation models are listed in the following: (1) gather simulation requirements; (2) select SM tool; (3) create AS-IS simulation model(s); (4) verify and validate the AS-IS simulation model; (5) create TO-BE simulation models; (6) verify and validate the TO-BE simulation models; (7) analyse results; and (8) implement TO-BE simulation models (where applicable). Figure 36 and Figure 37 show design steps undertaken for creating simulation models (A2-1 and A2-2).

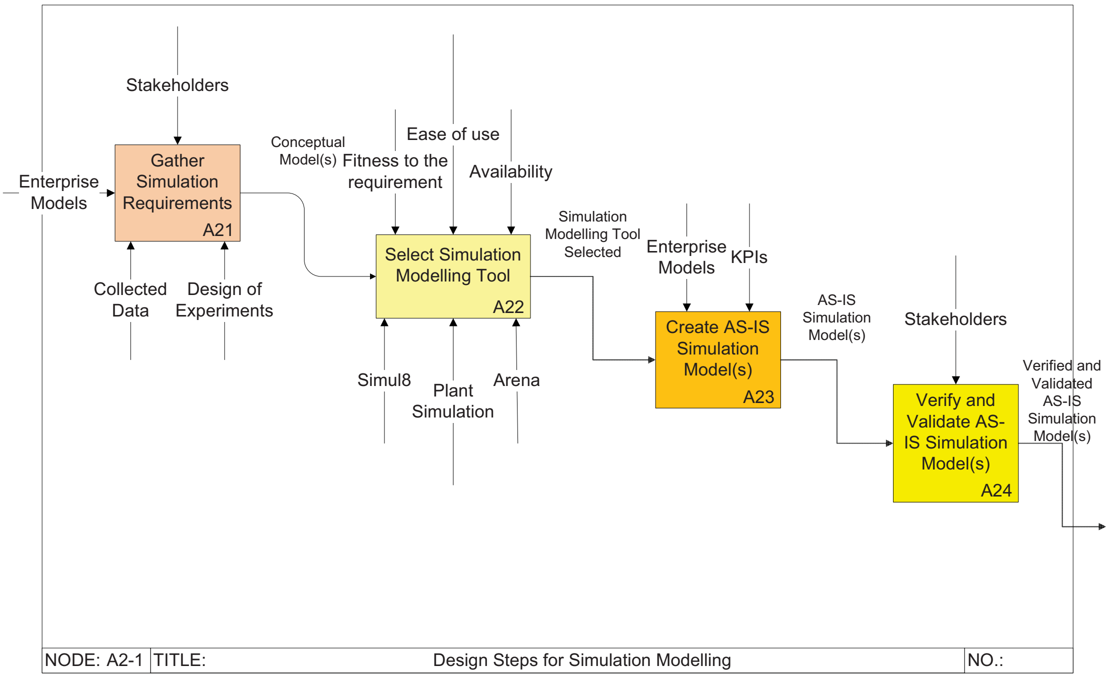


Figure 36: Design steps for creating simulation models (A2-1)

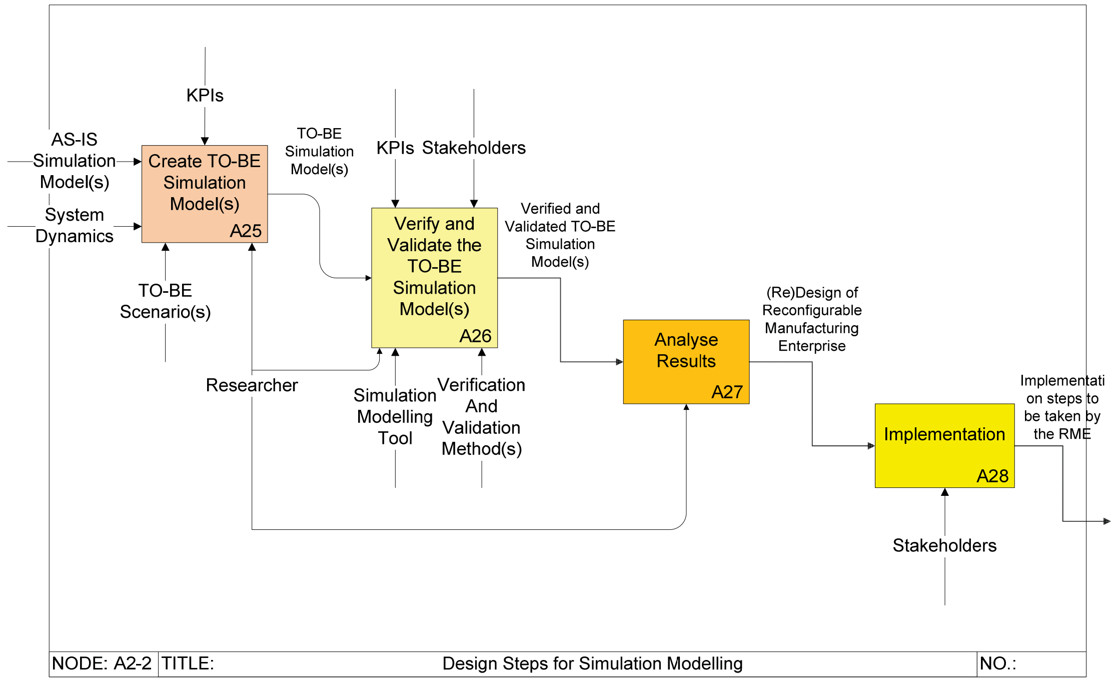


Figure 37: Design steps for creating simulation models – continued (A2-2)

The design process from 'AS-IS configurations' to 'TO-BE configurations' is based upon the specific problem requirements. This design process is affected by the fact that the problem is top-down or bottom-up. The undertaken research is focussed on cases where top-down design approach based upon ISO standardised CIMOSA is adopted. The design process from 'AS-IS configurations' to 'TO-BE configurations' is based upon the following:

- Results of AS-IS simulations;
- KPI sets used to assess performance of AS-IS configurations;
- TO-BE business and engineering process model requirements to accommodate unforeseen business changes;
- System dynamics involved in the transformation process from AS-IS to TO-BE configurations;
- Re-use of existing AS-IS model components according to TO-BE model requirements;
- Alternative reconfigurations available for TO-BE models; and

- Assessment of the migration path from AS-IS to TO-BE model configurations.

5.4.3 Analysis and selection of SM software tool set

It is assumed that a set of computer and manual technologies and systems will be used to understand the problem scenarios, execute the IMA and provide suitable interfaces to users and modellers for decision making. In this author's research, MS Visio® is used to create static enterprise and causal loop models. Simul8®, Plant Simulation®, Arena®, and iThink®/Stella® were among candidate proprietary software packages used to create simulation models along with MS Excel® as data interfacing tool at some instances. The selection of a specific software tool set will normally depend upon (1) model requirements; (2) model KPIs; (3) modeller's capability to successfully model the required configurations; (4) acceptance of results by the peers; and (5) availability. Table 14 shows author's capability set for selected simulation software tools.

Table 14: Author's capability set for selected simulation software tools

Selection Parameters	**Simulation Software Tool Set**					
	iThink®/ Stella®	*Simul8®*	*Plant Simulation®*	*Arena®*	*Matlab® / Simulink®*	*Petrinets*
Model requirements	CD	CD	CD	CD	CD	CD
Model KPIs	CD	CD	CD	CD	CD	CD
Modeller's capability	G	G	G	G	A	G
Peer acceptance	G	G	G	G	A	G
Software availability	G	G	G	G	G	G

G=Good, A=Average, L=Low, CD=Context Dependent

Other configurations and case studies by the author and his research colleagues have successfully utilised these software tool sets. Such interfaces enabled this author to: (1) capture requirements data; (2) input data into models; (3) reconfigure a simulation model to meet various specified needs; (4) conduct various experiments based upon different configurations; (5) collect results; and (6) conduct analysis of results.

The rationale for the use of different simulation software tools to undertake various case studies was:

- Changing simulation model requirements on case to case basis;

- Easier incorporation of KPIs into simulation models;
- Capabilities of the researcher and or the case study company modeller(s) to successfully model the required configurations;
- Acceptance of simulation model results by the peers;
- Availability of the software tool to the researcher and or the case study company for current research and future use.

It is intended to demonstrate that the application of the proposed approach is independent of the choice of simulation software. Hence, the use of three different simulation software tools provides a test of independence of the IMA/EIMA from any particular piece of software making it adaptable in at least three (or possibly more) industrial cases. The use of different simulation software tools will result in an additional variability which make the comparison of case studies' results more difficult. However, due to the nature of different businesses and specific problem domains and respective KPIs, it is difficult to compare results.

In addition to their case specific technical requirements, Arena® is chosen in Ford case partly because the Ford modellers at other plants are already using this software tool and it would be easier for the PD Factory to establish a link with them in future. Also, the onsite engineers are familiar with this piece of software. Simul8® is chosen in Bradgate case partly because researchers of Loughborough University (MSI Research Institute and CECA) working on Bradgate case are also using Simul8® so it is easier to discuss model inputs and results with them. Plant Simulation® is only used for advanced levels of the ACM case study during this research, i.e. where advanced controls are needed for simulation model development purposes.

5.5 Significance of the IMA to reconfiguring MEs

The IMA to reconfiguring MEs is an important development. The significance of its use is identified in the following:

- A structured way of modelling static and dynamic aspects of MEs with induced change capability;

- Reduced time and effort needed to reconfigure MEs in the event of changing requirements and conditions;
- Ability to extend integrated ME models in a stepwise, flexible, and extendable way;
- Reduced system complexity;
- Ease of reengineering processes;
- An advance in modelling MEs leading to practical implementation of the proposed modelling approach;

5.6 Need for industrial application of the IMA

Chen et al (2008) concluded that there had been a weak impact of enterprise architecture research in industry and insufficient maturity of standards on enterprise architectures including CIMOSA and GERAM in the past two decades (Chen et al. 2008). Hence it is important to know how to apply the IMA in general and then more specifically to the enterprise where users wish to implement it. Even though significant work has been done on enterprise application integration during past two decades but there are still several issues that have not been addressed, and they need to be studied further. One of such issues concerns ways of predicting the evolution of a particular piece of software or paradigm (Radhakrishnan 2003). This issue is crucial to achieving a near optimal trade-off for a particular enterprise between short-term gain and long-term suitability. A company could invest in an enterprise application software system today in order to obtain better support to its existing business functions, but software has a life and can become obsolete, say in 2-3 years. The obsolescence of this particular software may bring some constraints for introducing other new software systems due to their inability to communicate with the existing software. This issue could also be viewed in another way, namely how could one make decisions under uncertain situations (including uncertainty in the evolution of any selected software tool)? The proposed IMA intends to be generic in a sense that it could (re)use existing organisational resource systems (hardware, software, human) and organisational structure in order to achieve the benefits of 'openness', 'standardised view', 'low-cost of change' and 'easier adaptation by the organisation and its stake holders', to name a few. The following section will explain the selection criteria and relationship between various case studies to be undertaken during this research.

5.7 Selection criteria and relationship between case studies

The selection of case studies for implementation of the IMA and its enhanced version shall mainly depend on following criteria:

- Suitable complexity of design of assembly and production systems is required in the selection of industrial case studies for this research;
- The first case study should be of explorative nature and could be chosen from any suitable industrial sector;
- This first case study should potentially be capable of application of the initial stepwise IMA in terms of initial data collection and modelling;
- Case studies 2 and 3 should be more complex in nature to partially test the ideas developed during the first case study;
- Case studies 2 and 3 should be from different industrial sectors than that of the first case study and of different industrial size so that to see generality of the approach partially;
- The selection of case studies may be limited to available industrial collaborators for this research.

The available industrial collaborators to this research study were from automotive, furniture and composite bearing manufacturing sectors covering and fulfilling the complexity of design of assembly and production systems. The collaborating companies were facing problems of planning and control at pre-production and production stages and were willing to see and apply results of the IMA. Seeing the nature of the industrial problems and their scope, it was feasible that the pre-production control problem of automotive sector be taken as first explorative case study for this research. Then move forward to the production control problems of two different SMEs from different industrial sectors namely furniture and composite bearing manufacturing for second and third case studies for this research. The learning gained from application of the IMA in the first case study is expected to be applied in its enhanced form to the second and third case studies. Final chapters of this thesis will discuss application and outcomes of the initial and enhanced IMA in three different case studies.

5.8 Reflections and conclusions

The IMA to reconfiguring MEs is proposed in this chapter and is illustrated through IDEF0 diagrams. It is composed of an integrated use of EM and SM which is described in this chapter in detail. The development of the IMA also leads to development of a Manufacturing system integration UNified Environment (MUNE). Such an environment will play a pivotal role to enable responsiveness and reconfigurability in future MEs. The MUNE proposed in this study has three dimensions namely (1) modelling levels; (2) modelling views; and (3) production management levels. The modelling levels consists of the following: (a) product dynamics (PD); (b) customer order decoupling point (CODP); (c) work dynamic (WD); (d) performance metrics (PfM); (e) EM; and (f) SM. The modelling views include generic, partial and particular views that are similar to previously proposed CIMOSA modelling views. The MUNE is presented conceptually in Figure 38.

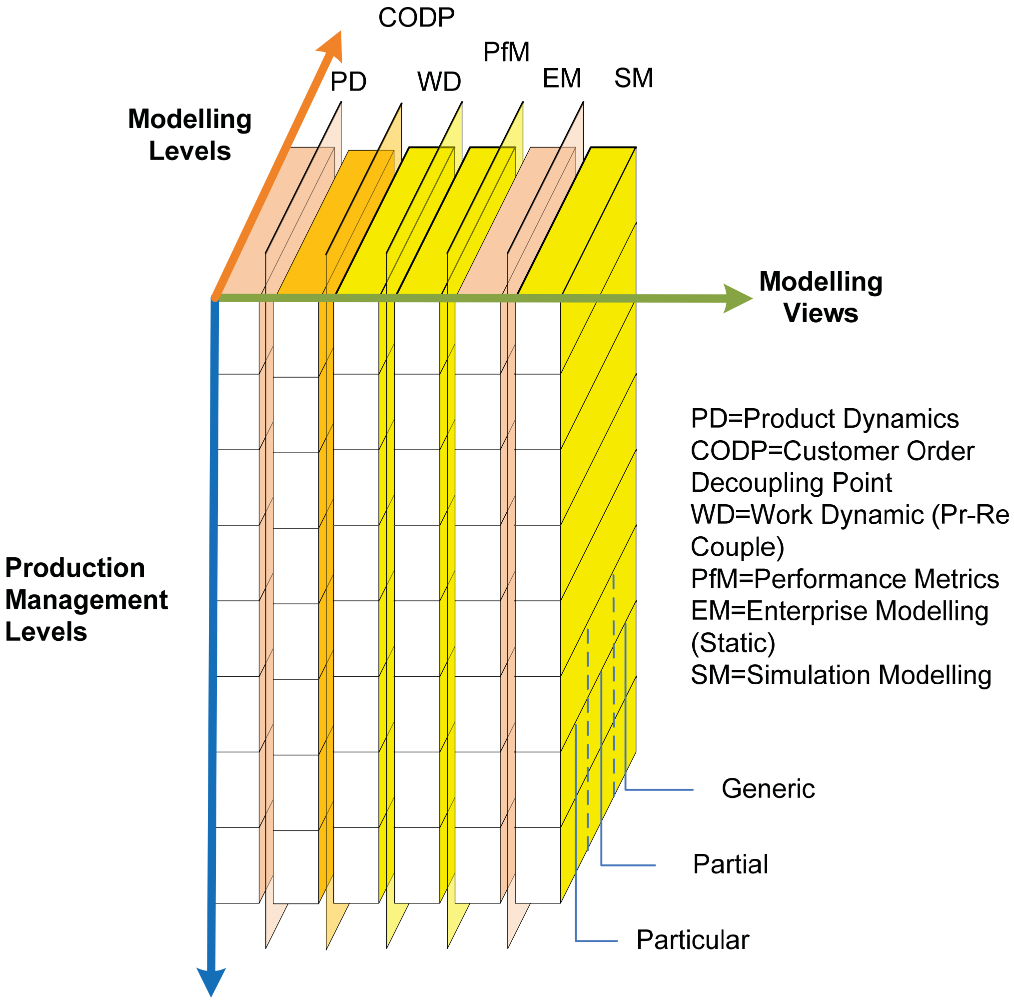


Figure 38: MSI UNified Environment (MUNE)

In theory the IMA offers the following solutions to the research challenges (as presented in section 5.1):

1) It provides a decomposition of the complexity in terms of delta orders, delta volume required, delta product variance, etc hence promises to provide a way to cope with customer related uncertainties and complexities ;

2) It is a structured modelling approach hence providing a structured, explicit and quantitative modelling approach to the design and develop production planning and control systems;

Table 15 shows weaknesses of formal methods found in specific literature review and how these are addressed in the IMA.

Table 15: Weaknesses of formal methods in literature and how these are addressed in IMA

Weaknesses of formal methods in the literature	How weaknesses are addressed in IMA
Lack of structured ways of presenting an enterprise statically.	**EM:** ❑ This stage provides a structured base to understand the business in context by usefully modelling the enterprise; ❑ It provides a way of systematic reuse of enterprise model fragments in the form of modelling diagram templates; ❑ The context, structure, interaction and activity diagrams help in producing and reconfiguring enterprise models in a rapid and effective way.
Lack of structured ways of presenting an enterprise dynamically.	**SM:** ❑ This stage provides benefits in terms of a structured dynamic analysis tool for decision making in terms of achieving reconfigurability and responsiveness; ❑ It provides a basis for structured decision making for TO-BE models by creating reconfigured simulation models and making comparisons with As-Is or other TO-BE models; ❑ It provides a way to analyse and predict about alternative future options available to ME.

Even though the IMA has its own benefits, it also has some remaining weaknesses viz: (a) depending upon the location of the modeller, it might be time consuming task to get hold of industrial data if the modeller is based outside of the industry; and (b) the training of a particular piece of software and understanding of the SM conceptual base may take longer for industry to get hold of its benefits in terms of reconfigurability and responsiveness. With all its benefits and weaknesses, it is believed that the IMA is quite practicable for use in the industry. But the case study work reported in following thesis chapters needed to prove or dis-prove this assertion.

5.9 The way forward

Having developed the IMA it is necessary to test it in different industrial environments. It is important to choose appropriate industrial cases which require complexity of design of related production and assembly manufacturing systems. At the same time the choice of industrial cases is limited to the available industrial collaborators. Chapter 6 illustrates first application of IMA in this thesis.

Chapter 6

Case 1: Application of the IMA in Ford Motor Company

6.1 Motivation and introduction

A case study was undertaken with the PD Factory of Ford Motor Company (to be named as Ford in the postscript) based at Dunton, UK where the author applied the proposed IMA. Ford was one of the industrial partners in the EPSRC project titled "Unified modelling of complex systems – to facilitate ongoing organisation design and change" (Grant No. EP/D05821X/1). The case presented in this chapter is based on the identified need from Ford to apply a systematic approach to decision making, regarding change capability and its after effects on any production release system. The company wished to investigate how changes in production release could impact on the work load of their Pre-Production Management (PPM) team following a design freeze. Therefore, the main aim of this case study was to improve the change capability of a production management system, so as to improve an associated production release process. This case study specifically looks at changes affecting lead time, cost and the work load of the PPM department in the Ford PD Factory.

The rest of the chapter is arranged in six sections. The research context of the Ford case study is presented in section 6.2. Section 6.3 provides background to the production release process at the Ford PD Factory. The aim and objectives of the Ford case are listed in section 6.4. Section 6.5 illustrates a step-by-step application of IMA in Ford. Section 6.6 includes reflections and conclusions. Section 6.7 outlines future research directions.

6.2 Ford case study – research context

In this case, a work dynamic starts with initiation of a customer order (CO) and then generally progresses through to the design, planning, and production management functions. The responsiveness of a manufacturing system depends upon many factors; the most important factors include reconfigurability and decoupling of work load assignments from the relevant P_r-R_e couple as the changing situation demands. For complex and longer projects, the design activities, including their production feasibility approvals, become more important and time consuming during product realisation stages and may impact on the overall project timeline. When such projects involve complex products, key performance indicators (KPIs) may include: (1) time in terms of responsiveness of a production system or part of it; (2) cost; and (3) resource work load. Keeping in view the complexity of projects a number of research questions are raised viz: (a) how work dynamics can be smoothed out so that the P_r-R_e can be decoupled in order to achieve flexibility and reconfigurability?; (b) how resources can be assigned and re-assigned to processes and activities flexibly so that project milestones are achieved?; (c) how design approvals can be usefully modelled using the IMA?; and (d) how production release can be usefully modelled using the IMA, so that its impact on overall project timelines may be made visible? Figure 39 shows the research context in the Ford case.

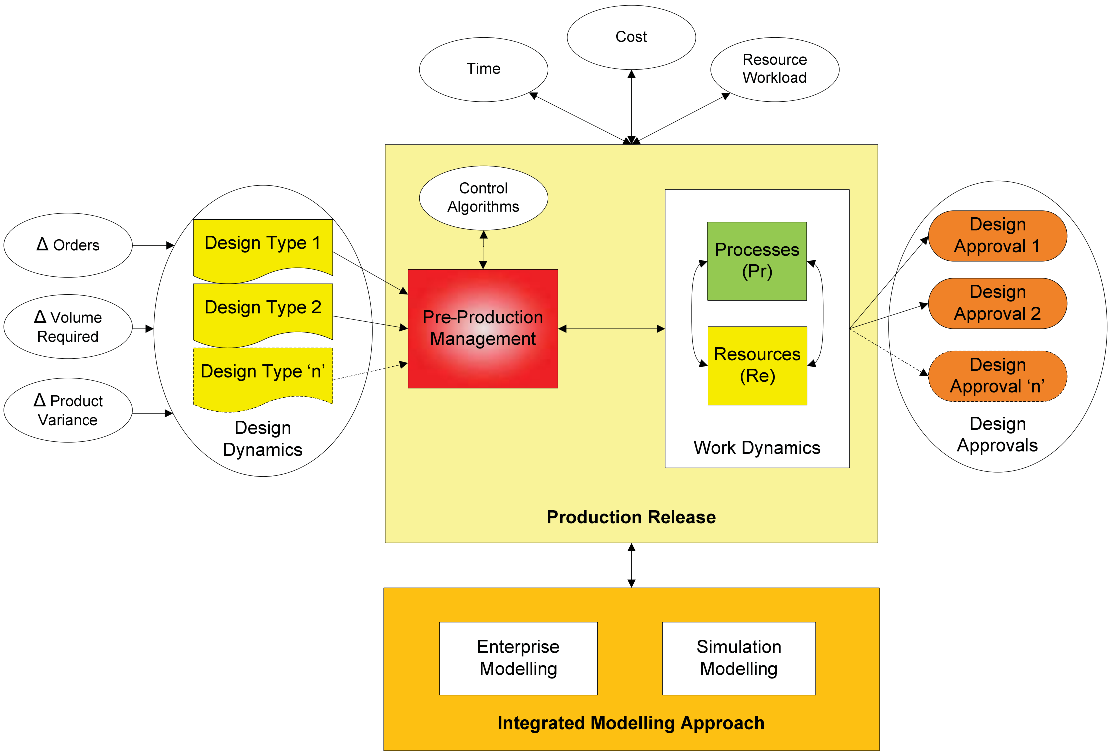


Figure 39: Research context of the Ford case study

The automobile sector is typified by its complex design, production and assembly functions. The right and timely allocation of resources becomes very important as the production launch (and in effect the product launch) depends upon achieving planned project milestones. Previous research has established that the delay in launching a product into a market can be very costly. For example a 6-month delay for the launch of a product which has a life of 5 years has been observed to cause a 32 percent reduction in profits (Lee et al. 2007). These figures apply to products, such as motor vehicles or large subassemblies. In cases where a product launch is delayed by few weeks, the loss in terms of profit margins may rise to millions of pounds for large automobile projects. This gives an insight into the gravity of this problem. Therefore, manufacturers are working to shorten the product launch times. For example reducing the development project times from 48-month to 24-month (Harrison et al. 2004; Lee et al. 2007; Monfared et al. 2002). In order to synchronize such efforts at a business level, automotive manufacturers are under increasing pressure to lower manufacturing times and at least avoid any delays in achieving project milestones. This drives the program managers and in effect engineers to find more efficient and robust ways to design and implement reconfigurable solutions in order to rapidly respond to changes and in a cheaper way.

6.3 Production release process at the Ford PD factory

The production release process at the Ford PD Factory finalises and releases technical (production) information about parts and subassemblies belonging to a new car model. This release process runs prior to a production launch and follows the completion of a number of design iterations and related prototyping. In Ford, a 'concern' is treated as a Production Order (PO) which in this case is targeted at pre-production release and is focused on a work load issued to the design department. The production release process at the Ford PD Factory starts with raising a *concern* for a part or a subassembly. Following which it goes through a series of approval stages, at the end of which production information about that part or subassembly is *checked, cross-checked and finalised*. The process is run for every part and subassembly. In a typical 3-month window previously this has resulted in the raising of approximately 11,000 concerns that need to be approved, therefore typically tens of thousands of completions of this overall release process is required each year. During the running of these instances of the production release process, work flows through Ford's *World Engineering Release System (WERS)* which is software run primarily for the PD Factory. Figure 40 illustrates the flow of the production release process in pre-production management department.

As part of their current operations all teams in the Ford PD Factory decide on the required start time of their specific instance of the release process. Here they estimate the *lead time* via backward scheduling from the *target launch date* (bearing in mind the overall constraint of time being a 3-month window). It follows that teams start their respective release process at different points in time within that 3-month window; mostly starting at a time that is close to the *due date*, i.e. the launch date. This results in a bottleneck during cross-checking activities towards the end of the 3-month window. Cross-checking between parts and subassemblies becomes intricate and much wasted effort is expended due to untimely sequences of activities.

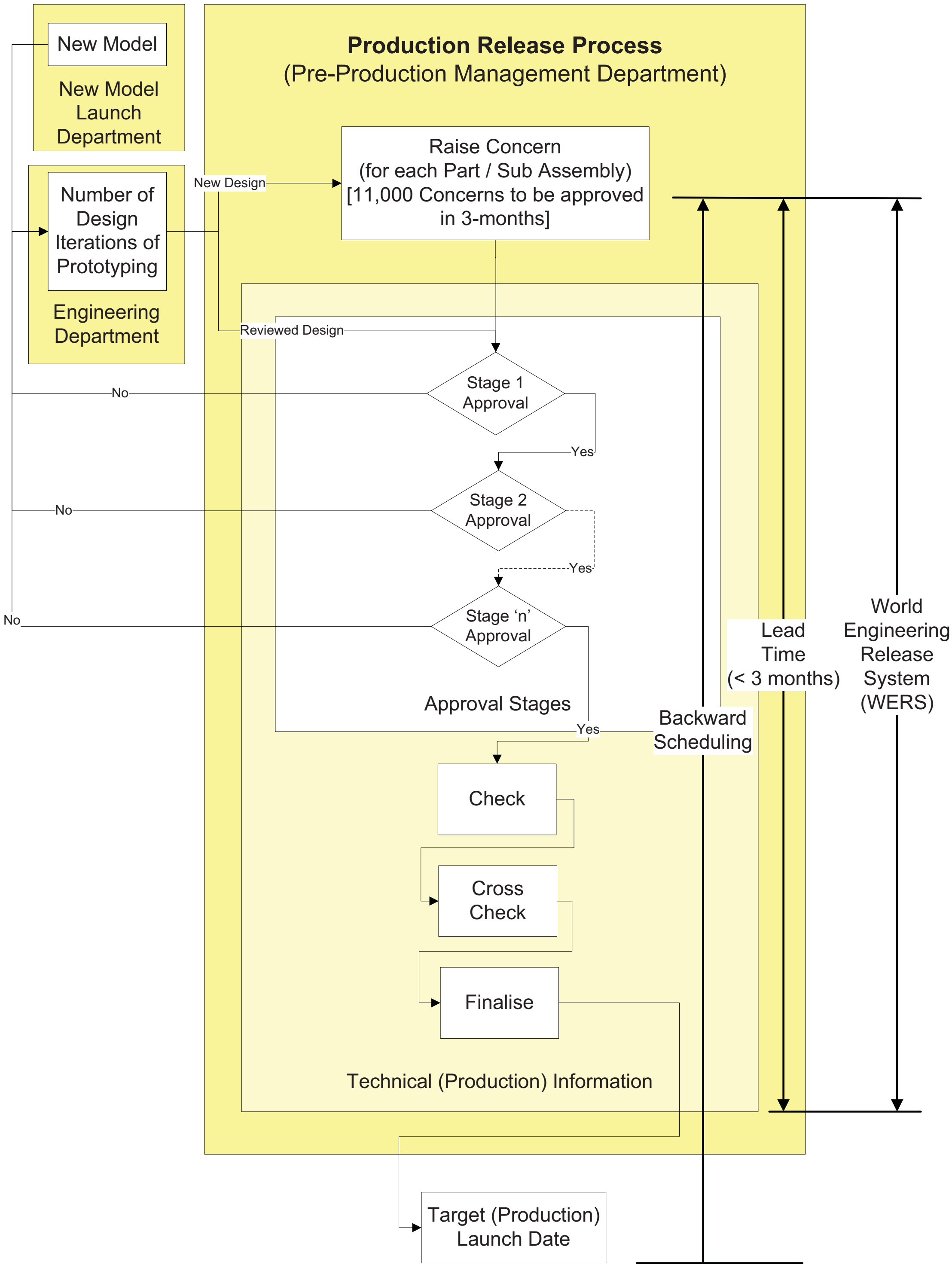


Figure 40: Production release process (pre-production management department)

6.4 Aim and objectives of the Ford case

A proposed change suggested by Ford was centred on reengineering selected aspects of the release process for use on future projects. According to the proposed change, *each team shall start their process instants at the same time regardless of their* *individual lead time.* By so doing the part and subassemblies can be cross-checked well before the end of 3-month period and necessary corrective actions can be taken within an acceptable time scale. Hence the research reported here aims to predicatively answer the question: *How would the proposed change affect the Pre-production management (PPM) team?* In accomplishing the aim and objectives, the IMA is applied and illustrated in the following. *The objectives of the case study include comparing the proposed change effects with the existing system in terms of time, cost and workload using the IMA.*

6.5 Application of the IMA in Ford

Application of IMA in the Ford case comprised two main stages, namely: enterprise modelling (EM) and simulation modelling (SM). EM (stage 1) involves use of CIMOSA based constructs; namely context diagrams, structure diagrams, interaction diagrams and activity diagrams. Specific process models are captured at this stage by gathering data from the company about the problem domain. During the SM (stage 2), simulation models are created of the captured system for both AS-IS and possible TO-BE configurations. Simulation models need to be built using a proprietary simulation software tool capable of computer executing process logics and numeric data so that the logical flow of AS-IS and TO-BE systems can be graphically represented; then flows need to be executed to generate process behaviours that show results using selected KPIs. The analysis and decision making is based upon the use of such KPIs that provide an organisation change designer with clear views about relativities of AS-IS and TO-BE configurations. A stepwise use of IMA was adopted to create a set of enterprise and simulation models related to the processes and the system specific to the production release. This stepwise use is illustrated in the following.

6.5.1 Stage 1: creating enterprise models

Enterprise models were developed to graphically represent relatively enduring aspects of the case study process; namely context diagrams, interaction diagrams, structure diagrams and activity diagrams. The overall context of the exercise is the production release of body and electric parts (CD345). Engineering (DM1), PPM (DM2) and new model launch (NML) (DM3) are CIMOSA-domains. Non-CIMOSA domains (which will not be modelled in detail) include program management (DM4), production cost estimation (PCE) (DM5), finance (DM6), purchasing (DM7), supply (DM8) and packaging and manufacturing (DM9). Figure 41 shows the overall context diagram of the production release of body and electric parts including CIMOSA and non-CIMOSA domains. Figure 42 is high level interaction diagram showing interactions between the CIMOSA and Non-CIMOSA DPs. Figure 43 illustrates the structure diagram of the engineering DP (DP1.1), its BPs and EAs.

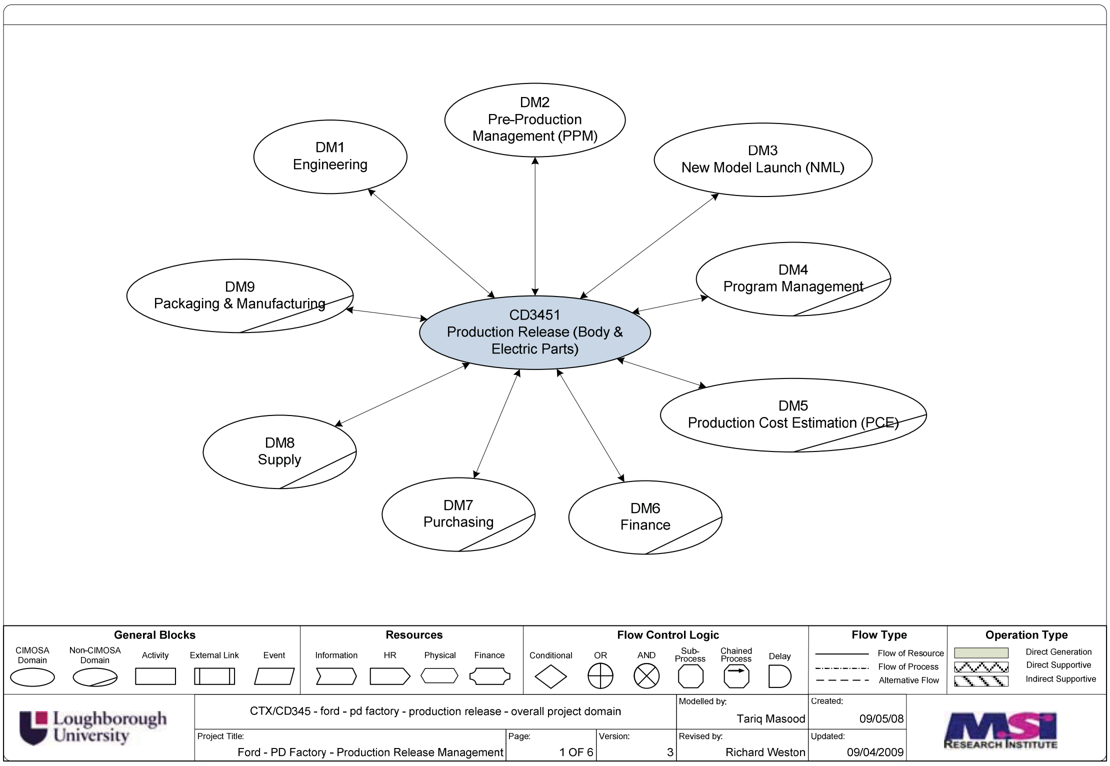


Figure 41: Ford case: context diagram of production release

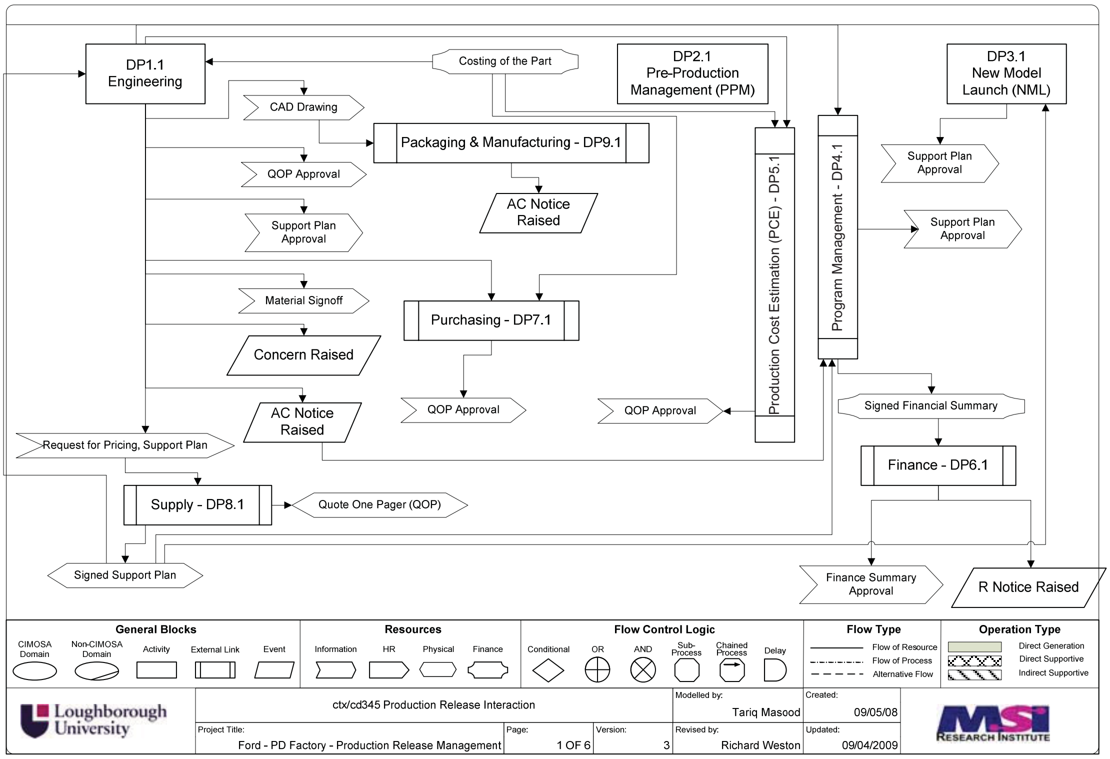


Figure 42: Ford case: interaction diagram of production release

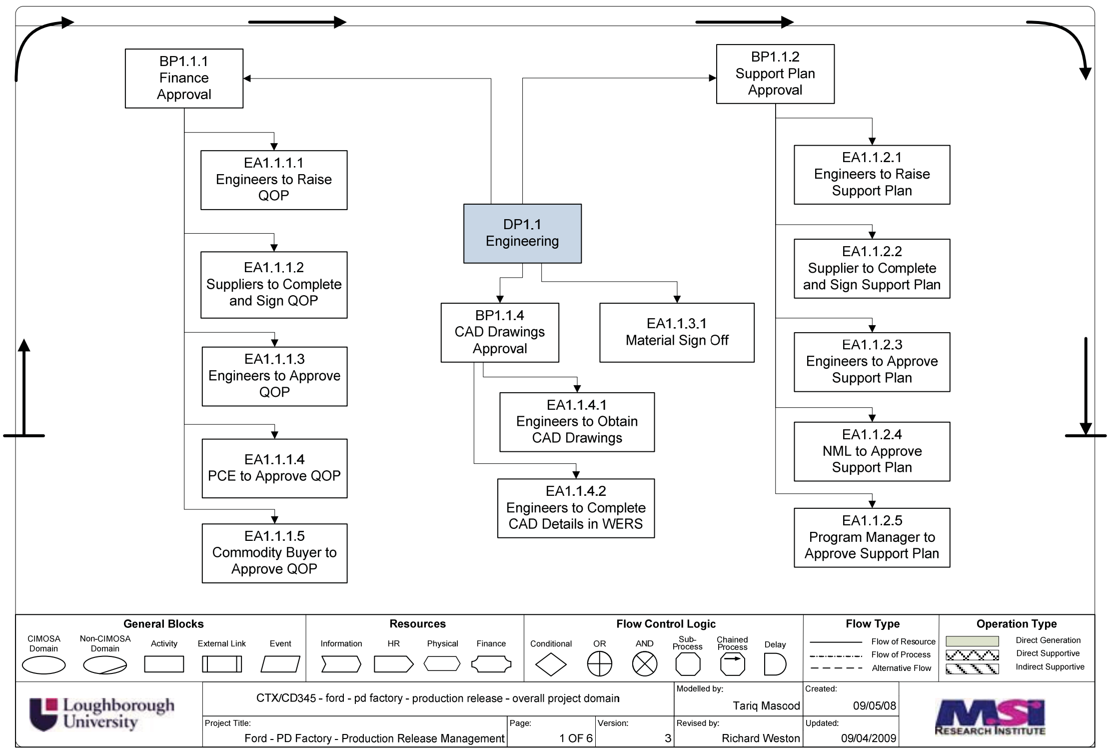


Figure 43: Ford case: structure diagram of production release

A production release process instance starts with engineers raising a ‘concern’ in WERS (EA1.1.0.1). The ‘concern’ is then reviewed to achieve financial approval (BP1.1.1) which has elemental EAs which are later discussed in this section. The engineers raise a Quote-One-Pager (QOP) (EA1.1.1.1) for finance approval after EA1.1.0.1, followed by a request to suppliers to complete and sign the QOP (EA1.1.1.2). The signed QOP is then sent for approvals to: (1) the engineers (EA1.1.1.3); (2) the PCE team (EA1.1.1.4); and (3) the commodity buyer (EA1.1.1.5). Upon getting these activities done, the BP of finance approval (BP1.1.1) is completed. In order to achieve support plan approval (BP1.1.2), the engineers raise a support plan (EA1.1.2.1) after EA1.1.0.1 followed by sending a request to the supplier to complete and sign the support plan (EA1.1.2.2). The signed support plan is then sent for approval to: (1) the engineers (EA1.1.2.3); (2) the NML team (EA1.1.2.4); (3) and the program manager (PM) (EA1.1.2.5). Upon getting these approvals, BP1.1.2 is completed.

In order to get CAD drawings approval (BP1.1.4), the engineers obtain CAD drawings (EA1.1.4.1) after EA1.1.0.1. The details of CAD data is completed in WERS (EA1.1.4.2) and material is signed off (EA1.1.3.1). Upon getting frozen CAD drawings and material is signed off, BP1.1.4 is completed.

After obtaining the aforementioned approvals (BP1.1.1, BP1.1.2, BP1.1.4), the engineers raise an AC notice (EA1.1.5.1). After receiving this notice, the package and manufacturing department checks the compatibility (EA1.1.6.1). The finance summary is then sent to the ‘PCE team’ or ‘PM’ for signing (EA1.1.7.1) and the technical specification approval is sent to ‘engineers’ to raise a release notice (R notice). After the finance summary is signed by PCE or PM, the finance approval status is logged into WERS (EA1.1.8.1). The PPM audits this approval process (EA1.1.9.1). Following this ‘engineers’ raise the R notice (EA1.1.10.1) which is the final activity before production launch. Figure 44 shows an activity diagram for the production release process.

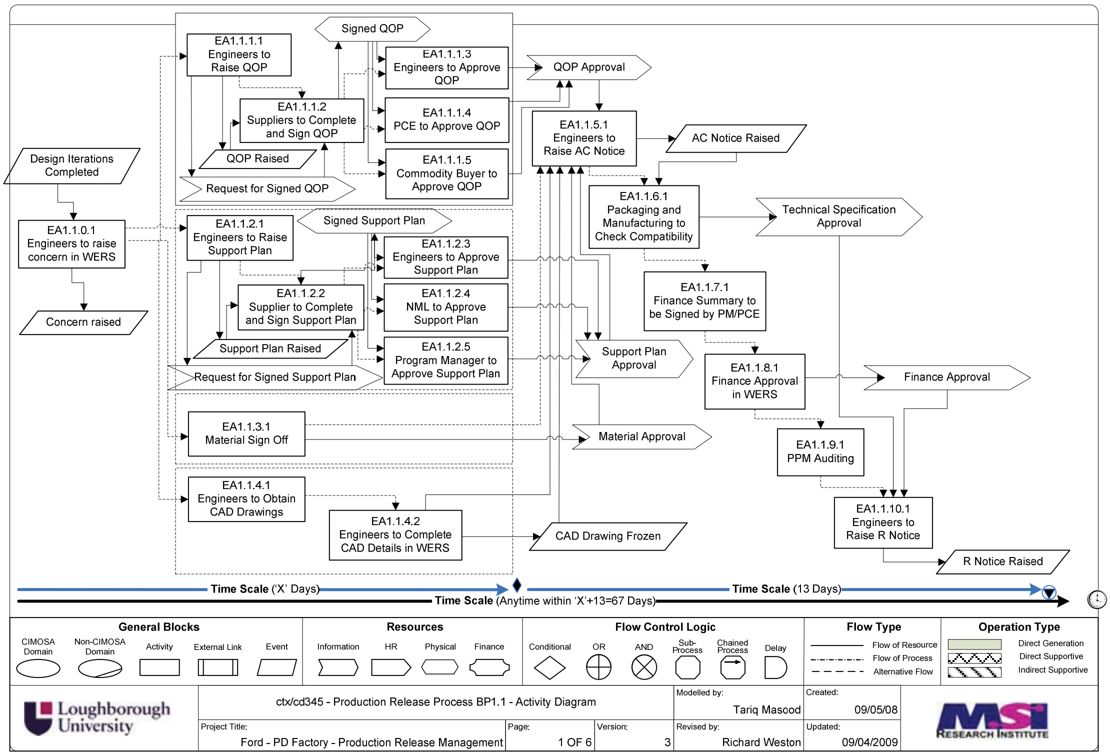


Figure 44: Ford case: activity diagram of production release process

6.5.2 Stage 2: creating simulation models

To test the proposed policy change when releasing instances of raised *concern* about car body and electric designs it was observed to be necessary to create a discrete event simulation model of BPs and EAs. After the EM had been developed, simulation models were conceived and developed for the AS-IS and TO-BE configurations in Ford. Even though the IMA is independent of a particular choice of simulation tool, the tool selection is very important for creating simulation models. A set of SM tools were potentially available during this research including Arena, Simul8 and Plant Simulation. Previous SM studies have shown their successful use. Arena was chosen for the Ford case due to its ease of use and ease of mapping enterprise models onto simulation models in terms of activities, timings and precedence relationships in this case.

The business processes have four different views (i.e., functional, information, resource and organisational) based on the CIMOSA modelling framework as described in Chapter 4. These four views define every business or engineering process including their inputs and outputs. In this research, all these views are categorised into two ‘objects’ called ‘functional objects’ and ‘behavioural objects’ in order to design, build and execute simulation models. Functional objects are those objects that are either inputs or outputs of each business and engineering process which may or may not be dependent on functional objects of other processes (e.g., physical resources, information flow, events, etc). While behavioural objects describe the logic or sequence of processes (i.e. to define process logically either to make sequential or concurrent). Both functional and behavioural objects were defined in Arena® software and were assigned by input or output variables to execute the processes.

In addition, the Arena tool supports quantitative analysis (e.g., probability functions and random generation of entities) as required in this research in order to measure and compare existing (AS-IS) and future (TO-BE) model configurations based on certain KPIs. It is important to note that Arena® software supports both hierarchical structure and modular elements that are required for complex manufacturing systems to analyse different segments of the system independently. Figure 45 - Figure 48 shows AS-IS simulation models, of ‘engineering’ domain process and related business processes, developed using Arena® during experimentation the sequential flow of which corresponds directly to relevant business processes and enterprise activities previously coded by CIMOSA activity diagrams. The simulation models shown in Figure 46-Figure 48 are basically sub models of the main simulation model as shown in Figure 45. The inputs to the AS-IS simulation models were based upon data captured during semi structured interviews with the Ford management. Such data was used to develop enterprise models, which were discussed earlier in this chapter, and were basis of developing simulation models.

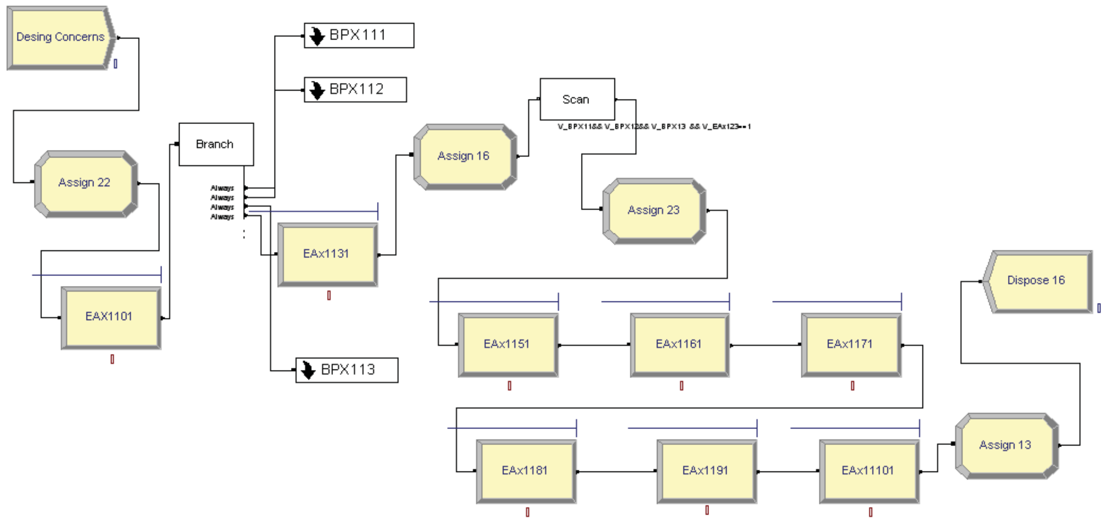


Figure 45: Ford case - AS-IS simulation model of 'engineering' domain process (DP1.1) developed in Arena®

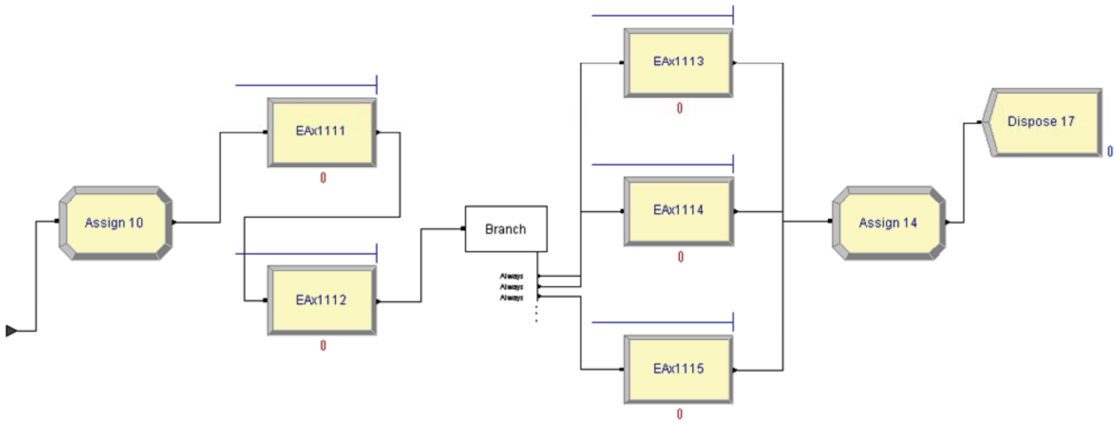


Figure 46: Ford case - AS-IS simulation model of 'QOP approval' business process (BPX111) developed in Arena®

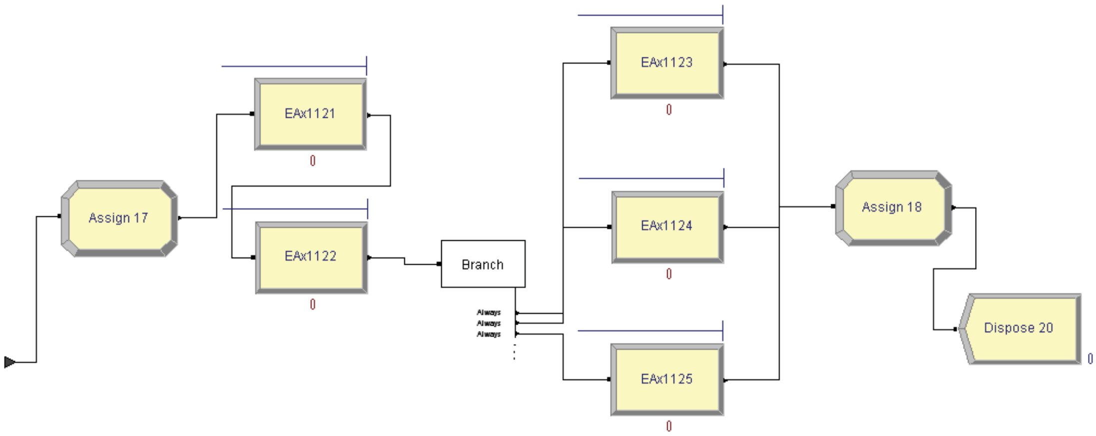


Figure 47: Ford case - AS-IS simulation model of 'support plan approval' business process (BPX112) developed in Arena®

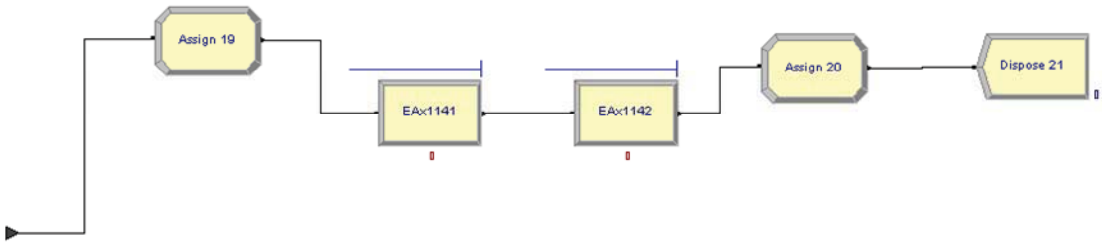


Figure 48: Ford case - AS-IS simulation model of 'CAD drawings' related business process (BPX113) developed in Arena®

Figure 45 shows AS-IS simulation model of the 'engineering' domain process (DP1.1). It consists of three business processes BP111 (Figure 46), BP112 (Figure 47) and BP113 (Figure 48) that related to QOP approval, support plan approval and CAD drawing release in pre-production management respectively. It also consists of approval processes from teams across the company. A 'Scan' condition is used to collect information of EAs from BP111, BP112, BP113 and EA1131 that are complete. When all EAs are complete then remaining approvals of EA1151 to EA11101 are obtained. The EAs numbered EA1113, EA1114 and EA1115 are parallel activities. Similarly, EA1123, EA1124 and EA1125 are also parallel activities. In the same manner, BP111, BP112, BP113 and EA1131 are parallel activities. In these Arena simulation models, enterprise activities and their precedence were defined while assigning resources and time. The AS-IS model properties were set. A set of variables was defined in the simulation models so that calculations of KPIs and reuse of variables could be made easier where required at later stages. The set of variables included more than 40 variables related to time, cost and resources that were used for calculations of KPIs at AS-IS and TO-BE simulation modelling stages. A partial list of time related variables is included in Appendix C. Figure 49 presents KPI results of time, resource load and resource cost of AS-IS simulation model.

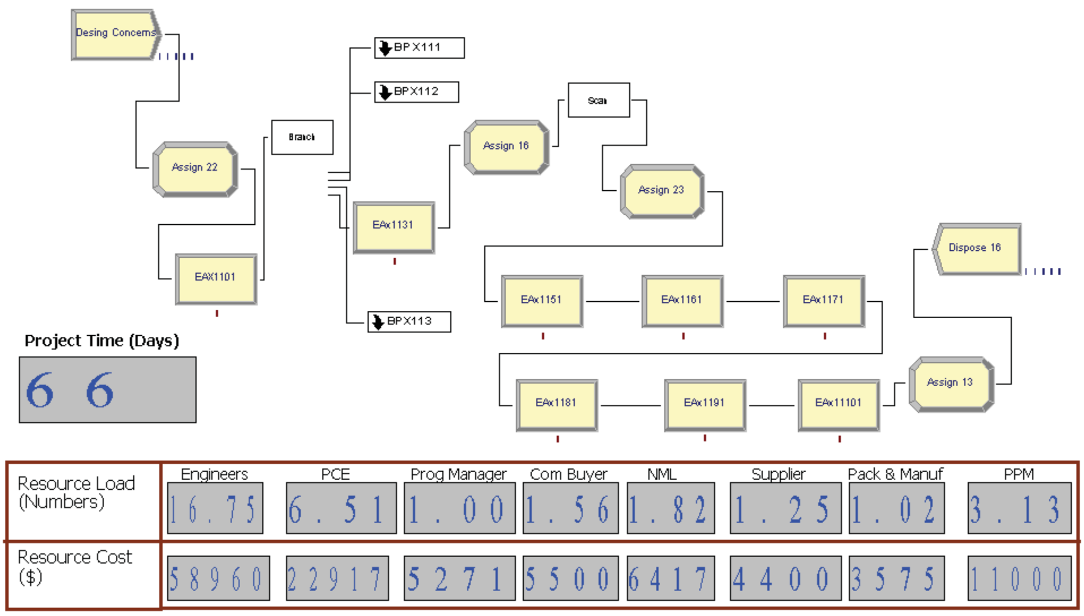


Figure 49: Ford case: results of AS-IS simulation model

TO-BE configuration of the pre-production management system was considered and virtually executed in simulation models. During AS-IS and TO-BE model development, the following KPIs were identified: (1) project time; (2) resource load (in terms of resources required viz: 'engineers', 'PCE' and 'PM', etc); and (3) cost. In AS-IS situation, the 'Engineers' resource is the most used and proves a bottle neck. For TO-BE model configuration, it was conceived to introduce 'Resource Sets' so that resource load of 'engineers' could be shared with other resources. In doing so, it was assumed that initially one-off training cost will be involved so that the sharing resources could perform required jobs. Table 16 shows resource sets used in TO-BE model configuration.

Table 16: Resource sets introduced in TO-BE model configuration

Model Configurations	**Resource Sets**	**Resource Set Members**	**EAs where Resource Sets were used**
TO-BE	Set 1	Engineers + PCE	EA1101, EA1111, EA1113, EA1121, EA1123, EA1141, EA1142, EA1151, EA11101
	Set 2	PPM + Commodity Buyers + Material Team	EA1131, EA1114
	Set 3	Program Manager + Engineers	EA1171, EA1181, EA1114, EA1125

By adopting IMA based TO-BE configuration, the author learnt to visualize and quantify considerable benefits in terms of time, resource load and cost. The AS-IS configuration was based upon random assignment of work in which dedicated resource groups were independent to initialise events as and when they became free from other project assignments. This approach lead to higher lead times and cost by keeping more work in progress. While generating TO-BE model configurations, one of the strategies adopted was based upon First Come First Serve basis along with making flexible resource sets. Such an approach showed better KPI results during execution of TO-BE computer models made in Arena® software as presented in Figure 50.

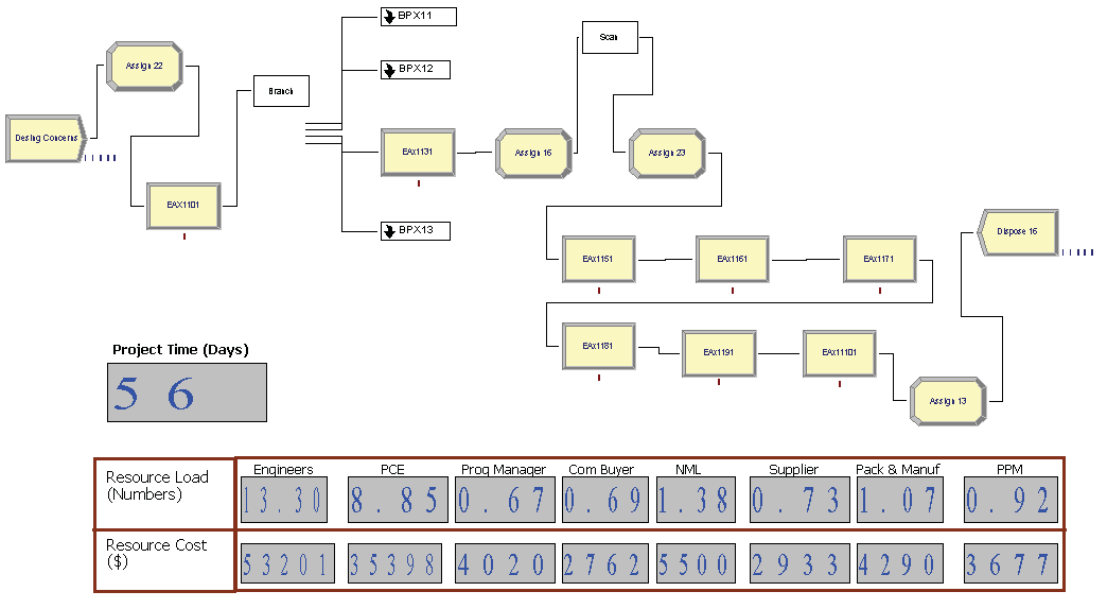


Figure 50: Ford case: results of TO-BE simulation model

Table 17 shows results of AS-IS and selected TO-BE model configurations considered during experimentation.

Table 17: AS-IS and TO-BE model configurations

Model Configurations	**Strategy**	**Lead Time (Days)**	**Resource Load (Engineers)**	**Cost of Engineers ($)**
AS-IS	Random assignment of work with dedicated resource groups	66	16.75 (Total: 33.04)	58960 (Total: 118094)
TO-BE	First Come First Serve with introduction of three flexible resource sets	56	13.30 (Total: 27.61)	53201 (Total: 111781)
Difference		*10*	*3.45 (Total: 5.43)*	*5759 (Total: 6313)*
Percent reduction (%)		*15.15%*	*20.60%*	*9.77% (Total: 5.35%)*

Figure 51, Figure 52 and Figure 53 shows comparisons of AS-IS and TO-BE KPI results of the Ford model configurations. The TO-BE model configuration clearly show improved results in these comparisons. Figure 51 shows a significant reduction in lead time of TO-BE model configuration, i.e. from 66 days to 56 days, while Figure 52 shows a decrease in total cost impact in TO-BE model configuration as well as in individual resource costs except PCE cost. The PCE cost becomes higher in TO-BE model configuration but if total impact is compared the TO-BE model configuration is still in benefit of $6313 as compared to AS-IS model configuration. It should be noted here that cost savings in terms of time savings are not included. Figure 53 shows resource load comparison of AS-IS and TO-BE model configurations. A major impact was seen in 'engineers' which was a bottle neck in this case study while some other resource load was also decreased. The 'PCE' resource load was increased instead but again the total impact of resource load saving was still positive. There was no change in resource load of 'NML' and 'commodity buyer' though.

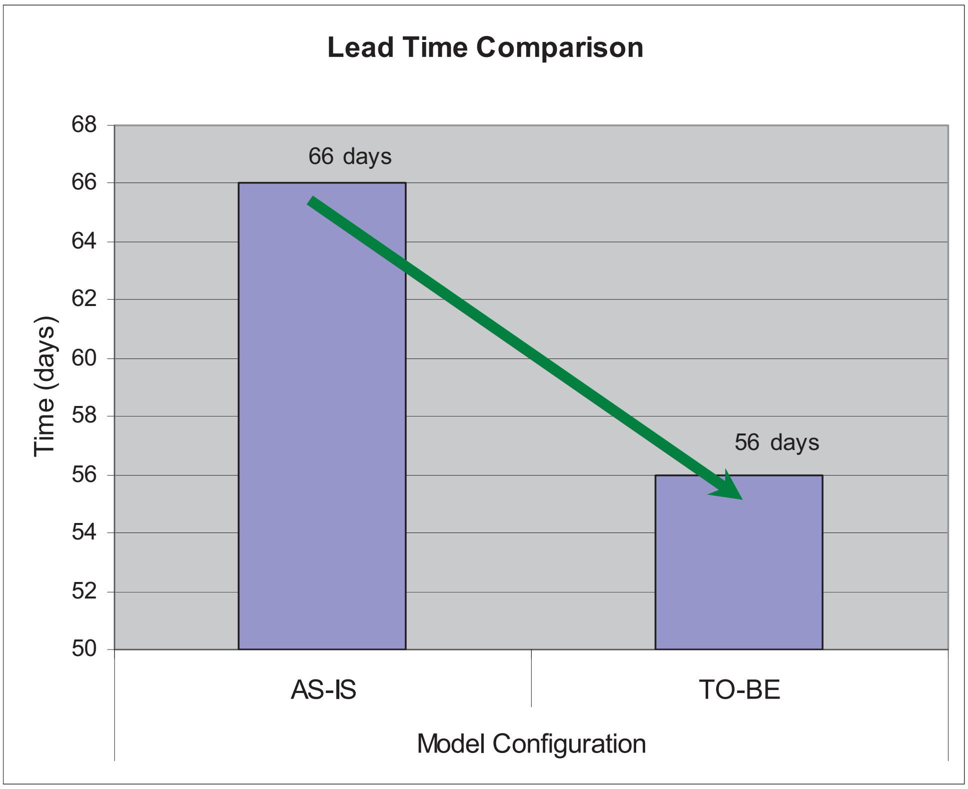
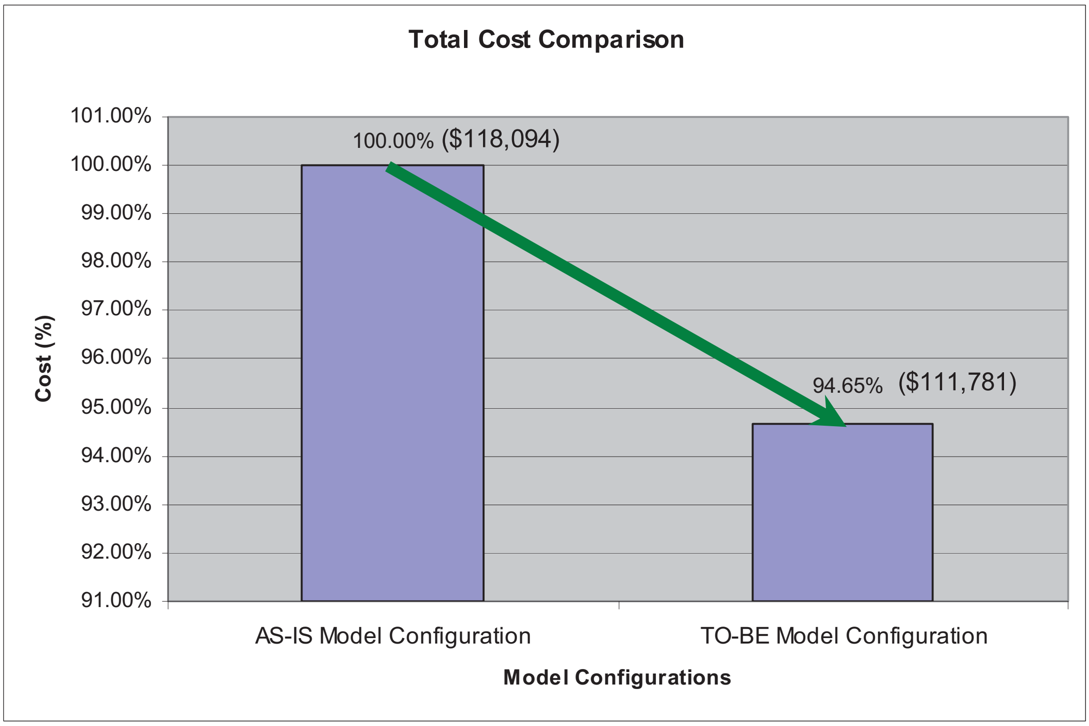


Figure 51: Lead time comparisons of Ford model configurations



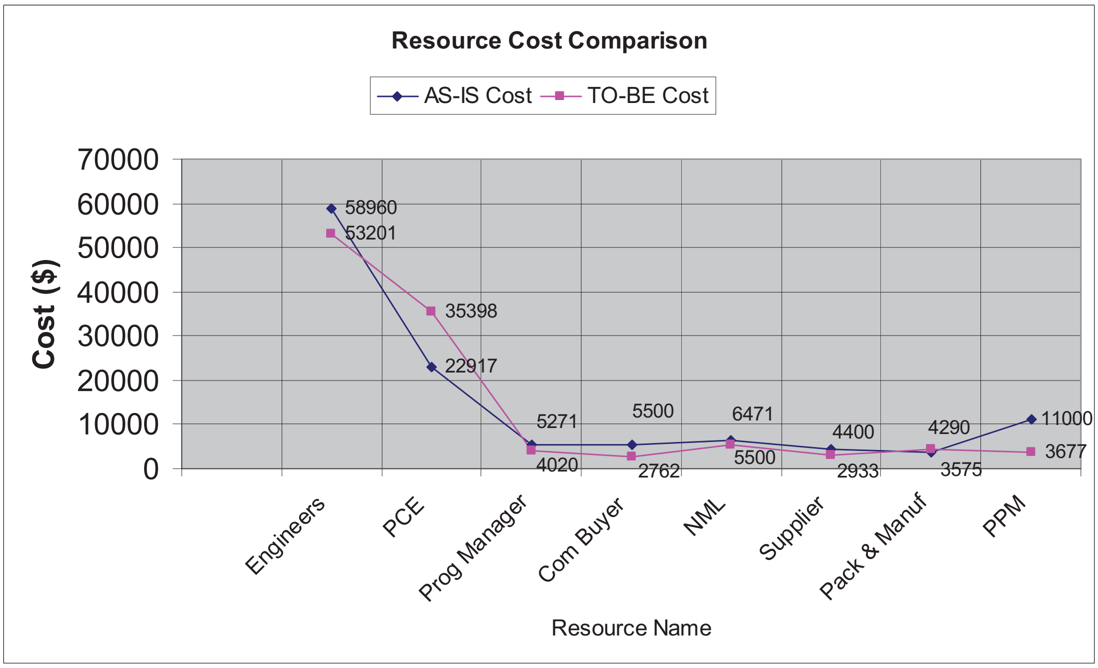


Figure 52: Cost comparisons of Ford model configurations

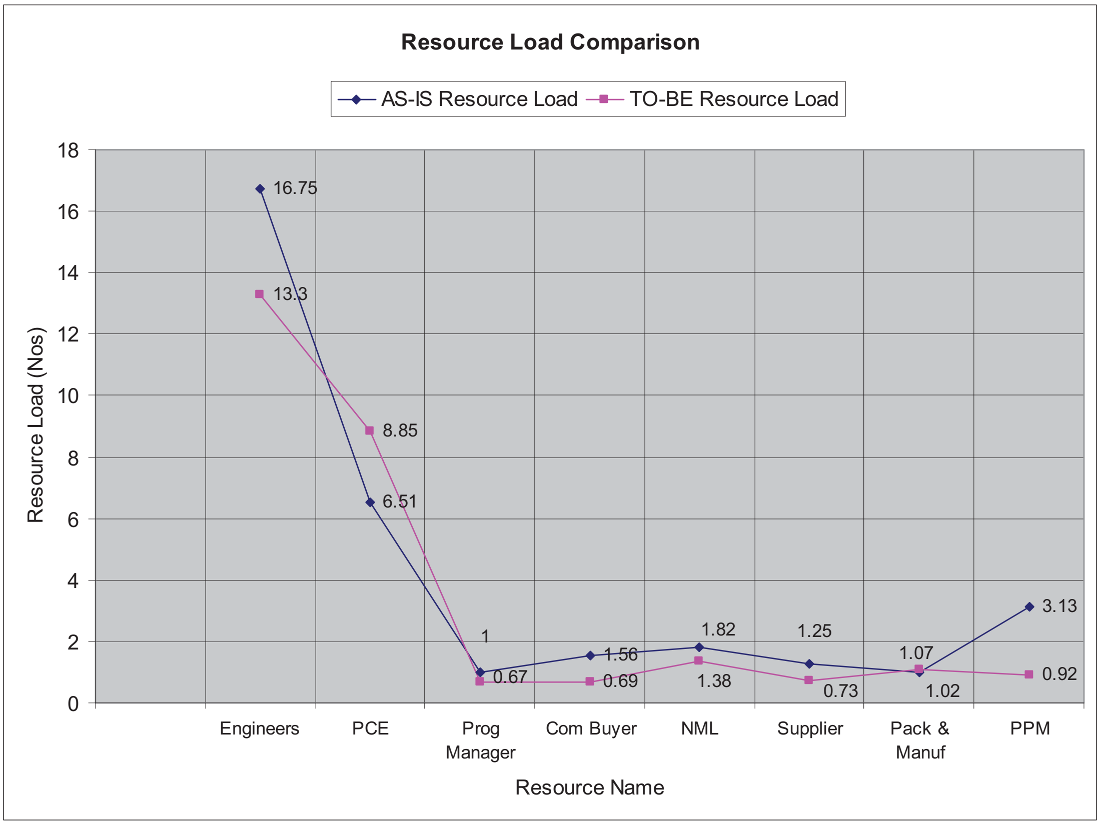


Figure 53: Resource load comparisons of Ford model configurations

Data types and model VVA:

The following describes different types of data that was used for different KPIs during this case study.

- *For EM:* Actual data was captured from semi structured interviews with Ford experts and researchers from MSI Research Institute and SEIC;
- *For AS-IS SM:* Actual data was gathered through author's observations and MSI researchers. Simulated data was used for resource loads based upon AS-IS resource sets assigned to processes with percentage availability of resources and cost estimation based on percentage availability of resources;
- *For TO-BE SM:* Actual data was gathered through author's observations and MSI researchers. Simulated data was used for resource loads based upon TO-BE resource sets assigned to processes with percentage availability of resources and cost estimation based on percentage availability of resources.

The model verifications were performed by the author. The model validation and accreditations were done by expert consultations which includes peers from Ford and researchers from MSI Research Institute.

The development of enterprise models and comparisons of AS-IS and TO-BE simulation model configurations of Ford case were carried out and reported to illustrate how the author did some early project work and learned with a purpose of specifying a developed version of the IMA. The useful learning from Ford case may be used for further enhancement of the approach.

6.6 Reflections and conclusions

This chapter reported on case testing the IMA in PD Factory of Ford Motor Company. The enterprise and simulation modelling stages of the proposed IMA were applied to the pre-production control problem during this case study. The development of the enterprise models helped to understand the processes, resources and their interrelationships related to the case study. It also provided a 'knowledge repository' in the form of a graphical 'process oriented structure'. This was designed to facilitate knowledge capture, in the form of a sequential flow of case-specific processing requirements and information needs, and an explicit definition of interactions between the process being modelled in detail and the specific environment in which that process must operate. The simulation models of the processes and resources involved in this case study have quantified dynamic aspects in terms of the behaviours of a set of KPIs. This facilitated decision making on new policy changes. The case study has shown benefits in terms of time, resource load and cost parameters of the project based upon comparisons of AS-IS and TO-BE configurations. The TO-BE model results have shown significant reduction i.e., 15.15% reduction in project/ lead time, 20.60% reduction in resource load, 9.77% reduction in cost of 'Engineers' resource and 5.35% reduction in total project cost. In doing so, this exercise proved useful learning resource for the development of the IMA.

6.7 The way forward

The Ford case study looked into a pre-production release problem in a MTS configuration and has resulted in a way forward to conceptually designing and computer executing an improved MTO production control configuration. Further case studies with different configuration(s) may help to see the applicability of the proposed IMA in wider aspect. However, before proceeding to new case studies, a review of the IMA on the basis of learning from Ford case is necessary which will be presented in Chapter 7.

Chapter 7

Enhanced Integrated Modelling Approach to the Reconfiguration of Manufacturing Enterprises

7.1 Motivation and introduction

The Ford case study (as presented in Chapter 6) provided a test case for industrial application of the IMA. Reduction in lead time, cost and work load on a pre-production management team were key issues for the management of Ford PD Factory. While applying IMA in this case study, comparisons of AS-IS and future (TO-BE) situations of pre-production control were presented. Based upon observations made during this case study, IMA proved to be useful but some limitations were also identified. Such limitations demanded for an enhancement of the IMA. Hence, this chapter will present an enhanced integrated modelling approach after taking into consideration lessons learnt during Ford case study.

The rest of the chapter is composed of eight sections. Section 7.2 reflects on the application of the IMA in Ford. Limitations of IMA and the need for enhancement are presented in section 7.3. Section 7.4 presents key developments in systems thinking. Verification, validation and accreditation of models is presented in section 7.5. Section 7.6 proposes enhanced integrated modelling approach (EIMA). An Enhanced MUNE (E-MUNE) is presented in section 7.7. Reflections and conclusions of the chapter are presented in section 7.8, followed by future research directions presented in section 7.9.

7.2 Reflections on application of the IMA in Ford

The industrial application at the Ford PD Factory showed the usefulness of the IMA but also raised concerns about its limitations. Hence there arose a need to review the approach for further enhancement. The IMA was based upon previously discussed general literature review, detailed literature review, and early modelling and results. The Ford case study provided an opportunity to case test the initially proposed IMA and see its benefits as well as its drawbacks. Lack of adequate structured data capturing methods and gaps between EMs and SMs were among some limitations of the IMA. Hence a need was raised to enhance the IMA in order to improve its application and achieve better results. Figure 54 reflects on the IMA application in Ford case and its identified gaps.

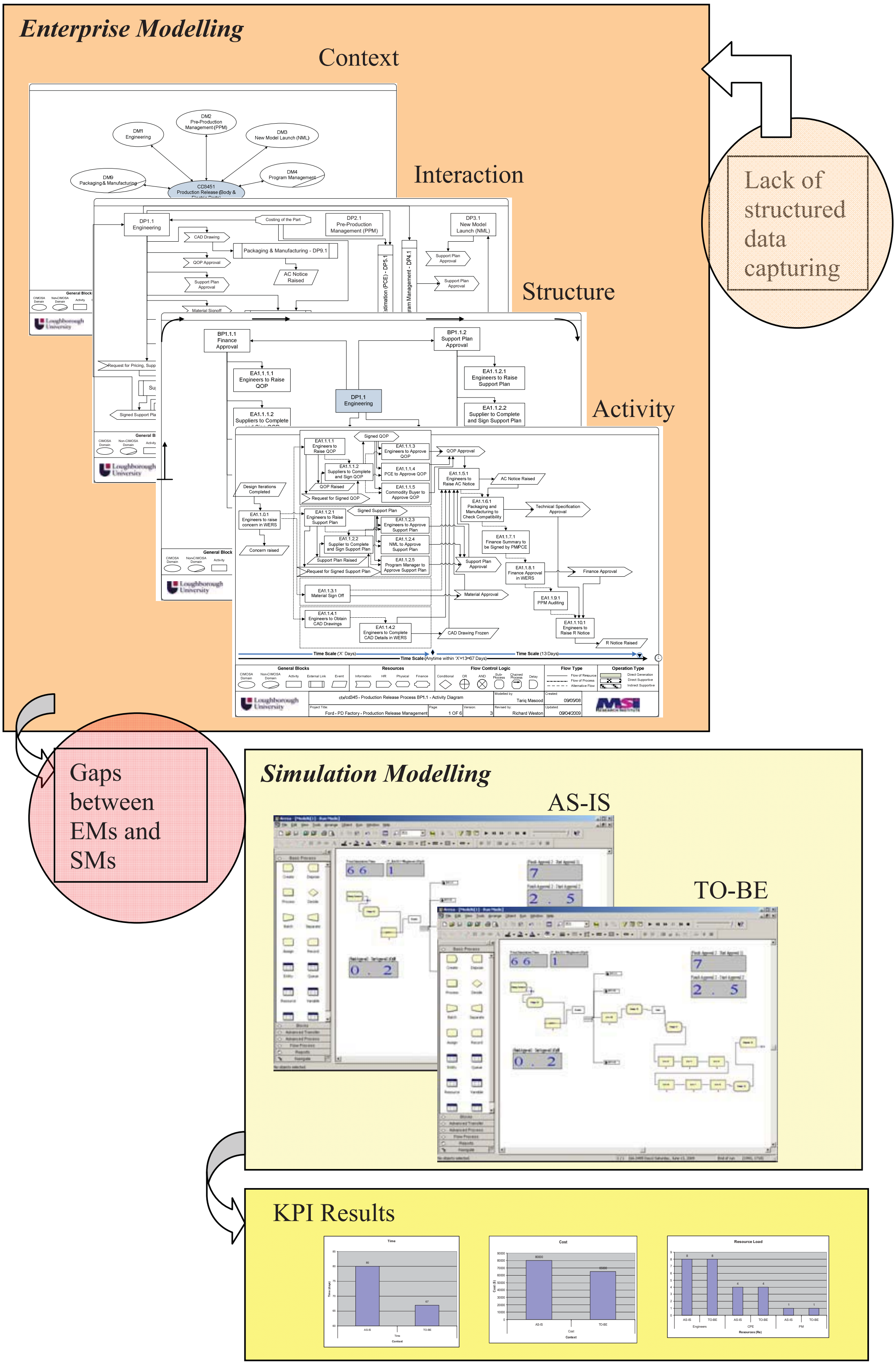


Figure 54: Reflections on the IMA application in Ford case and identified gaps

During the Ford case the author made following observations. CIMOSA provides a coherent set of modelling constructs to explicitly represent processes, resource systems, information flows and organisational structures of MEs; as depicted in Figure 18 (see Section CIMOSA framework). Along the ‘derivation’ dimension it provides multi-perspective modelling constructs that enable decomposition of the enterprise so as to handle high levels of complexity such that understandings gained about process segments can be understood in detail within the organisational context specified by the parent enterprise model. In this way understandings about relatively enduring structural aspects of processes can be gained at various levels of abstraction. Thereby both: ‘big picture understandings’ can be developed that cross organisational boundaries; and in depth process analysis can be enabled by ‘drilling into’ the model in great detail. The ‘generation’ dimension is concerned with the life cycle of the ME and its processes, resources, information flows and organisational structures. Here definitive separation is made between ‘models of requirements’ (generally expressed as process models that can be treated as a backbone model and attributed with other modelled entities) and ‘models of conceptual solutions’, ‘detailed models of specific solutions’ and ‘implementation descriptions’ used to document implemented systems capable of meeting defined requirements. In general such solutions will be configurations of active resource components (including people, automated machines and IT systems). The third CIMOSA cube dimension ‘instantiation’ is concerned with the extent to which ‘models’ and ‘implemented solutions’ are general or specific and is of prime concern later in this research. The basic idea is that enterprise models may describe MEs or parts of them in general; or may describe some industry sector or common structural aspects of many MEs; or may simply describe one particular ME; or even just one particular part of one particular ME. Here in principle enterprise modellers and other enterprise engineers and decision makers can particularise a generic model through a partially generic modelling stage to an ME specific one. Alternatively generalisation of specific or semi generic models can lead to models and solutions that can be generally applied. In this scheme of things therefore an ERP package is a semi-generic solution technology which can be made specific by inputting specific product, etc data related to a specific ME.

Enterprise modelling (including CIMOSA) is designed to represent and communicate primarily structural aspects of any ME. CIMOSA modelling constructs are not designed to be computer executed to simulate ME state change. Hence where simulation experiments are needed to predict future behaviours of ME processes configured in different ways, and when using alternative resource systems, it is necessary to complement the use of EM with SM technologies. This section reviews the basis of such a systematic approach to creating coherent sets of integrated models that can interoperate to replicate and predict changing organisational behaviours. The IMA in support of the reconfiguration of MEs can be positioned at the 'generic' level of CIMOSA modelling. The generic level of the IMA involves the following main stages:

Stage 1: Development of enterprise models; to represent a specific ME and its product realising processes; and

Stage 2: Development of simulation models of relevant processes where it is necessary to consider and encode: (a) the nature of the work that flows through production systems, where these systems comprise both 'process elements' and 'resource system elements') and (b) best ways of configuring the production system elements, such that required 'values' can be added to those work flows. Simulation models are run using alternative responsiveness strategies by inputting data into AS-IS and possible TO-BE configurations of production systems (for various organisational departments). Before (or during) running the simulations, certain KPIs are chosen to enable comparison and choice to be made between different combinations of responsiveness strategy and production systems configuration (composition). As soon as a near optimal solution is reached the modelling and decision-making process is stopped, otherwise it is carried on to find additional combinations of future responsiveness strategies and production system configurations (compositions). While reviewing the IMA, some of its limitations were identified which are presented in the following section.

7.3 Limitations of the IMA and need for enhancement

The application of the IMA in Ford proved useful in visualising alternative pre-production control management methods. But during the application process limitations of the IMA were also identified viz:

(1) Lack of adequate structured data collection for enterprise models;

(2) Lack of linking EMs with SMs effectively;

(3) Lack of verification, validations and accreditation of developed models; and

(4) Lack of structured output of the modelling exercises.

The author found that it was needed: (1) to introduce structured data collection methods during EM stages; (2) to deploy ‘systems thinking’ (via causal loop modelling) to help understand impacts of change better in complex manufacturing systems and thereby to design better SMs and SM experiments; (3) to exercise verification, validation and accreditation of enterprise and simulation models after all modelling stages; and (4) to tailor the generic IMA towards PPC policy selection. It is important to explore how to tackle with these identified IMA limitations. The following section will discuss about systems thinking.

7.4 Systems thinking via causal loop modelling

Causal loop models can represent causal effects of activities while product-based causal loop models can also be generated (Forrester 1961; Sterman 2000). This type of modelling helps identify aspects of complexities and dynamics can be modelled through this technique. Causal loop modelling (CLM), as a standalone technique, is not useful for complex manufacturing systems design. While applying singular, it may be useful for strategic decision making. However, when combined with suitable process modelling technique(s), it may prove useful for complex systems design. Due to its ability to capture dynamics in MEs it is a useful tool for qualitative analysis of businesses. Causal loop models by themselves can not be modelled but they can be transformed into equivalent iThink® models for simulation purposes. Research literature has not yet shown that causal loop models being used in support of CIM implementation (Agyapong-Kodua et al. 2009). Table 18 presents key literature on developments in causal loop modelling which is a part of systems thinking.

Table 18: Key literature on developments in systems thinking

Key References	Research Group	Key Work/Findings
(Forrester 1961; Forrester 1971; Forrester 1980; Forrester 1992)	MIT Sloan School of Management, MIT System Dynamics Group, USA	Industrial dynamics, world dynamics and policies, decisions and information sources for modelling the national economy.
(Randers 1980)	BI Norwegian School of Management, UK	Elements of the systems dynamics method.
(Coyle 1983; Coyle 1996)	Cranfield University, UK	A practical approach to system dynamics modelling and its technical elements.
(Richardson 1986; Richardson 1996; Richardson 1997; Richardson 1999)	State University of New York at Albany, USA	Problems in causal loop diagrams, modelling for management and reflections for the future of systems dynamics.
(Ford et al. 1998)	University of Bergen, UK	Dynamic modelling of product development processes in systems modelling perspective.
(Pearl 2000)	University of California, Los Angeles, USA	Causality related models, reasoning, and inference.
(Sterman 2000)	MIT Sloan School of Management, MIT System Dynamics Group, USA	Business dynamics: systems thinking and modelling for a complex world.
(Burns 2001; Burns et al. 2002a; Burns et al. 2002b)	Production Modelling Corporation and Texas Technical University, USA	A matrix architecture and component strategy for the formulation of system dynamics models and simplified translation of causal loop diagrams into stock and flow diagrams.
(Schuster 2003)	University of California San Diego (UCSD), USA	Systems Thinking View on the Situation of Unemployment in the United States.
(Weston et al. 2003)	MSI Research Institute, Loughborough University, UK	Use of CIMOSA and systems thinking to document and inform the design and development of car engine production systems.
(Binder et al. 2004)	University of Lubeck, UK	Developing system dynamics models from causal loop diagrams.
(Chatha et al. 2006)	MSI Research Institute, Loughborough University, UK	Combined discrete event simulation and systems thinking-based framework for management decision support.
(Agyapong-Kodua et al. 2009)	MSI Research Institute, Loughborough University, UK	Modelling dynamic value streams in support of process design and evaluation using CIMOSA based systems modelling.

The following section will discuss about model verification, validation and accreditation.

7.5 Verification, validation and accreditation of models

Verification, validation and accreditation (VVA) of models is very important in establishing confidence and trust in the model and results. VVA terms are defined as follows. Verification is the process of determining that a model implementation accurately represents the developer's conceptual description and specifications that the model was designed to (US Department of Defense 2001). Validation is the process of determining the manner and degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model, and of establishing the level of confidence that should be placed on this assessment (US Department of Defense 2001). Validation is the process of establishing confidence in the usefulness of a model (Chryssochoidis 2004). Being 'valid' means 'well suited to a purpose and soundly constructed' but does not imply that a model somehow becomes absolutely correct and true (Coyle 1996). It is important to validate the static models up to an acceptable level of accuracy. The performance of the model needs to be compared with the operation of the real system to build confidence in the results. It is important to note that the model may only be 'valid for the purpose'. In reality, it may not be possible to validate fully a model of a real system (Monfared et al. 2008; Robinson 1997; Sargent 2005; Sargent 2007). Accreditation is the formal certification that a model or simulation is acceptable for use for a specific purpose. The validation method adopted here generally follows the method suggested by Robinson (1997) (i.e., validation of static model, data, codes, and black box approaches). Accreditation is conferred by the ME best positioned to make the judgement that the model or simulation in question is acceptable (US Department of Defense 2001). That ME may be an operational user, the program office, or a contractor, depending upon the purposes intended. Figure 55 illustrates the basic differences between the VVA terms.

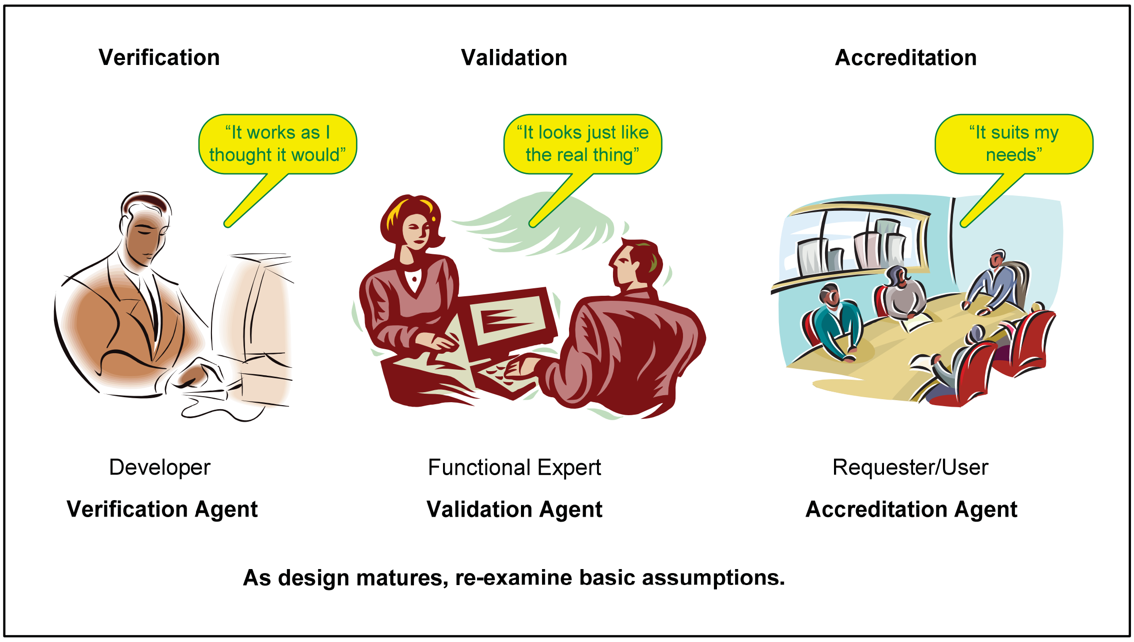


Figure 55: Verification, validation, and accreditation (US Department of Defense 2001)

Having explored the systems thinking and model verification, validation and accreditation, the next section will propose enhanced integrated modelling approach.

7.6 Enhanced IMA Proposed

In this section an enhanced form of the IMA is proposed which is based on observations made during Ford case study. The enhanced integrated modelling approach (EIMA) to the reconfiguration of MEs includes additional steps of (1) using structured data capturing methods during modelling stage 1; (2) creating causal loop models if and where necessary; (3) using structured modelling analysis based upon results of alternative configurations (e.g., production policy matrix within the IMA stages); (4) VVA of models after modelling stages and (5) model implementation, which aims to enhance the approach resulting in more logical models of a system in study. The step wise EIMA to designing the reconfiguration of MEs is shown in Figure 56 in a more descriptive manner also showing that:

$$EIMA = IMA + Stages\ of\ (CLM + Modelling\ Analysis + VVA + Implementation)$$

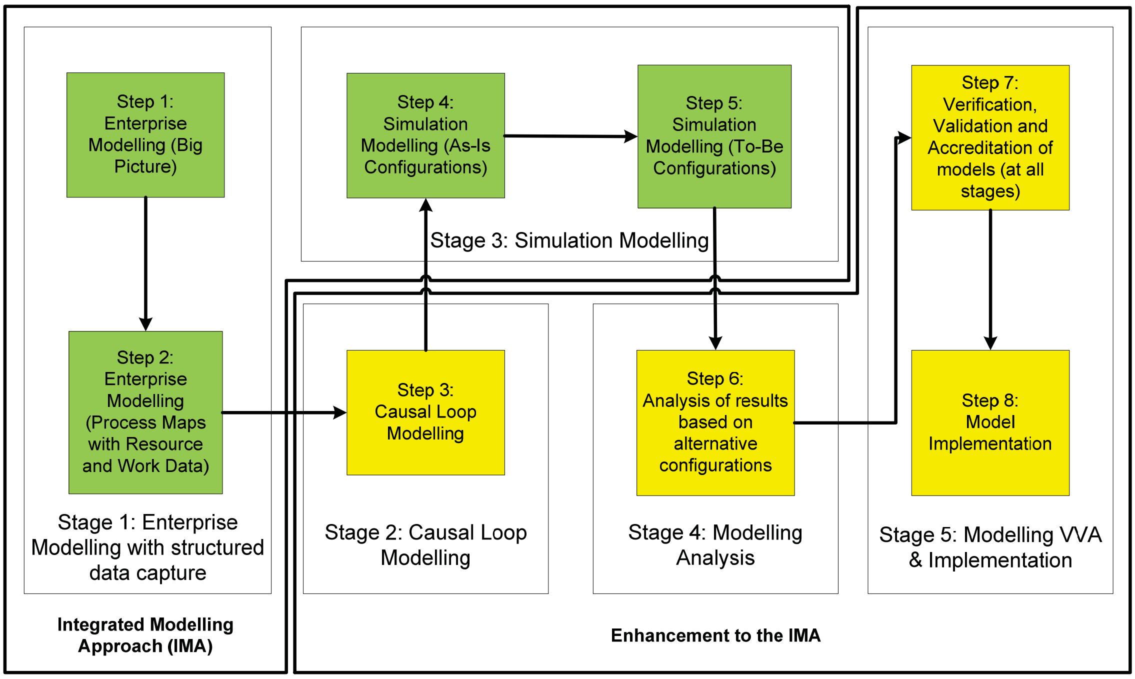


Figure 56: The EIMA to reconfiguring MEs

The IMA, in its initial and enhanced versions, has been published by the present author in synonymic forms that are included in Appendix B (Masood 2007; Masood et al. 2010b; Masood et al. 2010a; Masood et al. 2008a; Masood et al. 2008b). The additional steps included in the EIMA shall be discussed in the following.

Stage 2: CLM

Following EM but before moving to SM it was decided that CLM could usefully enhance the IMA resulting in: (1) improved system decomposition; (2) designing a set of experiments to deploy the simulation model to address issues of concern to the organisation being studied; and (3) identification and improved design of coherent set of computer executable simulation experiments. Causal loop modelling stage is shown in Figure 56 and IDEF0 based Figure 57 (after enhancement to the IDEF0 based figures presented in Chapter 5). The CLM stage consists of the following procedural steps (see Figure 58):

A21: Identify and document main issues involved

A22: Identify and document main causes

A23: Identify and document main effects

A24: Create causal loop model

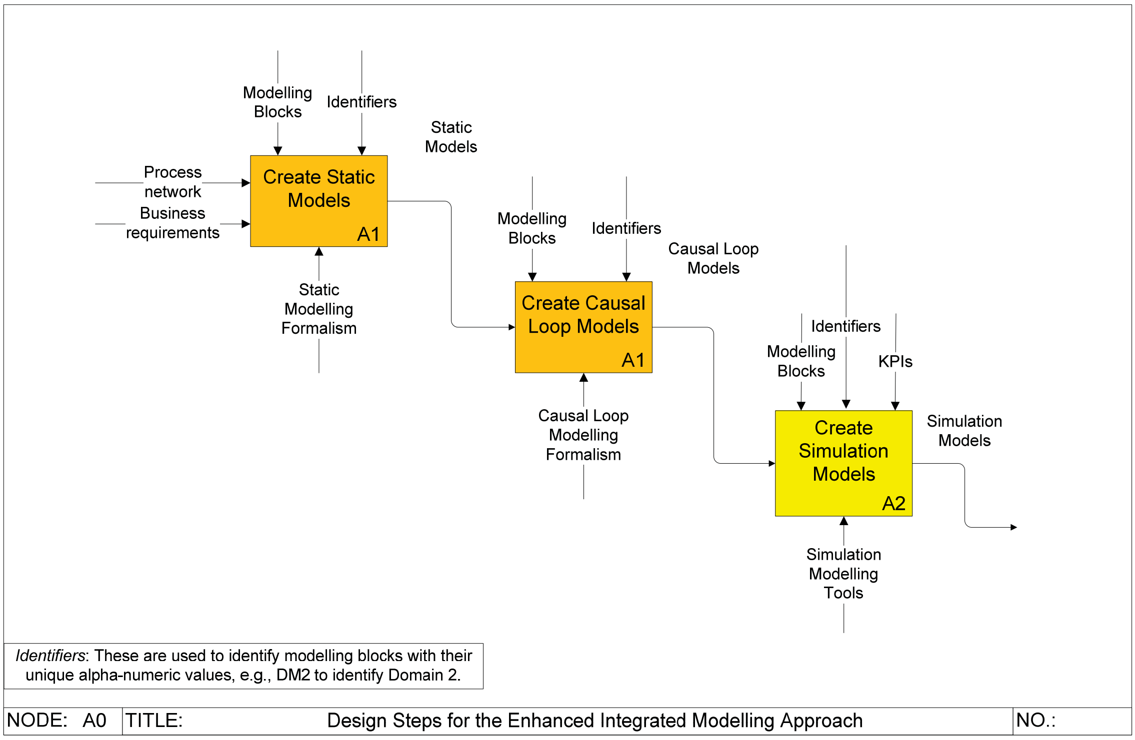


Figure 57: Design steps of EIMA to reconfiguring MEs

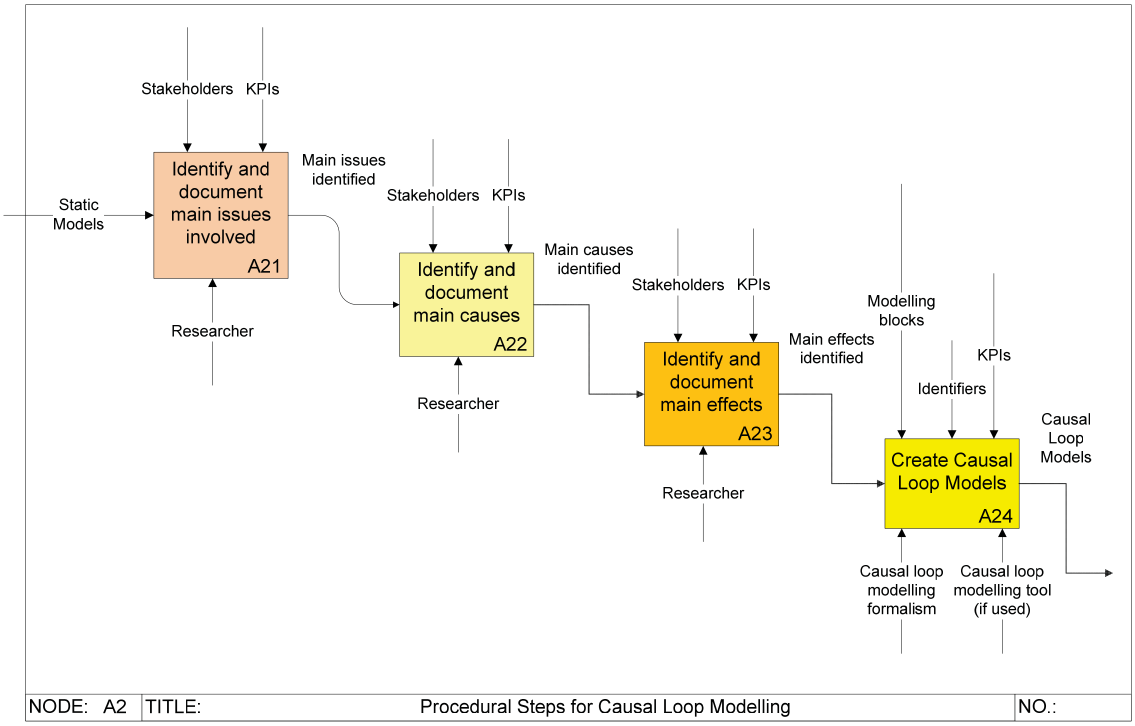


Figure 58: Procedural steps of CLM (A2)

Step 4: Modelling analysis

The modelling analysis stage enables the system designer to use simulation models (supported as required by CLM) in a structured way to replicate existing behaviours and predict, analyse and explain potential future behaviours arising from decision making. The selection of KPIs is a challenging task in today's dynamic environment and should show causal relationship (Hon 2005). Analysis of results is based on ME deployment of current (AS-IS) and possible future (TO-BE) responsiveness strategies; where KPIs are used to predict and compare production system behaviours under alternative strategies.

Step 5: Modelling VVA and implementation

The AS-IS enterprise and simulation models need VVA before starting TO-BE model generation. Also, upon reaching a near optimal model reconfiguration solution, the results require VVA. In effect, this process is carried out at all stages and formally acknowledged before implementation. Hence before final selection of strategy and production system configurations presentations are made to relevant funders and managers. Upon successful VVA, the ME management may approve the finalised TO-BE reconfiguration solution to be implemented within the ME.

Table 19 presents an overview of the methods and tools to be used in EIMA.

Table 19: Overview of the EIMA – the methods and tools to be used

EIMA Stages	Details / Steps	Reference architectures, methods or concepts (to be) used	Tools or templates (to be) used to apply EIMA
Stage 1: EM	Capture industrial data and create big picture	CIMOSA	Structured data capturing templates; MS Excel®
	Create detailed enterprise models using process maps, resource and work data	CIMOSA	EM templates: 'context diagram', 'interaction diagram', structure diagram' and 'activity diagram'; MS Visio®
Stage 2: CLM	Develop causal loop models (if and where required)	Systems thinking, CLM formalisms	CLM formalisms, MS Visio®
Stage 3: SM	Develop AS-IS simulation models for candidate strategies	CIMOSA (generic level); e.g., PPC methods (partial level); e.g., push, pull, Kanban, ConWIP (specific level)	Plant Simulation®, Simul8®, Arena®, iThink®/Stella®, MS Excel®
	Develop TO-BE simulation models for candidate strategies	CIMOSA (generic level); e.g., PPC methods (partial level); e.g., push, pull, Kanban, ConWIP (specific level)	Plant Simulation®, Simul8®, Arena®, iThink®/Stella®, MS Excel®
Stage 4: Modelling analysis	Analysis of AS-IS and TO-BE model configuration results based upon KPIs	Specific analysing methods	Structured ways; Enterprise models; Causal loop models; Simulation models.
Stage 5: Modelling VVA and implementation	VVA of enterprise models and As-Is simulation models	Specific VVA methods	*Verification*: By modeller *Validation*: By industrial partner *Accreditation*: By industrial partner
	Implementation of enterprise and simulation models	Specific implementation methods	Host ME tools (either owned or third party)

It is anticipated that the EIMA shall be tested in more complex situations by going into further depth of ME production control.

7.7 Significance of the EIMA to reconfiguring MEs

The EIMA is an enhanced version of the IMA and significance of its use is presented in the following:

- Structured data capturing during EM stage;
- Introduction of CLM stage providing rightful definition of objectives, broader situational analysis, more focussed way of looking into global objectives while considering side effects;
- Improved system decomposition;
- Designing a set of experiments to deploy the simulation model to address issues of concern to the organisation being studied;
- Identification and improved design of coherent set of computer executable simulation experiments;
- Structured way of modelling analysis based upon AS-IS and TO-BE model reconfiguration KPI results;
- Structured use of VVA stages enhancing credibility of models and hence their results;
- Providing structured modelling output by providing additional optional stages to the initial IMA that will facilitate a set of production policy mix for better decision making.

The importance of the EIMA presented above is in addition to the aforementioned significance of the IMA (see section 5.5).

7.8 Enhanced MUNE

The EIMA conceptual developments helped specify an *Enhanced MSI UNified Environment (E-MUNE),* which is based on the MUNE description presented in Chapter 5. The E-MUNE incorporates enhanced features of EIMA as described earlier in this chapter. The modelling view dimension of the E-MUNE includes the following:

1) Enhanced data capturing (EDC);

2) Enterprise Modelling (EM);

3) Causal Loop Modelling (CLM);

4) Simulation Modelling (SM);

5) Product dynamics (PD);

6) Customer Order Decoupling Point (CODP);

7) Work dynamic (Pr-Re couple);

8) Production policy mix (PPMix);

9) Solution space (SS);

10) Performance metrics (PfM);

The modelling levels dimension includes generic, partial and particular levels. The production planning levels dimension includes strategic, tactical and operational levels. *E-MUNE* is presented in Figure 59.

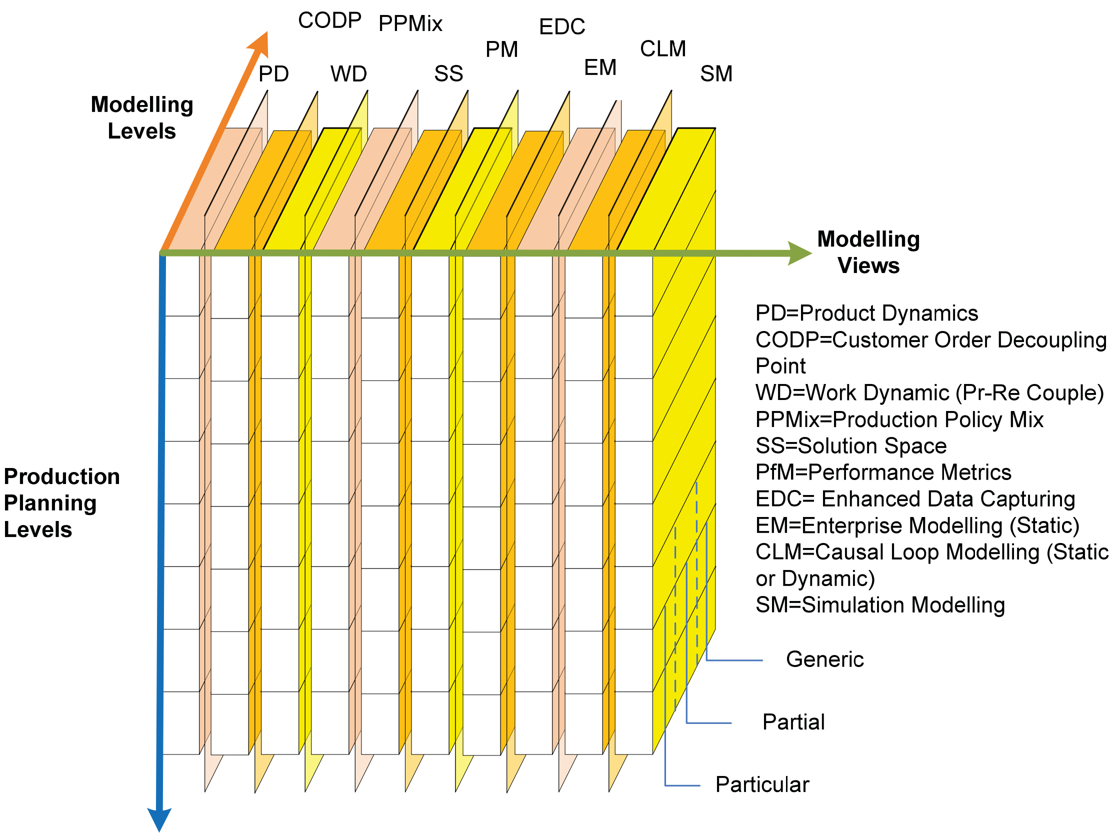


Figure 59: The E-MUNE

7.9 Reflections and conclusions

This chapter reports on EIMA to reconfiguring MEs which is an enhancement of the IMA as initially presented in Chapter 5 and its application in Ford case led to develop EIMA. A step-wise EIMA is presented in this chapter which also identified the importance of KPIs in change decision making process. Table 20 shows weaknesses of IMA and how these are addressed in EIMA.

Table 20: Weaknesses of IMA and how these are addressed in EIMA

Weaknesses of IMA	How these are addressed in EIMA
Lack of structured data capture for EM stage.	**EM:** Data capturing during EM stage in a structured way using templates will enhance the approach.
There was a lack of linking EMs with SMs effectively with following identified weaknesses: ❑ Chances of incorrect definition of objectives; ❑ Too much concentration on local objectives ignoring the global objectives; ❑ Limited situational analysis; ❑ Ignoring side effects	**CLM:** ❑ It provides rightful definition of objectives; ❑ It provides broader situational analysis; ❑ It provides more focussed way of looking into global objectives; ❑ It also considers side effects.
There was a need to enhance modelling analysis stage to predict in more quantitative terms.	**Modelling Analysis:** It provides a more structured way of modelling analysis based upon comparisons of AS-IS and TO-BE model reconfiguration results which are based upon focussed KPIs chosen for specific cases.
There was a lack of verification, validations and accreditation of developed models	**VVA:** It incorporates VVA of models enhancing their credibility and hence results.
Lack of structured output of the modelling exercises (e.g., difficulties in production policy decision making)	It provides a structured modelling output by providing additional stages to the initial IMA that will facilitate a set of production policy mix for better decision making.

Having established the EIMA, a need for its industrial application and testing arises. It is therefore important to see what type of industrial application would be suitable for the purpose.

7.10 The way forward

The IMA was applied in the MTS case of ‘pre-production management’ in the Ford PD Factory. The EIMA needs to be applied in more complex production control configurations viz: (1) MTO cases; and (2) ETO cases. As the Ford case only showed complexities involved in ‘pre-production management’, therefore it will be important to case test the EIMA in more complex and real ‘production control management’ problems.

Chapter 8

Case 2: Application of the EIMA in Bradgate Manufacturing Company

8.1 Motivation and introduction

The application of the IMA in Ford led to the development of EIMA as presented in Chapter 7. The research issue of 'pre-production management' was modelled in the Ford case – a large enterprise. The Ford case study, together with the development of the EIMA, raised the following research questions: (1) how can EIMA be applicable in more complex problems of 'production management'?; (2) how can EIMA behave in MTO configurations (other than the MTS as was in the Ford case)?; (3) how can EIMA behave in SMEs (other than large MEs as was in the Ford case)? To answer such questions, a furniture manufacturing company case was chosen, namely the Bradgate Manufacturing Company (which shall be referred as Bradgate in the postscript). Bradgate was one of the industrial partners in the EPSRC project titled "Unified modelling of complex systems – to facilitate ongoing organisation design and change" (Grant No. EP/D05821X/1).

The rest of this chapter is divided into six sections. Section 8.2 and 8.3 describes the overall research context and background of the Bradgate case respectively. The aims of the Bradgate case are listed in section 8.4. Section 8.5 illustrates a step-by-step application of the EIMA in the Bradgate case. Sections 8.6 includes reflections and conclusions. Section 8.7 gives future research directions.

8.2 Bradgate case – overall research context

In most of the world economies micro, small and medium-sized enterprises (SMEs)[14] are much greater in numbers. For example, in the 25-member EU there were approximately 23 million SMEs representing 99% of all EU companies and employing around 75 million people (European Commission 2005). Globally SMEs account for 99% of business numbers and 40%-50% of gross domestic product (GDP)[15]. SMEs are often prone to additional problems that are uncommon to the larger companies irrespective of the fact that both are facing the same challenges of managing product, work and resource dynamics. Today's SMEs face problems viz: (1) rapid response to changing customer demands; (2) lack of formal and well documented procedures; and (3) job allocation to the right resources in a timely manner (Gunasekaran et al. 2000; Oduoza et al. 2009; Wahid et al. 2008). Consequently, structured and formal ways to document SME processes and effective PPC are required to tackle such problems.

To answer a number of research questions raised during the Ford case study, the complex MTO production case of Bradgate, a SME, was chosen. On a global scale, furniture manufacturing is a big business and is estimated to be worth around US$240 billions. The UK is the world's fourth largest consumer of furniture and UK's furniture manufacturing industry is worth £10 billion making a significant contribution to the UK economy and directly employing around 124,000 people within 7,500 MEs (Davies 2009). The furniture manufacturing industry is prone to three major challenges at the macro level viz: (1) growing consumption; (2) globalisation; and (3) shift in production (Davies 2009). Bradgate is also facing such problems at the macro level as well as internal production control problems due to the growing complexities of the business. Due to uncertainty of order mix and high variety of products and its required volumes, lead times are becoming crucial for the *Bradgate Production System*. Davies (2009) also identified the lead times as an area of increasing importance in furniture MEs which currently averages at 4-6 weeks (Davies 2009). This chapter will illustrate the

[14] Micro, Small and Medium-sized Enterprises (SMEs), according to the revised definition, are made up of enterprises which employ fewer than 250 persons and which have an annual turnover not exceeding 50 million Euros, and/or an annual balance sheet total not exceeding 43 million Euros. European Commission (2003). The new SME definition. Official Journal of the European Union. Brussels, European Commission: 36.

[15] Gross Domestic Product (GDP) is used as an indicator of economic progress that measures the value of final goods and services produced in a given period of time. Gutierrez, C.M., C.A. Glassman, J.S. Landefeld and R.D. Marcuss (2007). Measuring the economy: a primer on GDP and the national income and product accounts. Washington, DC 20230, Bureau of Economic Analysis, U.S. Department of Commerce: 23.

application of EIMA in Bradgate. The research scope in Bradgate is illustrated in Figure 60 showing the use of EIMA in smoothing work dynamics in the Bradgate Production System while considering its incoming product dynamics and required outputs based on market demands.

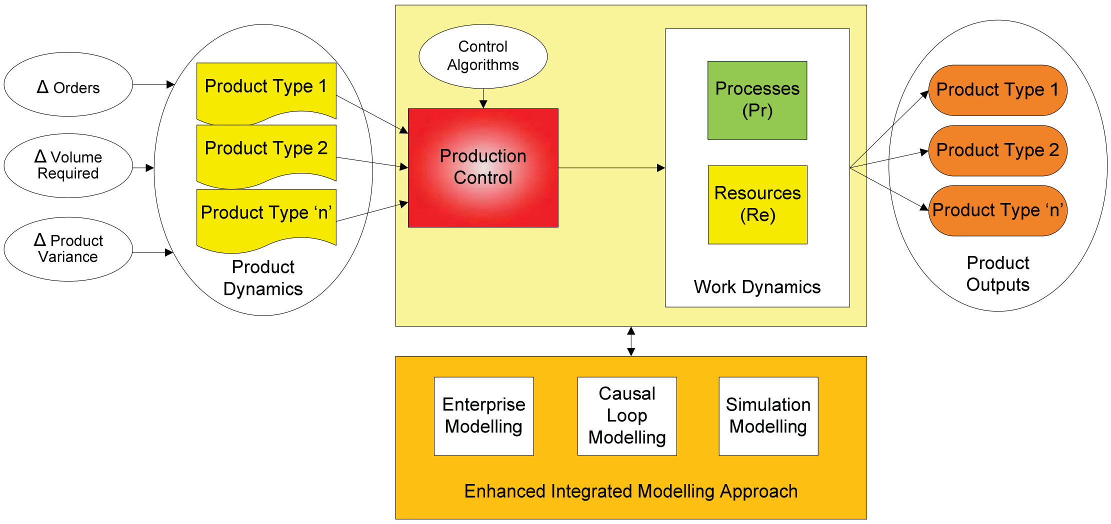


Figure 60: The research scope in Bradgate

8.3 Bradgate case study background

Bradgate is a furniture manufacturing SME with 50 employees. It operates primarily within the UK but has European suppliers of raw material. It manufactures over 300 different furniture products from pine wood; including a range of tables, cabinets, beds, wardrobes and other furniture items that are designed for both house hold and business users. The main production processes involved in Bradgate's furniture manufacturing are machining, assembly, spraying and finishing. Bradgate's current production system operates according to a MTO strategy, and is triggered by groupings of COs based upon logistical criteria related to customers categorized by UK location. A self owned fleet of lorries are used to deliver as per Cos. In practice however this logistical policy is known to constrain Bradgate. Production 'runs' to the capacity of these lorries or by the length of a pre-set maximum order collating time of four weeks (whichever constraint is exceeded first).

According to Bradgate's current PPC strategy, the company compiles orders received from customers on a weekly basis. The production starts with the issuance of a production order (PO)[16] to the assembly shop. The PO is then reviewed by the assembly shop coordinator who generates a 'Machine Shop Production Order (MSPO)' that requests needed parts from Bradgate's machine shop. The job list of the machine shop is regularly updated and priorities are set in order to maintain smooth running of the assembly shop. The PO is then moved through the assembly shop after receiving parts to be assembled from the machine shop, where assembly processes are carried out.

The assembly shop of Bradgate mainly consists of two sections, namely, cabinet assembly and table assembly sections. Each section has its own work organisation, but appeared to have commonalities in their adopted planning and scheduling approach. This section briefly explains related issues of the cabinet section and the overall assembly production planning system. In the cabinet section there are 6 main work benches that are organised into 3 sub sections. Some cabinets are being made in two stages in a flow shop fashion, the operators refer to them as 'first fix' and 'second fix' whereas others go through only a single stage before moving to next shop, i.e. the spray shop. Thus, in this section, out of six work benches, two are allocated to first fix operations and three are allocated to 'second fix' operations. The remaining one bench is allocated to single stage cabinet products. In addition to six main work benches there are two more workbenches that are specialised in making auxiliary cabinet parts and small items, namely, one is for making small items such as nest of tables, mirrors, CD racks and the other is for making auxiliary cabinet parts such as drawers, plinths and H-Frames. Since these two workbenches are working independently from the other sections of the cabinet area in terms of planning and work-loading, they remain outside the scope of the case study application of EIMA in Bradgate.

The assembly area deploys a 'real-time scheduling' approach where there is no frozen schedule and the question of 'what-to-do next' is attempted every time a job is finished based on the current status of ever changing job lists, level of resources and *due dates*. The (human) resources are almost fully floating across different sections, sometimes even across departments. The assembly area has three production supervisors, one being the overall assembly coordinator, the other two being the

[16] PO is known as 'sales order picking list' in Bradgate.

respective section sub-supervisors for table assembly and cabinet assembly sections. The picking list is received from the CO processing department twice a week by the assembly coordinator. Then he prepares 'partial picking lists' by highlighting the relevant furniture items for each assembly area and passes it to the work benches. Every time a workbench finishes a job the next job is picked from the highlighted list according to EDD[17] and MST[18] sequencing rules. The similar items are grouped together and some items are made in batches to save the setup time if they are in the same 'delivery run'.

It was noted that high variety of more than 300 products contains both less frequent and highly demanded products during certain periods which were unknown. There were no forecasting methods being adopted and product demands were unpredictable. After a number of visits to the company and number of semi structured interviews and discussions with company management and operators, initial data was collected. Following which enterprise models of the MTO processes of Bradgate were created and validated by the company management.

8.4 Aim and objectives of the Bradgate case

The main aim of this case study is to demonstrate that the EIMA to the reconfiguration of MEs is applicable in a MTO SME. In accomplishing this aim, the EIMA is applied and illustrated in the following. The objectives of the case study include engineering of Bradgate's PPC system to improve reconfigurability and responsiveness through application of EIMA.

8.5 Application of the EIMA in Bradgate

During application of the EIMA, a number of alternative PPC strategies were investigated in order to improve the responsiveness of Bradgate to rapidly changing market demands. Capturing and reusing enterprise and simulation models of Bradgate's BPs, (human and technical) resource systems and dynamic patterns of multi-product workflows were achieved. This section describes case study modelling in Bradgate which corresponds to the EIMA as described in Chapter 7 (Figure 51).

[17] EDD: Earliest Due Date sequencing rule processes jobs with earliest due date first.

[18] MST: Minimum Setup Time sequencing rule processes jobs with minimum total setup time under a given type sequence.

The EIMA is based upon a step wise combination of EM, CLM and SM techniques to create a coherent set of models that can structure and inform: (1) understanding of the problem domain; (2) development of a conceptual model in relation to problem domain; (3) information and data collection; (4) AS-IS model building for the present configuration(s) of processes and systems in Bradgate; (5) model building for TO-BE configurations; (6) VVA of models; and (7) experimental work and analysis based upon KPIs leading to system design and/or selection.

A set of computer and manual technologies and systems have been used to understand the problem domain, execute the EIMA and provide a suitable interface to users and modellers for decision making. MS Visio was used to create static enterprise and causal loop models. Simul8 ®, Plant Simulation ®, Arena ®, and iThink ® were among candidate proprietary software packages to create dynamic models. Such interfaces enabled the author to: (1) capture requirements data; (2) input data into the model; (3) reconfigure a simulation model to meet various specified needs; (4) conduct various experiments based upon alternative configurations; (5) collect results and (6) conduct analysis with respect to KPI driven results. The stepwise application of EIMA (see Figure 51) in Bradgate is presented in the following.

8.5.1 Stage 1: development of enterprise models

To capture an AS-IS model of the current combination of PPC strategy and production system configurations used by Bradgate, EMs of the company have been developed after several visits to the company. The case study static EMs including context diagram, interaction diagrams, structure diagrams and activity diagrams were created after several semi structured meetings and interviews with Bradgate management and production teams. Product introduction (DM1), produce and deliver (DM2) and business management (DM3) were the main CIMOSA domains studied in detail. These domains are shown as CIMOSA conformant domains in the context diagram. The non-CIMOSA domains related to the case study included stockists (DM4), raw material suppliers (DM5), sub-product (e.g. chairs) suppliers (DM6), miscellaneous fixture supplier (DM7), technology vendor (DM8), market analysis (DM9) and finance (DM10). Figure 61 shows the context diagram created for the Bradgate enterprise in respect to its 'Make Furniture to Order' processes.

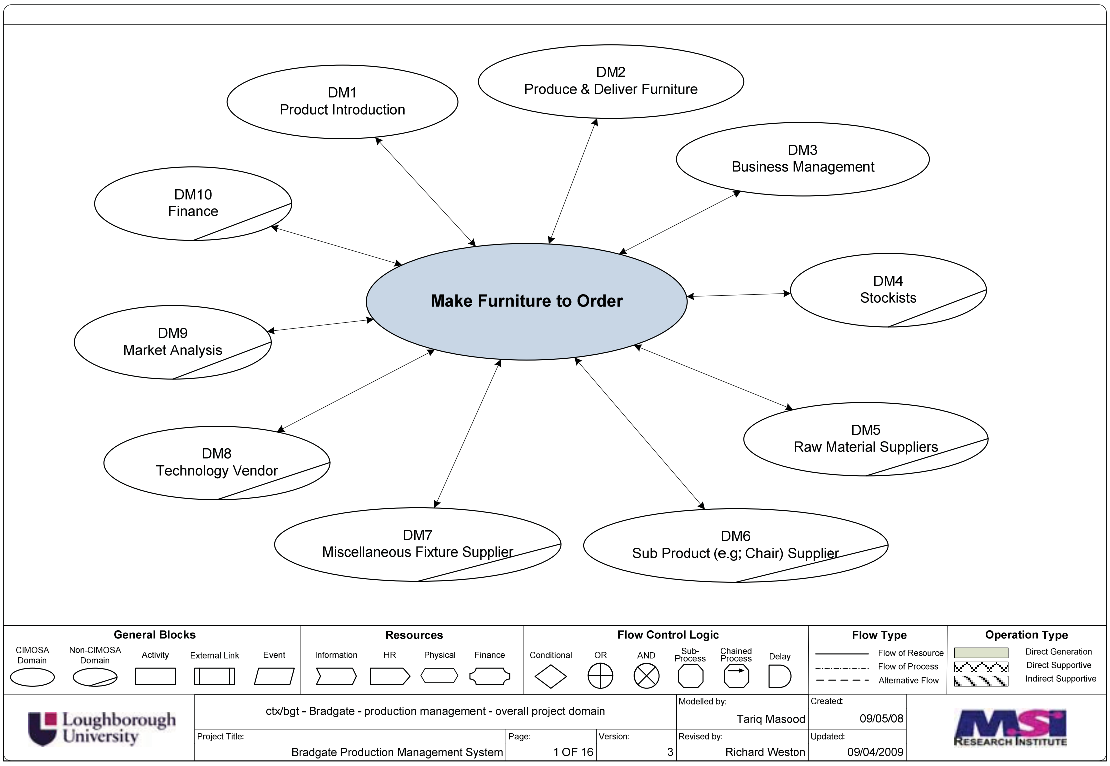


Figure 61: Bradgate case: context diagram

In the study reported here, focus was on improving best practice PPC in Bradgate and when so doing to consider other possible production system configurations which might enhance the responsiveness and profitability of Bradgate. Therefore, the interaction of plan and control product realisation (BP3.1.2) with other BPs is important to in respect of the design and operation of the Bradgate production system. The other BPs of prime concern include: interact with stockists (BP3.1.1), maintain stock level (BP3.1.3), control finances (BP3.1.4), develop strategy (BP3.1.5), improve business (BP3.1.6). The DPs interact with BPs viz: stockists (DP4.1), suppliers (DP5.1, 6.1, 7.1), produce and deliver furniture (DP2.1), introduce products (DP1.1), analyse market (DP9.1) and financing (DP10.1). Figure 62 shows interactions between plan and control product realisation BPs in a sub interaction diagram of Bradgate's DM3.

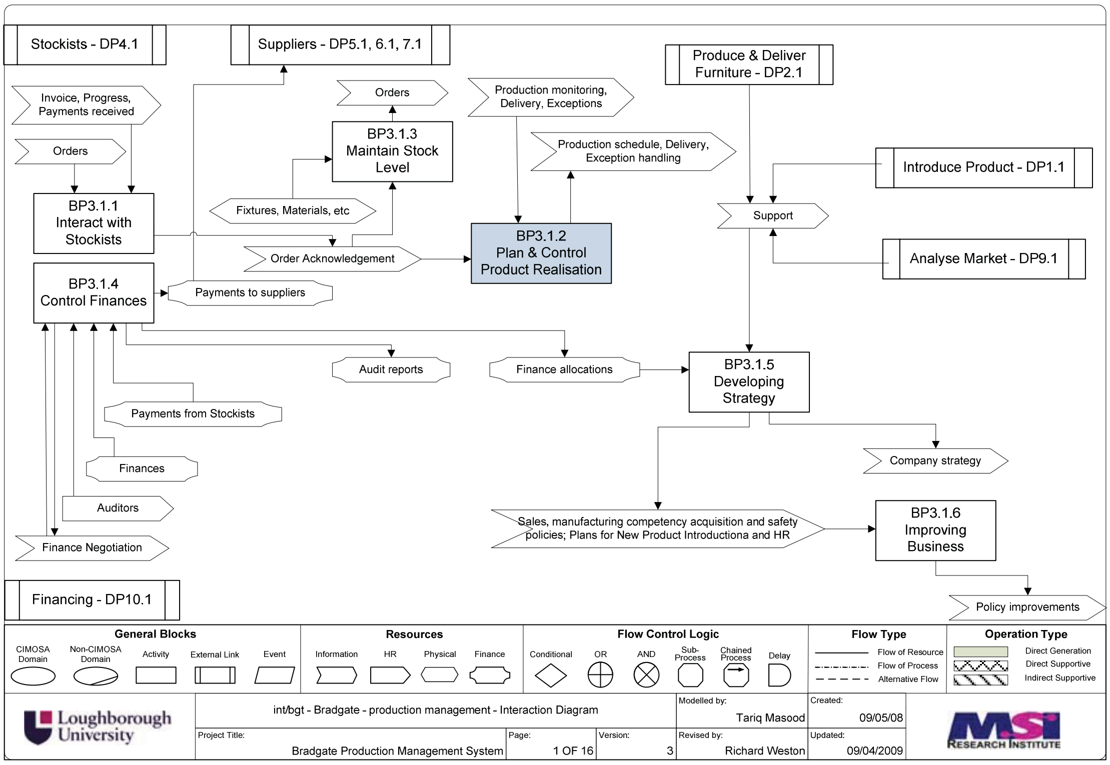


Figure 62: An interaction diagram of plan and control product realisation (BP3.1.2 of Bradgate's DM3)

The structures of DPs and in effect BPs are important in order to know about their sequences and precedence relationships. The structure of produce and deliver furniture (DP2.1) involves make furniture to order (BP2.1.1), spray and finish furniture production (BP2.1.2), package and deliver (BP2.1.3), manage and maintain production and transport activities (BP2.1.4) and support and implement product introduction (BP2.1.5). Figure 63 shows a structure diagram created for DP2.1 and its related BPs and sub BPs.

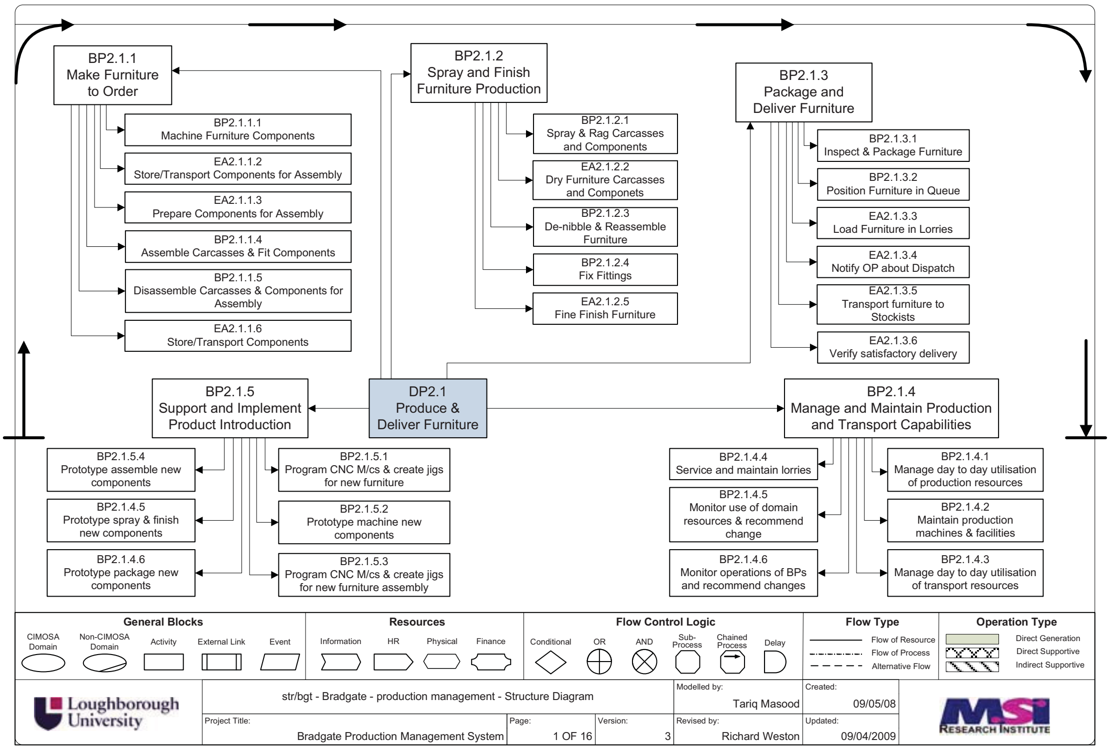


Figure 63: Structure diagram of produce and deliver furniture (DP2.1 of Bradgate's DM2)

The BPs are composed of ordered sequences of EAs which explicitly define what elemental activities need to be performed as part of BPs and DPs that are owned by modelled DMs. Interact with stockists (BP3.1.1) is composed of EAs that: receive orders (EA3.1.1.1), collate orders daily (EA3.1.1.2), enter order details into SAGE software system (EA3.1.1.3), send order acknowledgements to customers (EA3.1.1.4), and file copies of original customer orders (EA3.1.1.5). The EA3.1.1.1 is triggered with the arrival of CO events. Information detailing COs is received via fax, telephone or email and a sales executive (human resource) is deployed while executing these EAs. Plan and control product realisation (BP3.1.2) is composed of EAs that: assign each order to a classification based on the geographical location of the stockist/customer (EA3.1.2.1), file orders with respect to their geographical location (EA3.1.2.2), maintain control sheets (EA3.1.2.3), and generate Purchase Orders (PO) (EA3.1.2.4). The EA3.1.2.1 starts with the availability of CO acknowledgement information and EA3.1.2.4 generates information in the form of PO and PO acknowledgement. Figure 64 shows activity diagrams for BP3.1.1 and BP3.1.2.

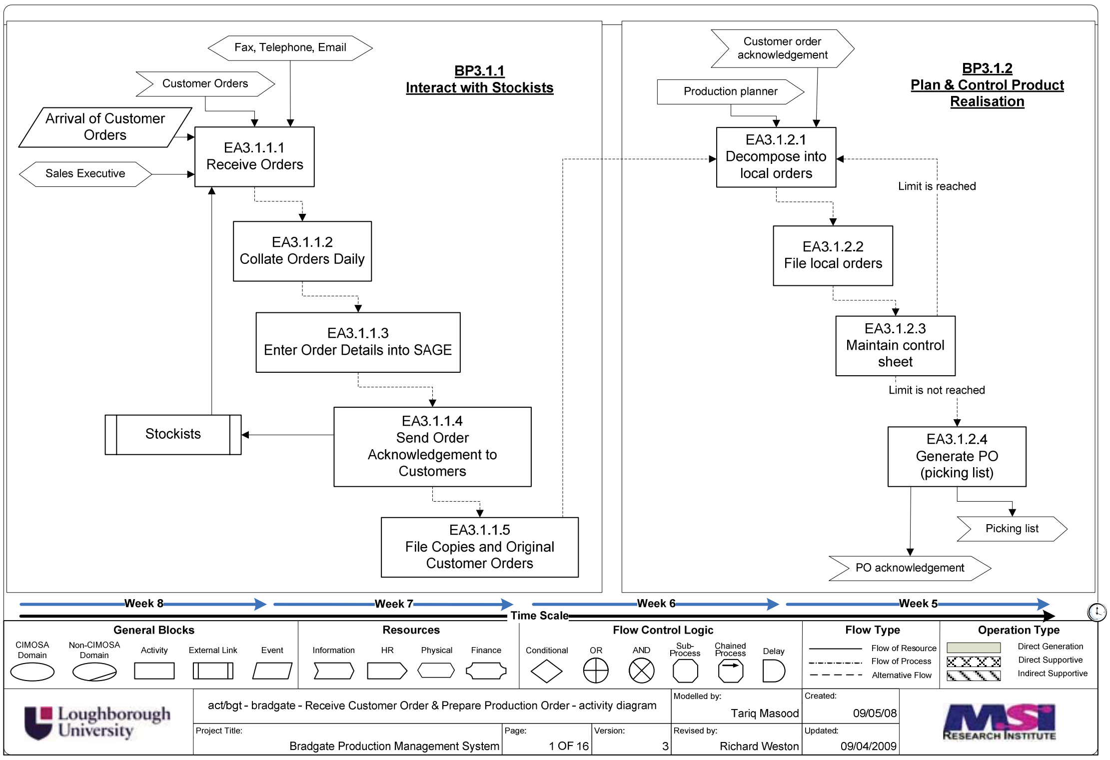


Figure 64: Activity diagram of Bradgate's business processes BP3.1.1 (interact with stockists) and BP3.1.2 (plan and control product realisation)

It was observed that the EMs of Bradgate provided an explicit description of relatively enduring relationships between activities carried out during planning and control, and during production and purchasing. It was evident that these relationships defined a process oriented structure that could be recoded using simulation technologies. This idea is developed in sections 8.4.3 and 8.4.5. The activity relationships made explicit by EMs were also used to create an information model related to planning and control of aspects of the Bradgate production system. This information model was developed to explicitly describe PPC decision making in Bradgate. Here UML™ [19] was used to encode information entities, and their relationships, that form POs of Bradgate. The information model created is presented in Figure 65.

[19] UML™: Unified Modelling Language is Object Management Group (OMG)'s specification and the modelling method for business process, application structure, data structure, behaviour and architecture OMG. (2009). "Unified Modelling Language (UML)." Retrieved 16 Feb 2009, from http://www.uml.org/.

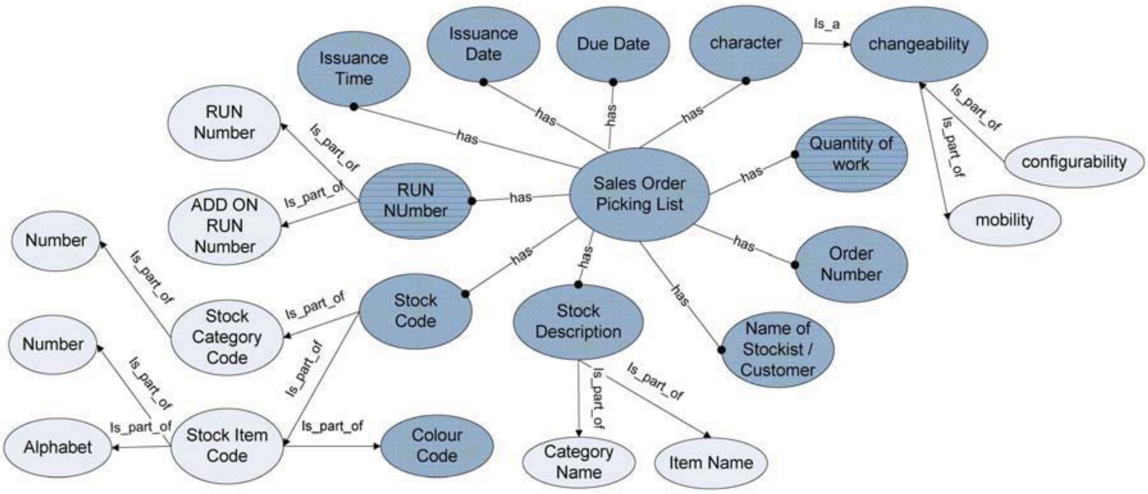


Figure 65: UML™ information model of Bradgate's PO

Bradgate's PO defines: (1) 'run number' / 'add on run number'; (2) (customer) order number; (3) quantity of work; (4) issue date and time; (5) *due date*; (6) stock category code (which has a numeric value); (7) stock item code (which has an alpha-numeric code); and (8) a colour code. Also it contains a stock description showing a category name and item name and the name of the stockist (customer). This information model aided the authors' understandings about characteristics of Bradgate's current production order system.

8.5.2 Stage 2: development of causal loop models

Causal loop models were introduced in the EIMA as described in Chapter 7. The Bradgate case is more complex than the Ford case in terms of its greater product dynamics, and larger number of human, machine and IT resources. There are a number of potential production policies and configurations that can be changed within the virtual environment. These parametric changes to the initial model will generate TO-BE configurations where potential benefits can be predicted and measured through use of KPIs. The potential production policies identified as being of major interest to Bradgate are as follows:

1) Removal of the logistical constraint – In TO-BE configurations the logistical constraints shall be removed in order to get optimal solution to the problem;

2) Release of 'PO' – This represents the frequency with which the work arrives at the start of the raw materials process, and will have an effect on work rate reproduced by the process and one or more operations. In TO-BE configurations the production orders shall be released to the production system as they arrive irrespective of the logistical criteria; and

3) Hybrid MTS/ATO[20] strategy – A hybrid MTS/ATO strategy shall be adopted. The products are grouped on basis of similarity in processes and process times. The grouped products are fed into the TO-BE simulation models to generate final results.

The KPIs identified as being of major interest to Bradgate are as follows:

a) Throughput time (Lead time) – The throughput time or lead time is one of the most frequently used KPI and was used in this case as a major comparator.

b) Cost – Cost is also a prime KPI on which alternative production policies are decided.

c) Utilisation of resources – The assignment of resources to work within the assembly section can be optimised for process improvements.

d) WIP[21] levels – The WIP levels play an important role in determining the amount of inventories held in a manufacturing business.

Reduction in lead time (and in effect throughput time) is therefore an important KPI in the engineering of an efficient and responsive PPC system. The current system is analysed with a view to the future implementation of a hybrid MTS/ATO system. We consider a hybrid approach here because the COs are characterised by order led customisation of products made up from common and/or similar parts and subassemblies. When populated order behaviours are available, the predictability of orders is better achievable using forecasting methods. Such a MTS/ATO system is known to be practicable in environments where standard parts are available to assemble using a postponement approach. With product (re)design, it is achievable to

[20] MTS/ATO: Make-To-Stock/Assemble-To-Order

[21] WIP: Work In Progress

make standard parts which are partially driven by a MTS strategy and partly by an ATO strategy. Implementation of a hybrid MTS/ATO system needs better product and process (re)design, availability of stock, availability of BOM[22] data, availability of forecasted orders, commonality of parts (standardisation of parts or modularisation) and better supplier relationships. Provided this kind of support is available, reduction in lead time is achievable which leads to customer satisfaction and then may result in an increased frequency of orders. All above-mentioned factors enhance the chances of success rate of implementation of hybrid MTS/ATO system. Some key impacts of implementation of a hybrid MTS/ATO system in support of engineering an efficient and responsive PPC system in Bradgate are illustrated by the cause and effect diagram shown in Figure 66.

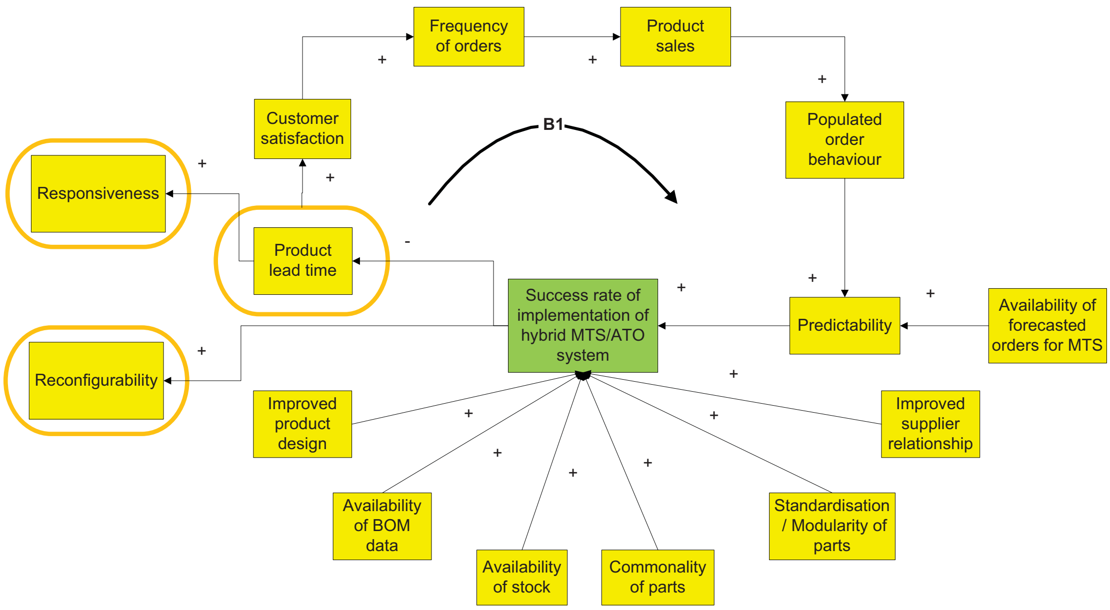


Figure 66: Causal loop model: implementation of hybrid MTS/ATO strategy in support of engineering PPC system in Bradgate

8.5.3 Stage 3 (Step 4): development of AS-IS simulation models

A general purpose simulation model of MTO production processes at Bradgate was built on the basis of the foregoing analysis. Here a proprietary discrete event simulator (namely Simul8®) was chosen as opposed to a system dynamics tool. This was mainly because, firstly, the timings of the events are of the prime importance to the purpose of the modelling exercise, i.e. inter-arrival time, lead time, queuing time etc.,

[22] Bill Of Material

and, secondly; the identification of specific products and/or product types with associated attributes needed to be maintained for benchmarking purposes. The simulation model developed was general purpose in that it facilitated experimentation (with respect to needed process variables identified during CLM stage), enabling impact analysis of changes to scheduling and work organisation policies. A set of SM experiments was designed and carried out so as to test effects of PPC policy change on KPIs including: 'lead times', 'inventory levels', 'bottlenecks', 'resource utilisation', 'value generation' and 'process costs'.

The AS-IS simulation model developed to bench mark the as-is configuration of cabinet assembly production at Bradgate is shown in Figure 67. The process flow of Figure 67 (AS-IS simulation model) was derived from enterprise models of Bradgate. In this simulation model, cabinet assembly section consists of three sub sections. The sub section 1 and 2 deals with cabinet groups C1-C8. The sub section 1 processes at the first instance (named as 1st fix) while the sub section 2 processes after sub section 1 finishes work and is named as 2nd fix. The sub section 1 has two cabinet fixers called cabinet 1st fixer1 and cabinet 1st fixer2. The sub section 2 has three cabinet fixers named as cabinet 2nd fixer1, cabinet 2nd fixer2 and cabinet 2nd fixer3 as shown in the AS-IS simulation model. The cabinet groups C9-C11 are processed by sub section 3 independently which has only one resource named as single stage cabinet maker. The data of cabinet batches and their inter-arrival times were input to an excel sheet as shown in Figure 67. This excel sheet was then linked as an external data source to the simulation model so that the model could run according to the number of cabinet batches and inter-arrival times after reading information column wise. 'Label' based routing out method was used in this simulation model that contained information in terms of numbers. The following 'labels' were used in this simulation model:

Batch1 – Batch11; used for batch distributions at work entry points as externally sourced from excel data sheet.

Pick1 – Pick11; used for pick distributions used at work entry points as externally sourced from excel data sheet.

partid; used for segregation of results according to the cabinet group types at work entry and exit points by setting its value to a specific numbered identification.

1stager; used for distribution at sub section 3 which comprised of single stage cabinet maker.

1stfixtime; used for distribution at sub section 1 which comprised of cabinet 1st fixer 1 and cabinet 1st fixer 2.

2ndfixtime; used for distribution at sub section 2 which comprised of cabinet 2nd fixer 1, cabinet 2nd fixer 2 and cabinet 2nd fixer 3; and

route; used for defining route of information flow.

In order to program the simulation model, 'visual logic' was also used at different stages with the help of the above mentioned 'labels' e.g., 'label' actions using '1stfixtime', '2ndfixtime', and '1stager' as following:

- *VL SECTION: C1 Entry Logic*

  SET 1stfixtime = opstimematrix[2,partid+1];

  SET 2ndfixtime = opstimematrix[3,partid+1];

- *VL SECTION: C9 Entry Logic*

  SET 1stager = opstimematrix[4,partid+1];

- *VL SECTION: C10 Entry Logic*

  SET 1stager = opstimematrix[4,partid+1];

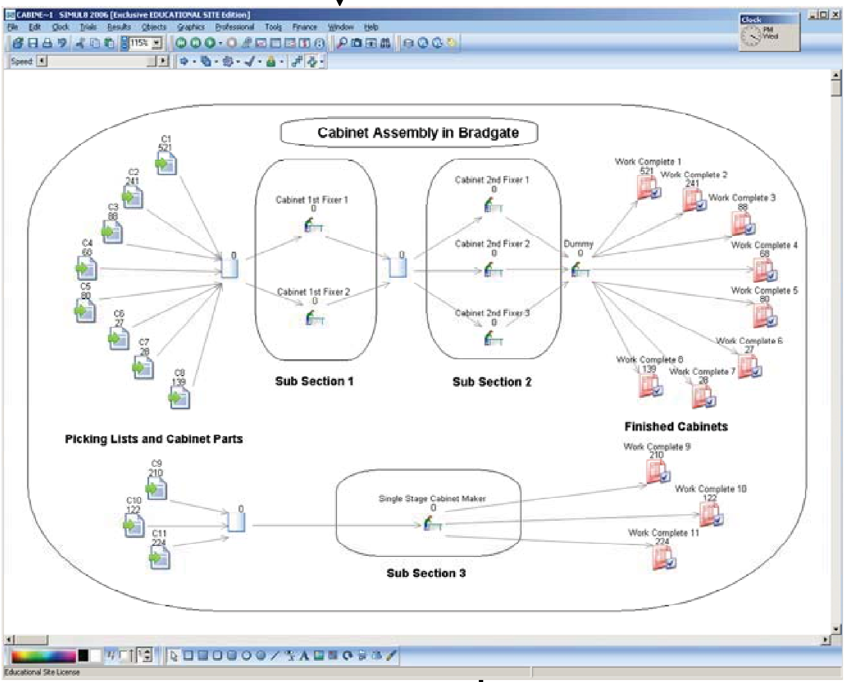
- *VL SECTION: C11 Entry Logic*

  SET 1stager = opstimematrix[4,partid+1]

Batches and Inter-arrival Times (Groups 1-11)

Group 5			Group 6			Group 7		
Interval Time (hrs)	Interval Time (min)	Batches	Interval Time (hrs)	Interval Time (min)	Batches	Interval Time (hrs)	Interval Time (min)	Batches
0	0	0	0	0	0	0	0	0
2	960	4	2	960	0	2	960	0
4	1920	0	4	1920	0	4	1920	0
4	1920	1	4	1920	2	4	1920	0
1	480	3	1	480	0	1	480	0
4	1920	2	4	1920	0	4	1920	0
4	1920	1	4	1920	0	4	1920	1
4	1920	1	4	1920	0	4	1920	2
2	960	5	2	960	0	2	960	0
1	480	5	1	480	0	1	480	1

AS-IS Simulation Model developed in Simul8®



Outputs

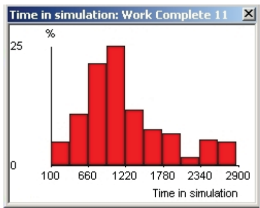


Figure 67: AS-IS simulation model of cabinet assembly production in Bradgate

8.5.4 Stage 3 (Step 5): development of TO-BE simulation models

It was proposed when conceptually designing and developing TO-BE configurations that the cabinet assembly orders should be routed through a PPC section. Therefore the TO-BE conceptual model incorporates the proposed MTS/ATO hybrid strategy. It was assumed in TO-BE simulation models creation that the products were grouped on the basis of their process types and process times. The TO-BE simulation models were subsequently run with representative real customer order data for 6-month, based upon the cabinet groups already developed. Since the cabinet groups 9-11 use a dedicated resource for production, these groups have been treated separately in the simulation models and related results have been separated out. Figure 68 illustrates the conceptual base model of the TO-BE cabinet assembly systems along with points of foci.

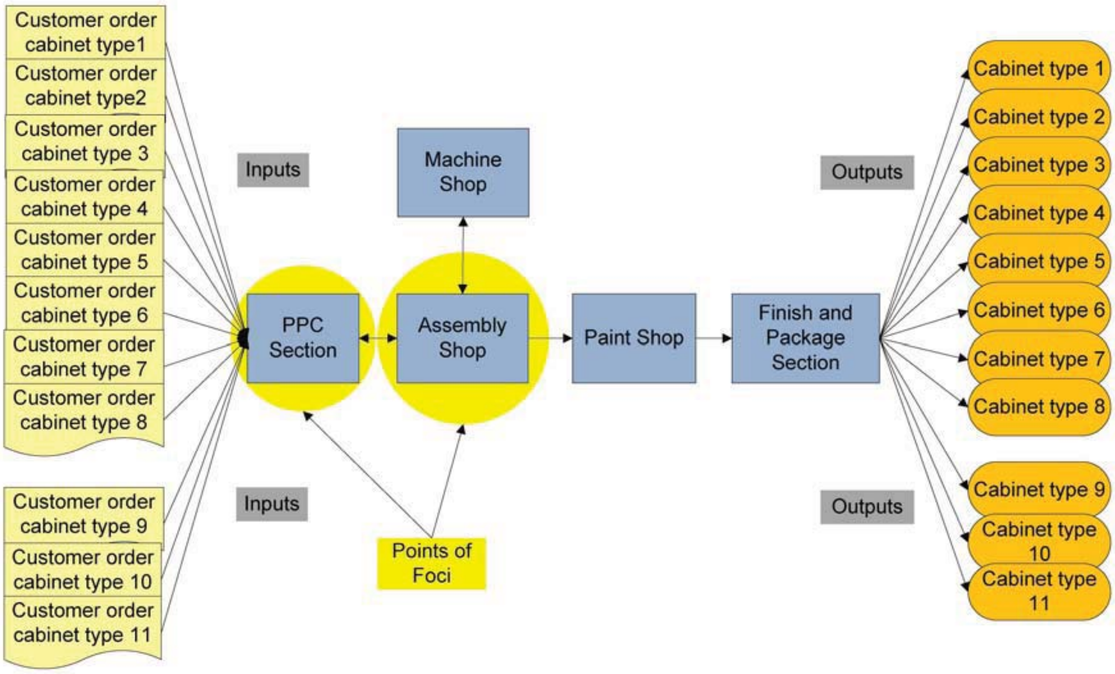
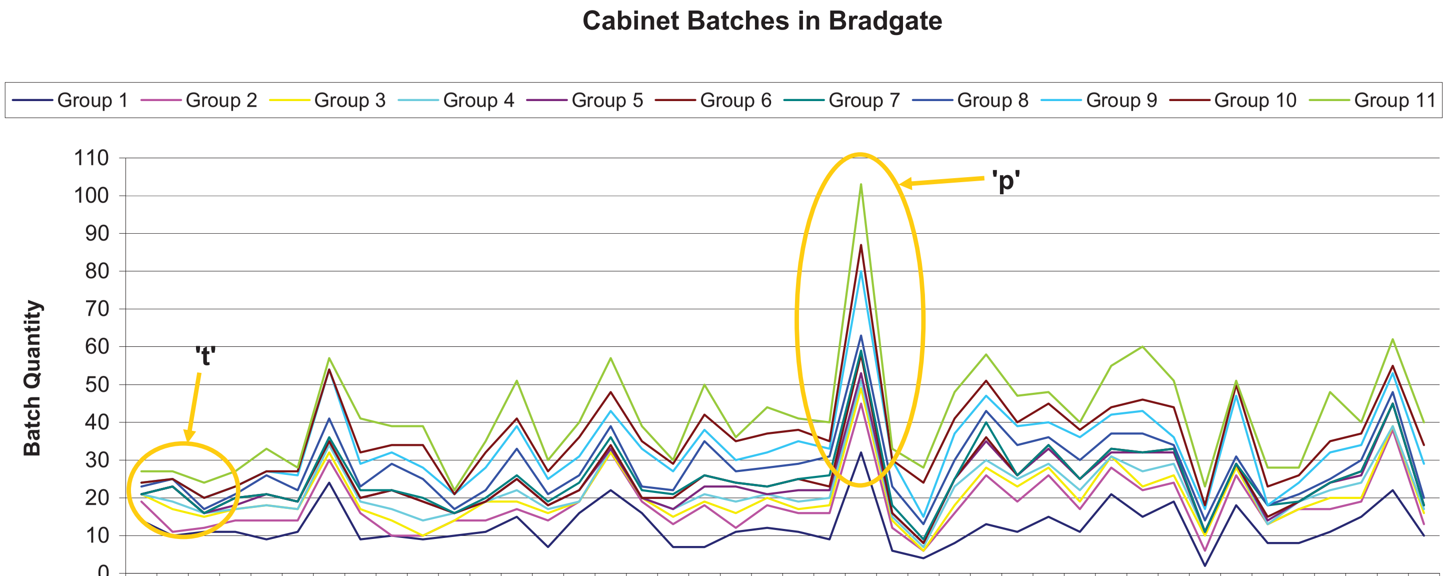


Figure 68: Conceptual base model of the TO-BE cabinet assembly system

After consultation with the Bradgate management executives and the operators, the eleven groups of cabinet products referred to earlier were conceived. These groups are based mainly upon the commonality of their processes, process sequences, process times and required resources. Figure 69 shows real customer order data for batches of cabinets grouped in Bradgate. It also shows data table of batch quantities for groups 1-11 drawn against order numbers 1-42. The same set of order data was used for TO-BE configuration testing with simulation model based experimentation. The ‘peaks’ and ‘troughs’ of the batch quantities for this 6-month period may be found in the figure as “p” and “t”.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Group 11	3	2	4	4	6	1	3	9	5	5	1	3	10	3	4	9	4	1	8	1	7
Group 10	0	0	0	0	0	1	0	3	2	6	0	4	2	2	5	5	2	2	4	5	5
Group 9	1	0	3	2	1	4	13	6	3	3	4	6	6	4	5	4	10	5	3	3	4
Group 8	2	2	1	1	5	3	5	1	7	5	1	2	7	2	2	3	1	1	9	3	5
Group 7	0	0	0	0	0	0	1	2	0	1	0	1	1	1	2	2	2	1	0	0	0
Group 6	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	3	3	1	2
Group 5	0	4	0	1	3	2	1	1	5	5	0	0	3	1	3	0	0	0	2	4	0
Group 4	0	2	1	0	0	0	2	2	3	4	2	0	3	1	0	1	0	2	2	3	1
Group 3	2	6	3	3	4	3	2	1	4	0	0	5	2	2	0	0	1	2	1	4	2
Group 2	5	1	1	3	5	3	6	7	0	1	4	3	2	7	3	10	3	6	11	1	6
Group 1	14	10	11	11	9	11	24	9	10	9	10	11	15	7	16	22	16	7	7	11	12

	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Group 11	3	5	16	3	4	7	7	7	3	2	11	14	7	5	1	5	2	13	3	7	6
Group 10	3	2	7	0	9	4	4	1	5	2	2	3	8	1	3	5	2	3	3	2	5
Group 9	6	2	17	7	2	7	4	5	4	6	5	6	2	3	16	0	3	7	4	5	9
Group 8	4	5	4	5	4	5	3	8	2	5	4	5	1	3	2	0	2	1	3	3	2
Group 7	0	3	1	2	1	0	4	0	0	0	0	0	0	0	0	3	0	0	0	0	0
Group 6	3	1	5	0	0	0	1	0	1	0	1	0	1	0	0	1	0	0	1	0	0
Group 5	3	2	2	1	1	2	5	1	4	3	1	5	3	0	0	1	0	2	2	6	1
Group 4	2	2	2	1	1	5	2	2	1	3	0	4	3	1	1	0	2	2	4	0	1
Group 3	1	2	4	2	0	2	2	4	2	2	3	1	2	4	2	0	0	3	1	1	3
Group 2	5	7	13	6	2	8	13	8	11	6	7	7	5	4	8	5	9	6	4	16	3
Group 1	11	9	32	6	4	8	13	11	15	11	21	15	19	2	18	8	8	11	15	22	10

Order Numbers

Figure 69: Order behaviour of grouped cabinet batches in Bradgate over 6-month period

The customer order data on inter-arrival times is important in understanding the order behaviour. Figure 70 shows real customer order data for inter-arrival times of grouped cabinet products in Bradgate. The same set of order data was used as input to TO-BE configurations. The ‘peaks’ and ‘troughs’ of the inter-arrival times for this 6-month period may be found in the figure as “p” and “t”.

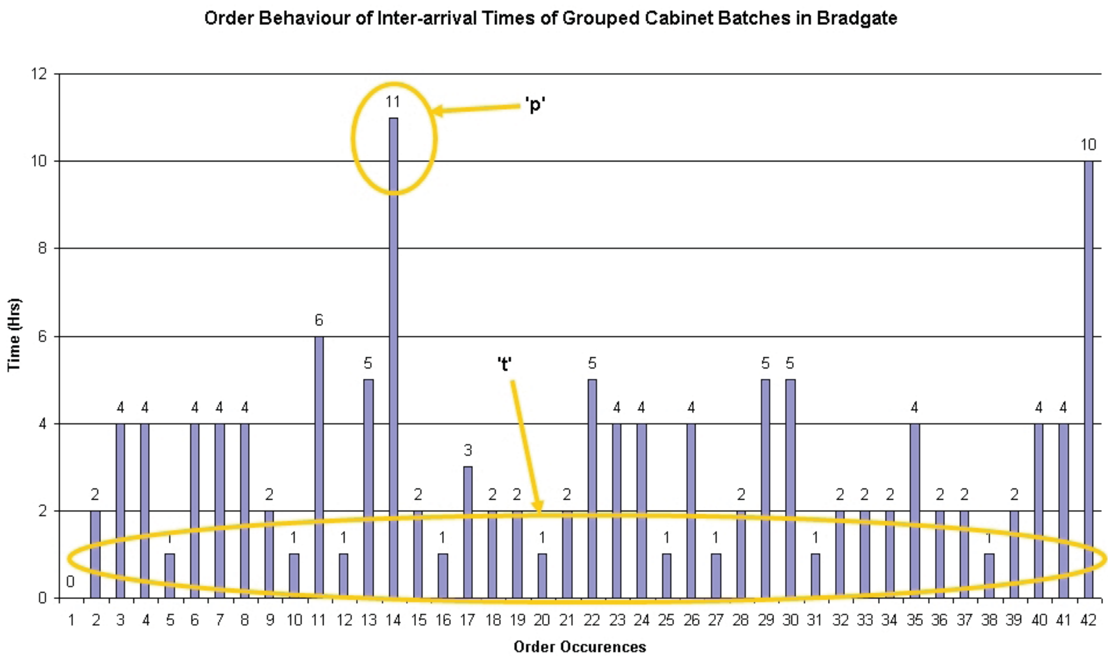


Figure 70: Order behaviour of inter-arrival times of grouped cabinet batches in Bradgate over 6-month period

In candidate TO-BE configurations, the product input (an external environment variable) was kept frozen to the real 6-month customer order data for cabinet products. However selected internal environment variables including resources etc. have been changed to seek to achieve improved production behaviours and KPI performances. In candidate TO-BE configurations, a PPC section was added to the AS-IS simulation model, as also presented in the conceptual model. This was to enable switching between alternative plan and control production policies. It was assumed that the PPC section had only one resource and takes 30 minutes on an average distribution to process an order. A TO-BE simulation model, developed using Simul8®, is shown in Figure 71.

Batches and Inter-arrival Times (Groups 1-11)

Group 5			Group 6			Group 7		
Interval Time (hrs)	Interval Time (min)	Batches	Interval Time (hrs)	Interval Time (min)	Batches	Interval Time (hrs)	Interval Time (min)	Batches
0	0	0	0	0	0	0	0	0
2	960	4	2	960	0	2	960	0
4	1920	0	4	1920	0	4	1920	0
4	1920	1	4	1920	2	4	1920	0
1	480	3	1	480	0	1	480	0
4	1920	2	4	1920	0	4	1920	0
4	1920	1	4	1920	0	4	1920	1
4	1920	1	4	1920	0	4	1920	2
2	960	5	2	960	0	2	960	0
1	480	5	1	480	0	1	480	1

TO-BE Simulation Model developed in Simul8®

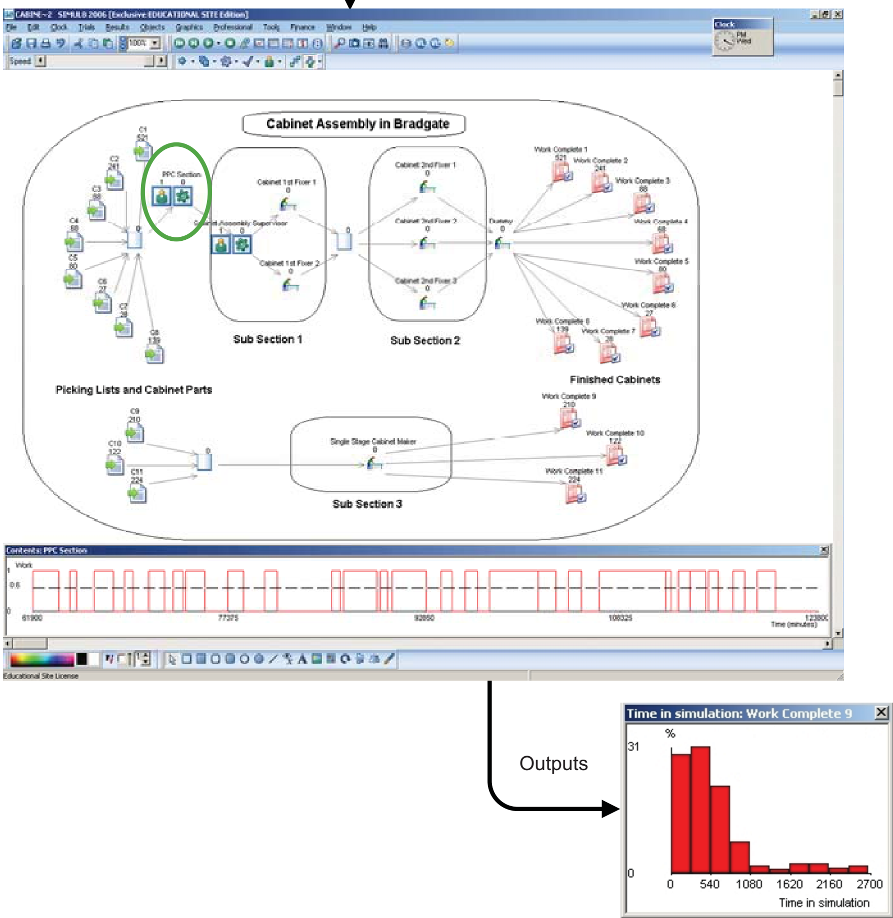


Figure 71: TO-BE simulation model of Bradgate cabinet assembly after addition of a PPC section

8.5.5 Stage 4: modelling analysis

The results of the initial simulation modelling experiments demonstrated that the “single stage cabinet maker 1” was the most occupied resource in “Sub Section 3”. The addition of alternative resources generated alternative TO-BE configurations and results were recorded. Alternative production scheduling policies were also incorporated in the simulation models to generate enhanced behaviours and performance outcomes. PPC section model properties and ‘Routing in’ and ‘Routing out’ options in Simul8® are shown in Figure 72.

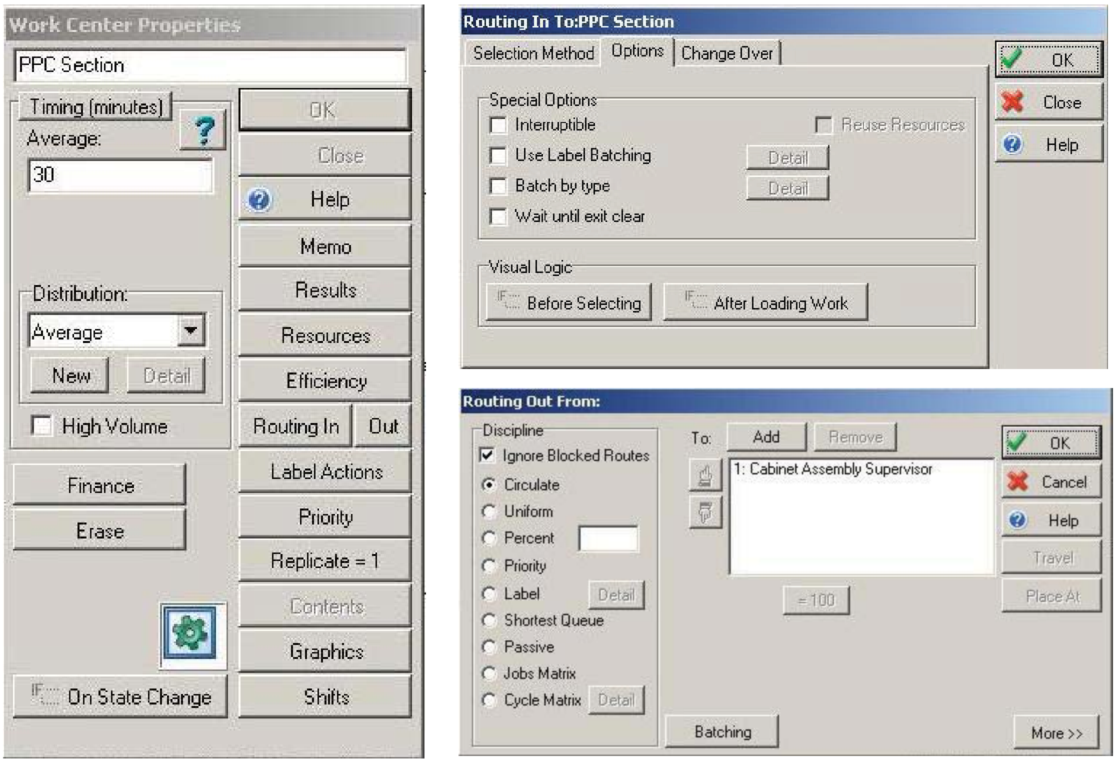


Figure 72: PPC section model properties and ‘routing in’ and ‘routing out’ options in Simul8®

The results were collected after running the simulation models for 61900 minutes (approximately 6-month on the basis of 5-days a week, 8-hours a day and 60-minutes an hour) after warming up for the same length of time. The TO-BE configurations have shown improvements in lead times of certain cabinet groups. Figure 73 shows a lead time improvement trend for alternative candidate TO-BE configurations of Bradgate cabinet assembly.

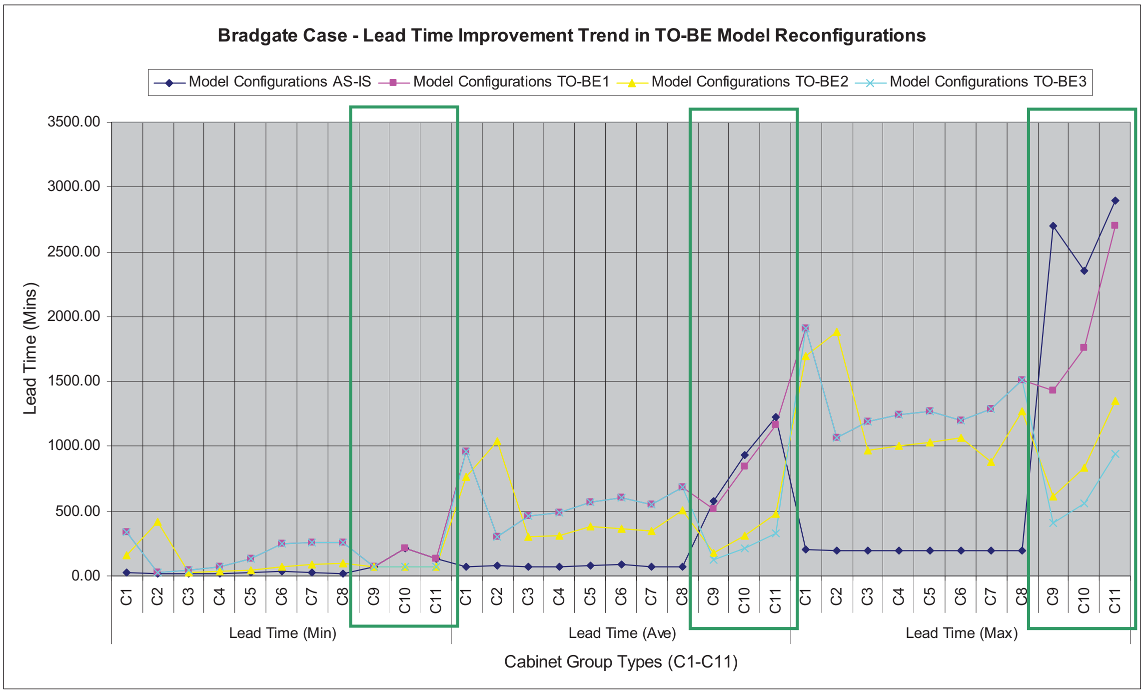


Figure 73: Lead time improvement trend in alternative TO-BE configurations of Bradgate cabinet assembly

8.5.6 Stage 5 (Step 7): VVA of models (at all stages)

The following describes various types of data that was used for different KPIs during this case study.

- *For EM:* Actual data was captured from COs and POs of Bradgate, author's observations, semi structured interviews with Bradgate experts and researchers from MSI Research Institute and CECA;

- *For AS-IS CLM:* Actual data was gathered through author's observations and semi structured interviews with Bradgate experts and MSI/CECA researchers;

- *For AS-IS SM:* Actual data was gathered through company COs and POs, author's observations on process flows, product classifications, time and resource data and MSI/CECA researchers. Simulated data was used for AS-IS resource utilisation, scheduling rules and product classifications;

- *For TO-BE SM:* Actual data was gathered through company COs and POs, author's observations on TO-BE process flows, product classifications, time and resource data, semi structured interviews with Bradgate experts and MSI/CECA researchers. Simulated data was used for TO-BE resource utilisation, scheduling rules and product classifications.

The static models of the Bradgate production system were verified by the author and validated and accredited by the Bradgate management. Having identified a suitable grouping of Bradgate product types, that share similar processing routes, processing operations and operation times, these product types were fed into AS-IS simulation model of the Bradgate production system, both individually and in different product type mixes. In general terms the Simul8 models of AS-IS Bradgate production system behaved in a similar fashion to that observed during the actual production system. In this way the AS-IS simulation models were verified by the author and validated and accredited by the Bradgate management. Therefore it was deemed that these models could be used as a basis for 'what if' decision making. It is important to verify, validate and accredit the TO-BE simulation models up to an acceptable level of accuracy. The performance of a model needs to be compared with operational outcomes of the real system or the performance of the designed TO-BE system to build confidence in the results. The TO-BE simulation models were verified by the author and validated and accredited by the peers in Bradgate, MSI Research Institute and CECA having knowledge and experience of *Bradgate Production System*.

8.5.7 Stage 5 (Step 8): model implementation

The experiments proved useful to PPC personnel of Bradgate and led to the use of an improved push scheduling policy. Bradgate needs to standardise its components in respect of product (re)design so that the components may be produced on forecasted demands and assembled whenever an order is received by applying a postponement approach. There is a scope to further implement the results in the real system if possible.

8.6 Reflections and conclusions

The case study application has shown how the EIMA has benefited Bradgate in better responding to the fast changing customer demands for PPC strategy selection and realisation. It was noted that the combined use of EM, CLM and SM techniques helped to gain an in-depth understanding about Bradgate's current production strategies, their shortcomings and possible ways of achieving improvements. The proposed EIMA was applied to the cabinet assembly section of the Bradgate production system in order to achieve enhanced responsiveness.

There is no aggregate planning method being adopted in Bradgate at this stage resulting in non-visibility of CO behaviours. The extent of visibility into the future COs plays a pivotal role in realising fast responses to market demands. The hidden CO behaviour in Bradgate resulted in slowness to react to market needs. In order to achieve optimal results, Bradgate needs to develop an up-to-date comprehensive data base to support forecasting needs. The analysts and modellers of the TO-BE systems could better utilize it to peep into the future CO behaviours by applying appropriate historical data analysis tools.

MTO strategy is presently adopted by Bradgate as a CODP[23]. Apart from its advantages, a key disadvantage of this strategy is that the majority of production starts after arrival of a customer order. This results in increased product lead times. On basis of the proposed approach at Bradgate it is envisaged that a hybrid MTS/ATO strategy can be adopted. In the proposed strategy production of parts shall initiate with the placement of internal production orders, based upon forecasted batches and inter-arrival times. Inclusion of the postponement theory at this level shall result in improved lead times hence throughput times.

The present Bradgate system works on a 'push'[24] approach which also results in long lead times. A proposition for Bradgate is to adopt a 'pull'[25] approach where possible. Production based upon commonality of parts has been discussed in the superscript

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[23] CODP: Customer Order Decoupling Point is normally defined as the point in the flow of goods where forecast driven production and customer order driven production are separated Wikner;, J. and M. Rudberg (2005). "Integrating production and engineering perspectives on the customer order decoupling point." International Journal of Operations & Production Management **25**(7): 623-641. It is sometimes also referred to as the order penetration point (OPP) which defines the stage in the manufacturing value chain, where a particular product is linked to a specific customer order Olhager, J. (2003). "Strategic positioning of the order penetration point." International Journal of Production Economics **85**(3): 319-329.

[24] 'Push' is a traditional production management system in which information regarding demand forecasts or customer orders for end products are released at first stage and then the order is processed (pushed) through all stages in the production system Olhager, J. and B. Östlund (1990). "An integrated push-pull manufacturing strategy." European Journal of Operational Research **45**(2-3): 135-142.

[25] 'Pull' production system makes use of information about customer orders (and forecasts) which is processed to the finished goods inventory or to the last production stage. If demand can not be satisfied directly, this stage will order and withdraw parts from the buffer storage of the preceding stage and so on, hence providing a serial ordering system of successive production orders and transportation orders.

sections which potentially adds to advantages of the proposed approach. The parts standardisation for different groups or sub groups may be a future work for Bradgate in order to achieve full benefits of the 'pull' strategy.

The Bradgate's approach to generating an accumulated customer order list due to the logistical constraints has resulted in highly increased lead times and throughput times. Due to this approach a high variety of products has been induced in the system bottleneck. It has been discussed in the superscript sections that the proposed TO-BE systems are based upon the break up of production order list by removing the logistical constraint.

The present Bradgate working environment is based upon deciding upon the next work to do on the basis of minimum set up time. The present strategy is partly working okay at the local section or sub section level, however results in grave consequences in achieving the global objectives of the business. It does not take into account overall lead time performance across assembly shop and Bradgate as a whole. The overall lead times are still high and rising and need to be tackled in order to sustain the business. The adoption of dynamic sequencing rules proposed may help achieve the global objectives. These strategies (based upon the use of dynamic rules that may be minimum number of remaining operations on a product or minimum remaining process times) may mean that the Bradgate could finish many products earlier than the normal expected lead times. Table 21 summarizes key existing Bradgate approaches, authors' observations and proposed strategies related to PPC.

Table 21: Summary of observations and proposed production strategies in Bradgate

PPC Strategies	Existing Bradgate Approaches	Observations	Proposed strategies for Bradgate
PPC Hierarchy	❑ No aggregate planning based on forecasting	❑ No visibility of order behaviour ❑ Slow to react	❑ Needs forecasting ❑ Historical data analysis
CODP	❑ MTO	❑ Majority of production starts with order arrival	❑ ATO ❑ Inclusion of Postponement theory
Push vs. Pull System	❑ Push system	❑ Longer lead time	❑ Pull system where possible ❑ Production based upon commonality of parts ❑ Parts standardisation
Production Scheduling	❑ Accumulated order list due to logistic constraints	❑ High variety induced in system bottleneck	❑ Break up of job list by removing the constraint
Production Sequencing	❑ FIFO/FCFS[26] ❑ Minimum set up time	❑ Does not reflect global objectives ❑ Does not take into account overall lead time performance across Assembly Shop and Bradgate	❑ Adoption of dynamic sequencing rules ○ Minimum number of remaining operations ○ Minimum remaining process time

The application of EIMA in Bradgate demonstrated its significant role to enable decision making in a reconfigurable and responsive ME. This is true with respect to the engineering of PPC systems in MEs being representative of manufacturing responsiveness. In order to understand CO dynamics and ME processing abilities and constraints prior to engineering a PPC system, specific ME segments need to be modelled with reference to the overall (ME) business context in which they need to operate. The basis of the EIMA to creating coherent sets of integrated models that facilitate manufacturing responsiveness is described along with the case study of engineering of a PPC system. Enterprise models, causal loop models and simulation models played key complementary roles to enable PPC decision making by using the proposed EIMA. The design of a PPC system needs to cater for current and future product variance and enable new product introduction. Case study models are presented in this chapter which aided PPC strategy design and resultantly manufacturing responsiveness decision making in Bradgate.

[26] First In First Out / First Come First Served

8.7 The way forward

There is a need to test the EIMA in other manufacturing SMEs and include more complex situations than the Bradgate industrial case. It may be worth applying the proposed strategies of the Bradgate case in other (1) SME configurations e.g., ETO job shop environment, (2) production control strategies e.g., Kanban, ConWIP, postponement. This research may also lead to the use and updating of integrated production control models in order to enable future change capable SMEs.

Chapter 9

Case 3: Application of the EIMA in ACM Bearings Company

9.1 Motivation and introduction

Following the Bradgate case study, the following research questions were raised: (1) can EIMA be applicable in ETO MEs, or for a mix of ETO and MTO configurations of MEs; and (2) can the proposed EIMA be applicable for selecting and analysing various typical PPC methods in such cases. Keeping in mind these research questions, a new case of the ACM Bearings Company (referred to as ACM) was investigated which it was claimed deploys a mix of ETO and MTO configurations. ACM was one of the industrial partners in the EPSRC project titled "Unified modelling of complex systems – to facilitate ongoing organisation design and change" (Grant No. EP/D05821X/1). The case study presented in this chapter was designed to answer the research questions by (1) applying the EIMA through systematic use of EM, CLM and SM; (2) measuring the responsiveness of the *ACM Production System*; and (3) analysing and discussing the results of the case study application.

The rest of the chapter is divided into four sections. Section 9.2 gives a background to the ACM case study. A step-by-step application of the EIMA in the ACM case is illustrated in Section 9.3. Section 9.4 gives case study reflections and conclusions. Possible future research directions are discussed in section 9.5.

9.2 ACM case study background

ACM is a bearing manufacturing SME which is rapidly growing with its main production and administrative base in South Yorkshire, England. ACM presently has five competitors within approximately 1000 miles area. ACM is an ISO 9001:2000 certified business which produces and delivers bearings to its global customer and stakeholder base all over the world. The company employs over 35 regular workers in its Yorkshire base. A second production facility, similar to the England operational base, has recently been developed at Shin Won, South Korea. New production facilities are currently being developed in other parts of the world including the USA in the wake of increasing market share. At both of its current manufacturing sites, ACM manufactures a wide range of advanced composite products suitable for mechanical, marine, agricultural, pharmaceutical and food processing environments and applications. ACM products are basically reinforced plastic laminates composed of synthetic fabrics impregnated with thermosetting resins and solid lubricant fillers. The ACM products are available in tube and sheet forms as well as in fully finished components such as structural bearings, washers, wear rings, sphericals, wear pads, wear strips, rollers, and bushes. A few sample ACM products, their applications and installation locations are included in *Appendix E – ACM Case Extension.*

There are mainly two production shops that comprise the *ACM Production System* that both receive purchase orders (POs)[27] from the Technical Department instructing them to realise products. These shops are: the Raw Material Shop (RM Shop) and Operations Shop (Op Shop). The Op Shop comprises two sub shops, classified on the basis of their operations: Saw and Sanding Shop (SS Shop) and Machine Shop (M Shop). The RM Shop realises POs involving raw material processing, SS Shop deals with POs involving flat machining while M Shop deals with POs involving round machining. Presently the *ACM Production System* follows a *push* production system. ACM follows strategic stocking policies therefore, no inventory related problems are reported at present. The management measures efficiency (as a kind of productivity) in terms of a ratio of Sales Value to Time Input, i.e., *Efficiency = Sales Value (£) / Time Input (Hr).* Even though apparently the *ACM Production System* portrays a good picture but it still has late delivery problems. In order to look into the problem, the following section will apply the EIMA to the ACM case.

[27] POs are named as job cards in ACM.

9.3 Application of the EIMA in ACM

This section describes case study modelling conducted by the author at ACM, which corresponds to a 'particular application of the EIMA'. The step-wise approach shall case test possible solutions to problems observed in ACM by creating: (1) enterprise models; (2) causal loop models; (3) simulation models; and (4) VVA of models and implementation. The following shall describe a step-wise application of the EIMA in ACM.

9.3.1 Stage 1: development of enterprise models

9.3.1.1 Enterprise model capture

To capture and explicitly document the AS-IS state of *ACM Production System*, enterprise models were developed after several visits to the company during which semi structured discussions and semi structured interviews were conducted with company's management and production teams. In the study reported here, focus was on improving reconfigurability of the ME through use of the EIMA in company's PPC system and when so doing to consider other possible production system configurations which might enhance the profitability of ACM.

During EM exercise, the CIMOSA domains were specified as: DM1 which deals with business management; DM2 which deals with technical management; and DM3 which deals with production management. The non-CIMOSA domains DM4-DM8 deal with customers, raw material suppliers, technology vendors, financial management and human resource management respectively. Figure 74 shows the context diagram of the ACM case study that elaborates CIMOSA and non-CIMOSA domains. Figure 75 presents top level interaction diagram of ACM case that shows interactions of CIMOSA domain processes DP1.1, DP2.1 and DP3.1 with each other and with non-CIMOSA domain processes DP4.1 (customers) and DP5.1 (raw material suppliers). It also shows physical resources, financial resources and information being used during these interactions.

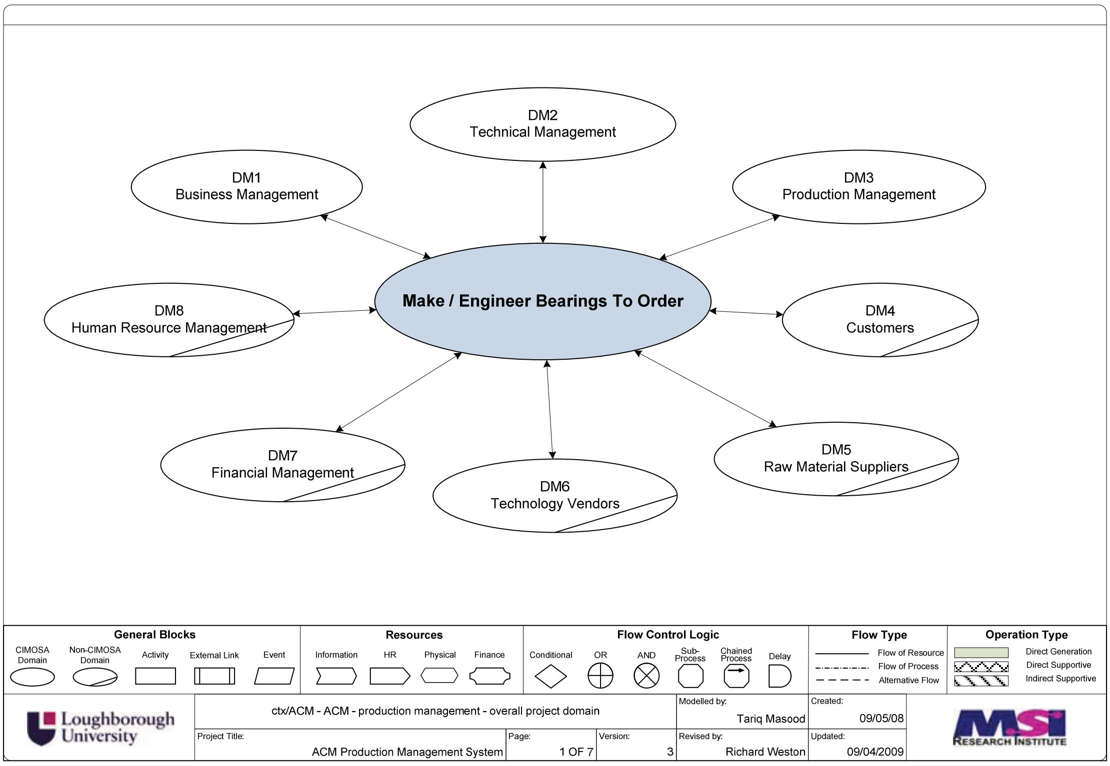


Figure 74: ACM case: context diagram

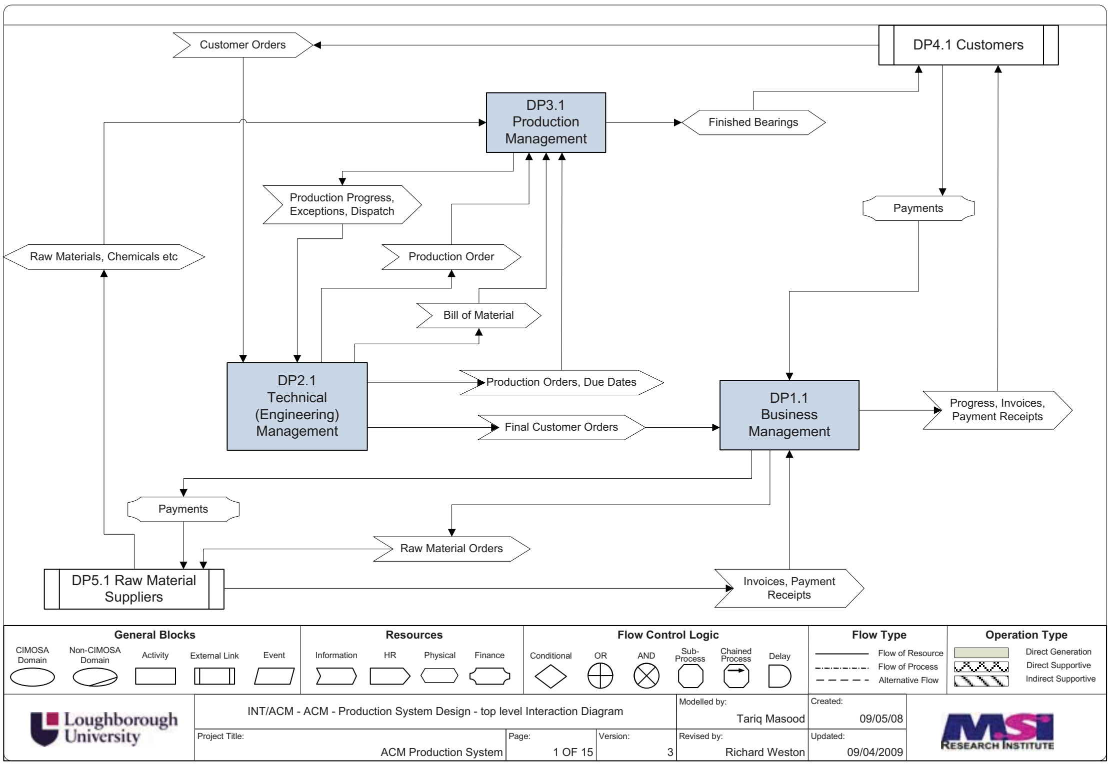


Figure 75: ACM case: top level interaction diagram

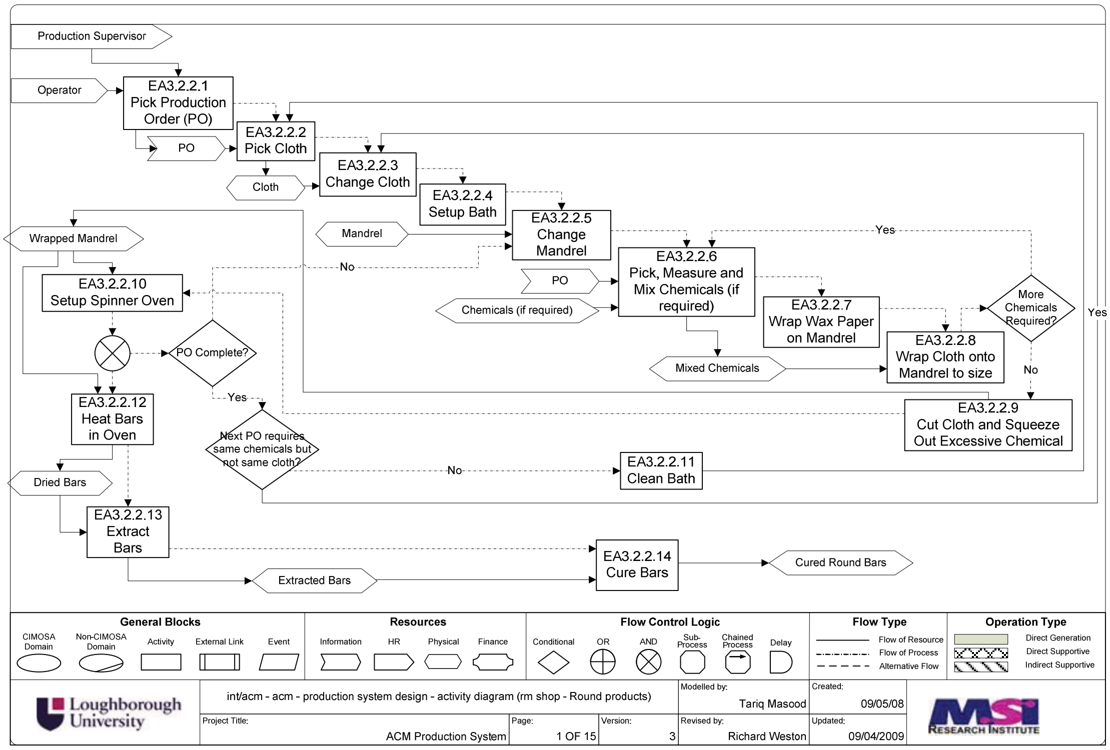


Figure 76: ACM case: activity diagram for production of round products in RM Shop

Having captured the AS-IS state of the firm in the form of enterprise models of *ACM Production System*, this enabled the author to gain a good understanding of day to day operations in ACM to reflect on its present production system and challenges. The AS-IS Push *ACM Production System* is illustrated in Figure 77. In the present push production system, the technical department receives a customer order and produces and issues a production order in respect of that. The RM Shop and Op Shop (SS Shop and M Shop) accomplish jobs assigned to them by POs. The present *ACM Production System* faces challenges which are discussed in the following section 9.3.1.2.

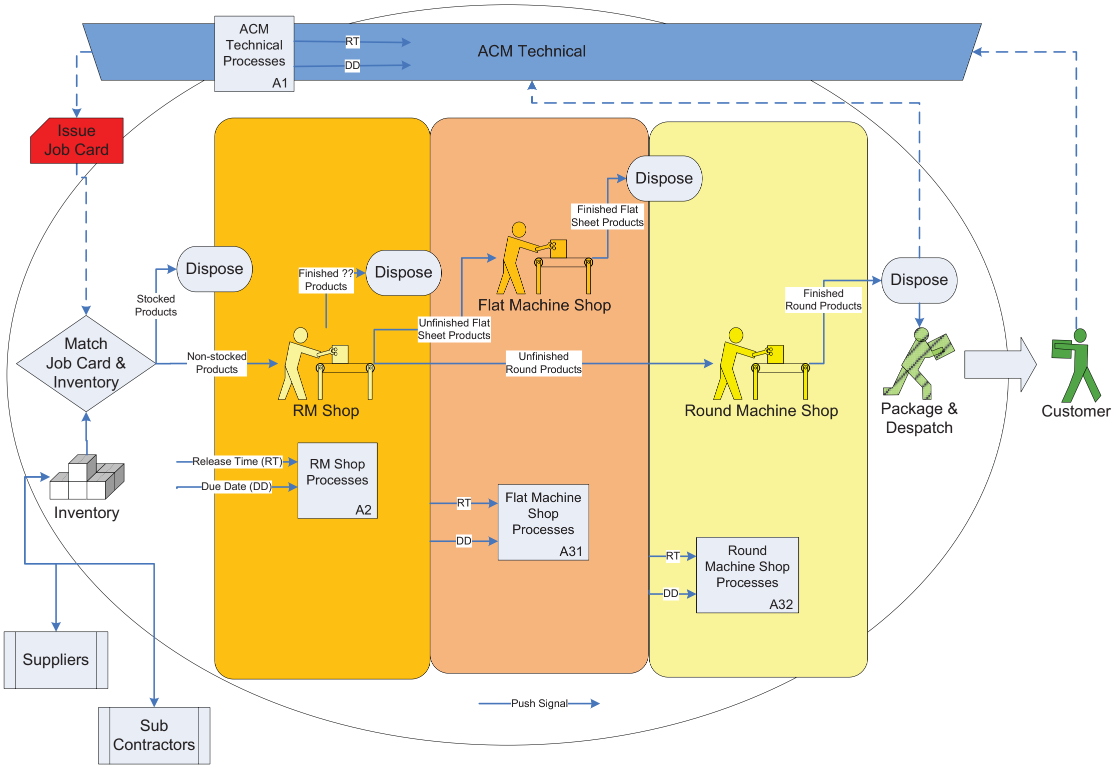


Figure 77: AS-IS 'push' *ACM Production System*

9.3.1.2 Present challenges at ACM – the problem definition

Following the capture of the EM to explicitly document the present state of the *ACM Production System,* further discussions were held with ACM management and operational staff. The discussions highlighted that ACM was facing strategic level challenges which are summarised in Table 22.

Table 22: Challenges to ACM (strategic level)

Challenges to ACM	Details
Globalization	The company is growing and is getting more international business. The company operates in Mainland UK, USA and South Korea. In the wake of globalization and an increasing customer base, ACM needs to improve its present production system so that it can cope with more customer orders.
Responsiveness	Even though ACM is overall growing, the continuity of the business in today's contracting economy is a big challenge. According to the management of ACM, very quick responses to change are required to remain in the business. The CEO of the company had worked at director levels in large aerospace companies. He compared responses needed to the changes as being much quicker in SMEs than in larger companies in order to sustain. Presently, there are no formal methods to measure the state of responsiveness of the *ACM Production System*.
Resource limitations	The human resources are less than required, so for example 60hrs of work is commonly done by a 30hr working person. Due to the same reason, there is approximately one week delay in the issuance of a PO to the RM Shop after receiving order from customer.
Technology up gradation	The up gradation of existing technical resources, procurement of new machines and selling of old machine resources is always ongoing whenever and wherever required in the company. Therefore, incorporation of changes in the system required due to such technology up gradation is a challenge to the company. It is also important in the wake of company's business growth.
Management and PPC	Even though the present management has got a good control on production and management issues, meeting customer deadlines still becomes a challenge sometimes. Therefore, stronger management and PPC is needed in order to overcome the present and future challenges to ACM and to achieve its strategic, tactical and operational goals.

At tactical and operational levels, the *ACM Production System* was facing challenges related to scheduling as summarised in Table 23.

Table 23: Scheduling challenges at ACM (tactical and operational level)

Scheduling Challenges to ACM	**Details**
Late Deliveries	The *ACM Production System* was prone to late delivery of orders to customers. The exact state of ACM's responsiveness was unknown to the management but they had a feeling that ACM's responsiveness needed much improvement in the wake of the present and future growth of the business. It was worth noting that ACM had no material issues in terms of procurement, at the time of case study, due to its strategic stocking policies but scheduling was a problem.
Overproduction and Rework	ACM was also prone to overproduction and rework on parts at shops due to which overall throughput times were increased.
Departmental Interaction:	The departmental interaction was poor and needed improvement.
Classification of products	The classification of products was a mix: process-based for Raw Material Shop and dimensional-based for M Shop. There were no further classification schemes followed in ACM.
Mandrel Availability for Processing in RM Shop	The availability of a right size mandrel for processing in RM Shop was a big issue for management of production orders and meeting customer dead lines.
Failure of T-Card System	The company had to withdraw its T-Card system for updating the supervisory and managerial levels about production status due to its ineffective use.

There were some limitations imposed by the ACM management on any potential future solution proposals that would be offered to them through this research. The limitations were based upon experience of the management as summarised in Table 24.

Table 24: Limitations on potential future solutions (imposed by ACM management)

Limitations on Future Propositions	**Details**
Forecasting Limitations	No forecasting was feasible in such a variety of CO patterns.
Pulling Limitations	The M shop could not be pulled but the RM Shop could be pulled as a potential future solution.
Resource Limitations	ACM had limited resources, therefore at times of high demand, it adopted a policy to hire human resources from approved hiring agencies and ran on a double shift basis. This policy was adopted recently during the course of this case study.

After creating the EM and identifying challenges and limitations related to the *ACM Production System*, it was necessary to develop causal loop models (i.e. the second stage of EIMA application) which is illustrated in the following section.

9.3.2 Stage 2: development of causal loop models

The most demanding challenges to ACM included improving the reconfigurability and responsiveness of its business and production systems. The *ACM Production System* had no clear vision to see its present status of responsiveness at any given time. Partly due to this reason, the company could not decide on reconfiguring its processes or models (in whatever form these were available). With the aid of reusable enterprise models, causal loop models, simulation models with a reusable and updated PO database, it was presumed that the EIMA could be implemented in the case of *ACM Production System*. A structured approach was needed in the wake of increasing frequency of orders and product sales which were also increasing the globalisation of the business. It was also presumed that such an implementation could reduce lead times, overproduction and rework by giving a clear view of the system. As a by-produce it was through that it might enhance departmental interaction and mandrel availability in the RM Shop. These benefits may lead to higher responsiveness and reconfigurability with an improvement in management and PPC of *ACM Production System* and with a possibility to overcome resource limitation to some extent. With this opportunity in mind, a causal loop model of *ACM Production System* was created as presented in Figure 78.

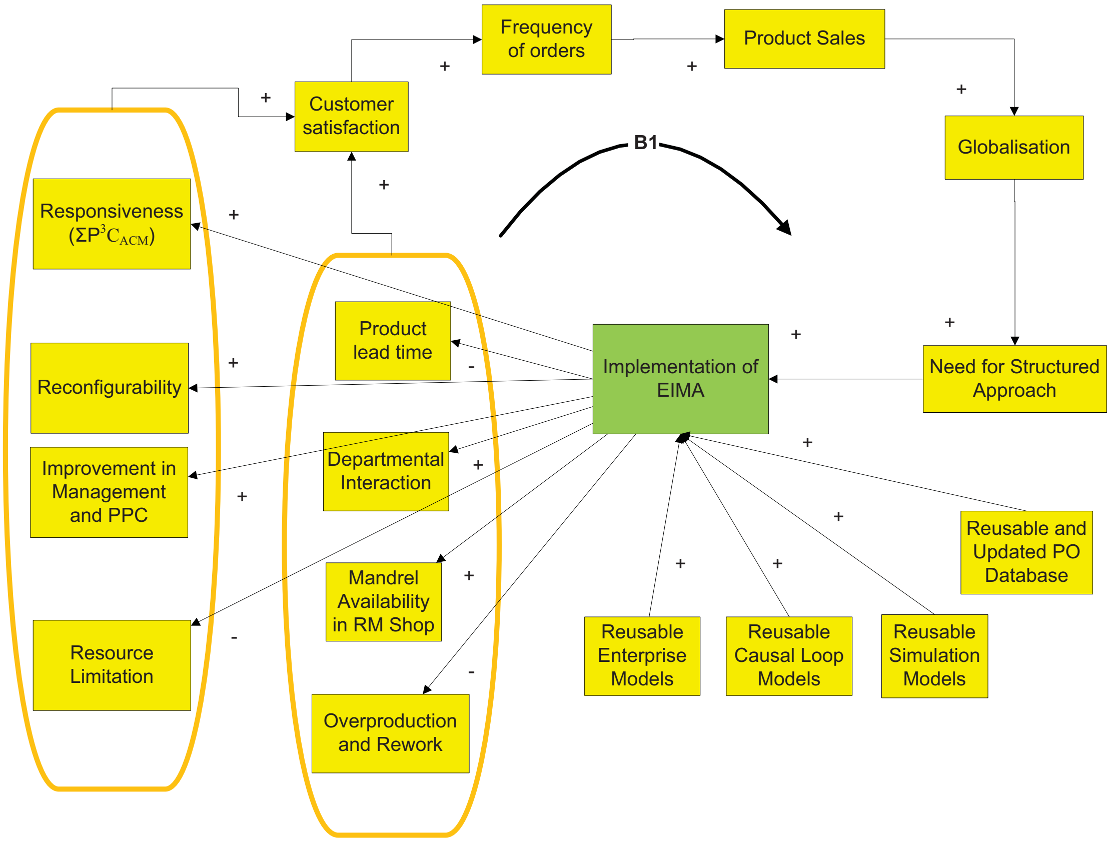


Figure 78: Causal loop model of *ACM Production System*

On the basis of the foregoing causal analysis, PO data analysis related to the *ACM Production System* was needed in order to view and understand the current state, past behaviours in terms of responsiveness of the system. Partly from author's previous industrial experience and partly from use of 'percent plan complete' in construction management domain by (Ballard 2000), here it was assumed that system responsiveness could be measured in terms of *Percent of Production Plan Complete (P^3C)* (in a given time frame), as described in the following section.

9.3.2.1 Responsiveness measurement in terms of P^3C:

Percent of production plan complete (P^3C) is defined as 'a state of completeness of a production plan in percentage form at a given instance' e.g., percentage of completed production orders at a planned due date to the total production orders issued. During this case study, it was observed that no formal methods were adopted to measure and monitor the completeness level of production plans at ACM. Actually no formal PPC methods were adopted. During observations, it was found that even though the *ACM Production System* was not prone to any formal PPC methods, it was a Push-schedule system. The POs were prepared during the first week of receiving an order from customers. Then POs were sent to the RM Shop on a FIFO/FCFS basis. The RM Shop then decides how to proceed with the PO. To make this decision the RM Shop identifies the processing requirements . Apart from this no particular approach is adopted for prioritising a PO unless an urgency is shown by the management. When RM Shop processing is complete unfinished parts are sent to the SS Shop or the M Shop as required. The respective Shops set job priorities according to their assessment. Again no formal methods are adopted to achieve this prioritisation. Hence, production planning and hence the control of work is achieved in a distributed manner. The Technical Department, that issued POs in the first instance, is also responsible for collecting information about the despatch of final products; and this appeared to be the main integration mechanism used by ACM to unify planning efforts.

During the authors' ACM visits and discussions with the management and employees, the need to formalise the PPC methods became evident. At previous points in time, the management had decided to adopt a formal MRP system and even selected and procured a MRP software (named FUSION). However ACM management could not implement this software due to training and operational costs and the complexities involved. The need to measure and monitor the progress of the current and future systems is also evident. Hence P^3C was conceived by the present author as a possible means of measuring and monitoring the present state of responsiveness of the *ACM Production System* at a given time. Ultimately it was hoped that such an approach might prove useful and suitable to ACM in terms of P^3C delivering greater benefit from the cost and time involved in its implementation.

9.3.2.2 P^3C - data analysis, results and discussion at ACM level

The author analysed historical PO data collected from the *ACM Production System* in order to determine the level of P^3C. Data recorded into 843 POs was extracted from the PO data base for the period from November 2004 to January 2005 Data concerned with 21 POs was excluded due to inconsistency, hence a useful data set of 822 POs was used for further analysis. Table 25 shows weekly numbers of POs generated and also the numbers of POs completed on time and those completed late.

Table 25: Data analysis of POs – *ACM Production System*

Week	**Total POs Issued**	**POs Completed In Time**	**POs Completed Late**
1	33	10	23
2	46	25	21
3	104	47	57
4	64	35	29
5	105	58	47
6	66	47	19
7	60	44	16
8	76	21	55
9	98	38	60
10	138	68	70
11	32	14	18
Σ	**822**	**407**	**415**

The data analysis related to the *ACM Production System* that is presented in Table 25 was re-plotted in terms of P^3C and 4-Week Moving Average. This is shown in Figure 79. The observed responsiveness of the *ACM Production System* measured in terms of P^3C_{ACM} during weeks 1, 3 and 8-11 was particularly below ΣP^3C_{ACM} (i.e. 49.43%). The Σ 4-weeks Moving Average of ΣP^3C_{ACM} remained 37.76% during that period.

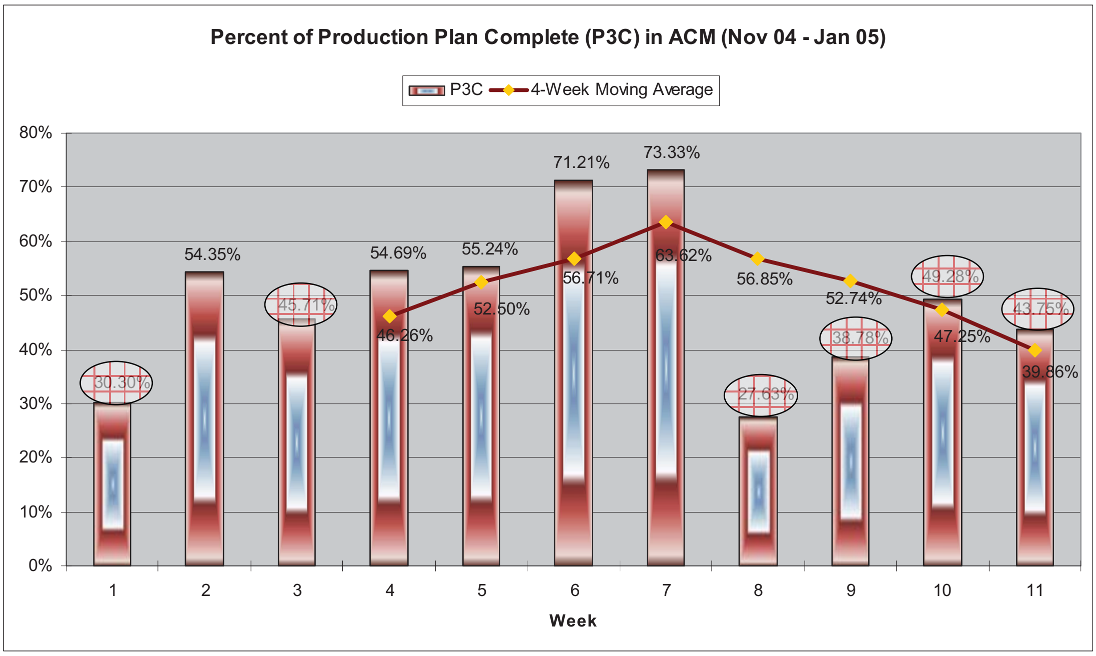


Figure 79: P^3C – *ACM Production System*

The observations depicted by Figure 79, initiated a further investigation with a focus on individual shops where the products were late most of the time. Further data analysis devised a correlation between POs issued and P^3C in ACM. The results are presented in Figure 80 which showed a negative trend when the number of issued POs increased during weeks 3 and 8-10. This suggested that resource constraints might be one of the reasons for the *ACM Production System* not being able to meet *due dates* assigned to POs. During the remaining weeks 1-2, 4-7 and 11, the number of issued POs remained between 32-66 and this resulted in the P^3C being higher than 30% during this time.

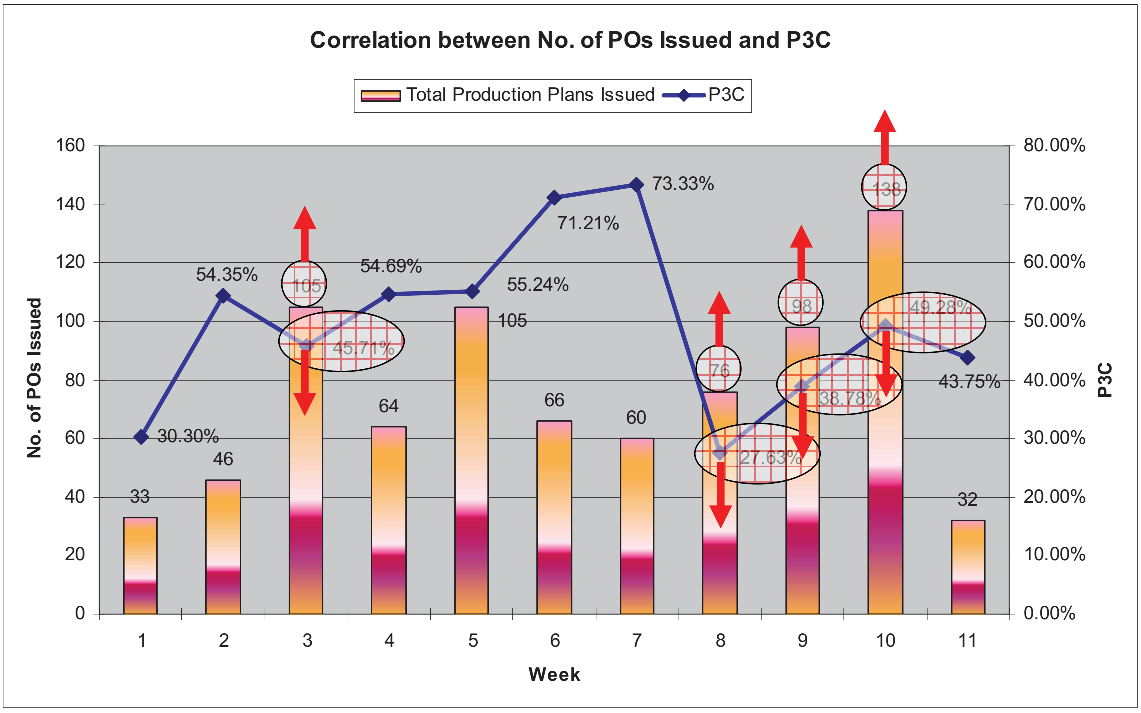


Figure 80: Correlation between POs issued and P^{3}C – *ACM Production System*

The discussion so far suggested a need to perform P^{3}C data analysis for the individual shops of the *ACM Production System.*

9.3.2.3 P^{3}C - data analysis, results and discussion at the RM Shop level

Historical data related to 843 POs from the *ACM Production System* was analysed for a period from November 2004 to January 2005. Data related to 165 POs was excluded due to inconsistency in *RM Shop* data; mainly due to the unavailability of PO completion dates in *RM Shop*. Therefore, a total of 678 POs were analysed for the *RM Shop.* Table 26 presents the data analysis of the *RM Shop* POs. The results relate only to the final *due dates* of the *ACM Production System*

Table 26: Data analysis of POs – RM Shop

Week	**Total Orders (Cumulative)**	**Total Orders**	**Completed In time**	**Completed Late**	**P^3C**	**4-Week Moving Average**
1	31	31	24	7	**77.42%**	
2	68	37	29	8	**78.38%**	
3	154	86	70	16	**81.40%**	
4	207	53	47	6	**88.68%**	**81.47%**
5	291	84	80	4	**95.24%**	**85.92%**
6	349	58	56	2	**96.55%**	**90.47%**
7	395	46	44	2	**95.65%**	**94.03%**
8	461	66	66	0	**100.00%**	**96.86%**
9	537	76	71	5	**93.42%**	**96.41%**
10	657	120	92	28	**76.67%**	**91.43%**
11	678	21	16	5	**76.19%**	**86.57%**
Σ		**678**	**595**	**83**	**87.24%**	**65.74%**

The data analysis of POs shown in Table 26 is plotted in Figure 81. The P^3C for the *RM Shop* during weeks 1-3 and 10-11 was significantly lower than ΣP^3C for the *RM Shop*, which was 87.24%. The Σ4-Week Moving Average of P^3C for the *RM Shop* remained at 65.74% during the period.

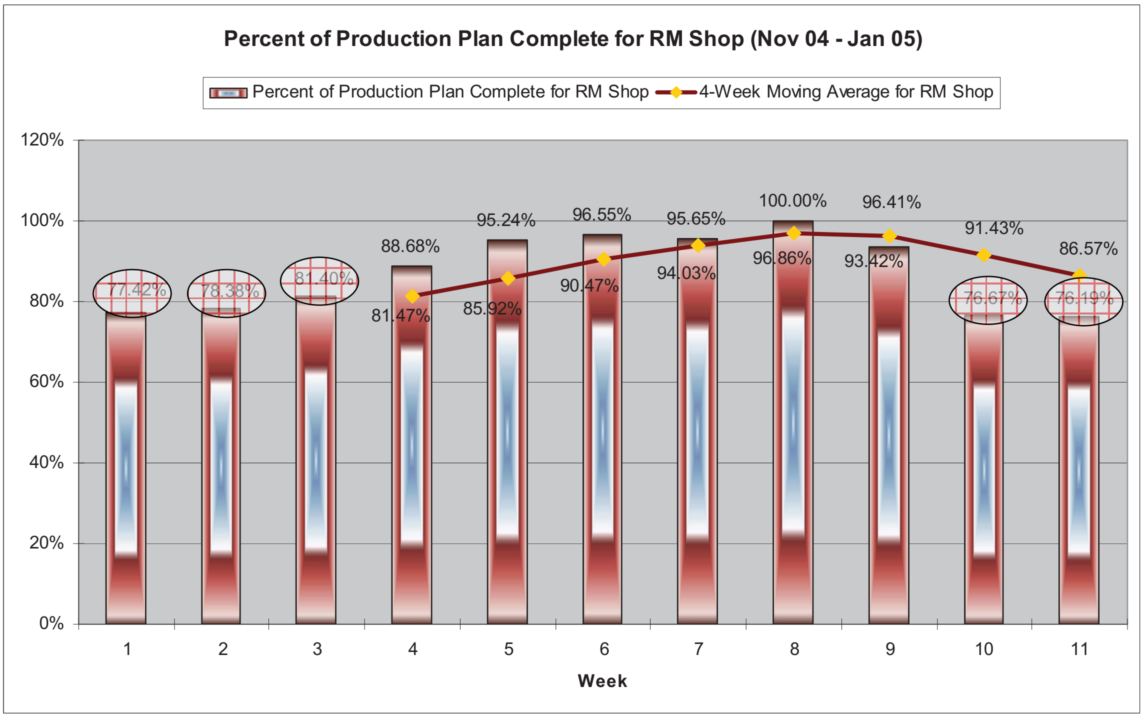


Figure 81: P^3C – RM Shop

Here it was thought to investigate the possibility of a correlation between the number of POs issued and P^3C in the *RM Shop*. The results were analysed and are plotted in Figure 82. The responsiveness of the *RM Shop* in terms of P^3C remained higher than 76.19%. There was only one instance during week 10 when the number of issued POs was higher than the average for the *RM Shop* resulting in a decrease in P^3C. It was important to confirm the results of there being a higher responsiveness in the *RM Shop* where 87.24% of total POs of ACM were *on-time;* irrespective of the fact that the overall responsiveness of ACM was 49.43%.

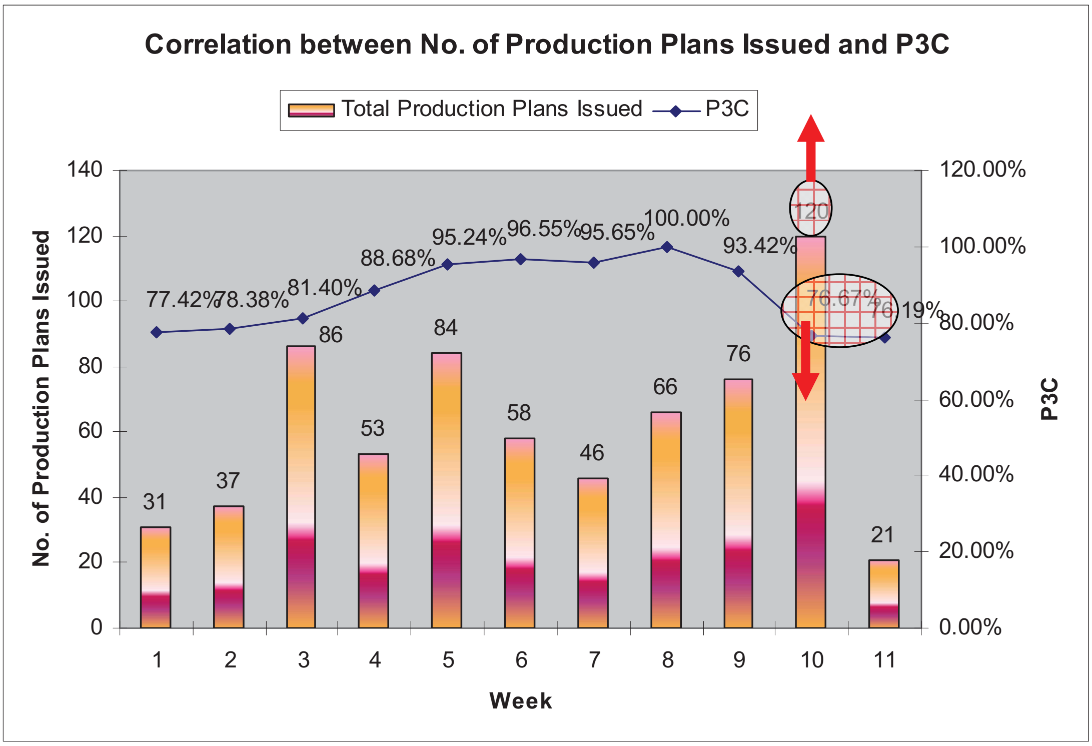


Figure 82: Correlation between POs issued and P^3C – RM Shop

9.3.2.4 P^3C - data analysis, results and discussion for the Op Shop

Data related to 843 POs issued to the *ACM Production System* was analysed for the period from November 2004 to January 2005. Data related to 103 POs was excluded due to inconsistency in *Op Shop* data; mainly due to the unavailability of PO completion dates in *Op Shop*. Therefore, a total of 740 POs were analysed for the *Op Shop*. Table 27 presents the data analysis of *Op Shop* POs. The results are based upon the final *due dates* of the *ACM Production System* only.

Table 27: Data analysis of POs - Op Shop

Week	Total Orders (Cumulative)	Total Orders	Completed In time	Completed Late	P^3C	4-Week Moving Average
1	22	22	16	6	**72.73%**	
2	63	41	30	11	**73.17%**	
3	153	90	57	33	**63.33%**	
4	208	55	47	8	**85.45%**	**73.67%**
5	305	97	69	28	**71.13%**	**73.27%**
6	371	66	62	4	**93.94%**	**78.47%**
7	411	40	30	10	**75.00%**	**81.38%**
8	483	72	43	29	**59.72%**	**74.95%**
9	576	93	48	45	**51.61%**	**70.07%**
10	709	133	91	42	**68.42%**	**63.69%**
11	740	31	19	12	**61.29%**	**60.26%**
Σ		**740**	**512**	**228**	**70.53%**	**52.34%**

The data analysis of POs for the *Op Shop* presented in Table 27 is re-plotted in Figure 83, and this shows results of P^3C for the *Op Shop*. The P^3C of the *Op Shop* during weeks 3 and 8-11 was significantly lower than Σ P^3C for the *Op Shop* which was 70.53%. The Σ 4-weeks Moving Average of P^3C for the *Op Shop* remained at 52.34% during the period.

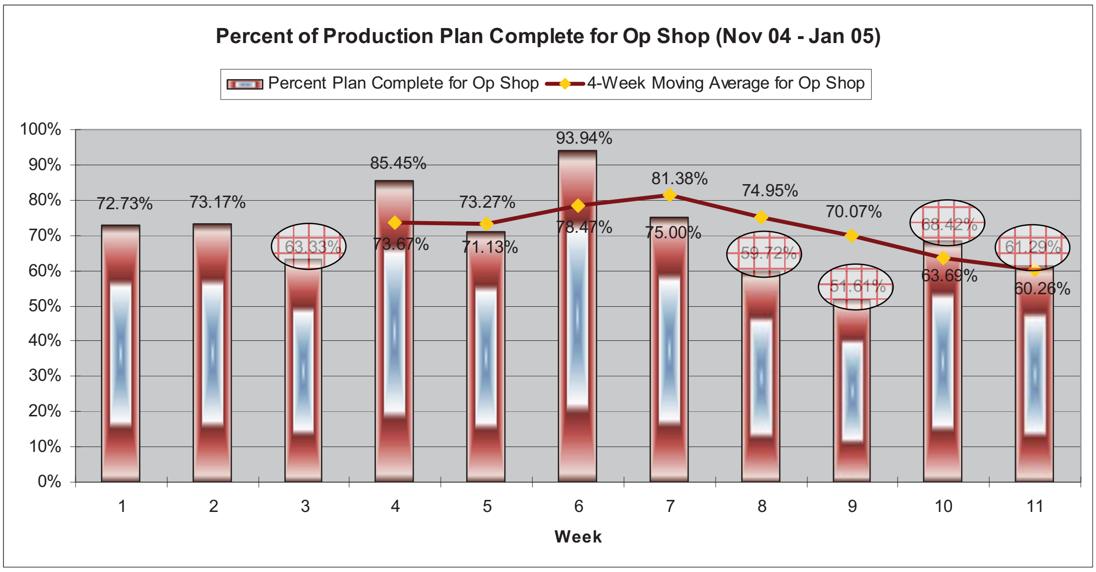


Figure 83: P^3C - Op Shop

Further to the results shown in Figure 83, it was necessary to investigate the correlation between the number of POs issued and P^3C in the Op Shop. The related results are shown in Figure 84. The responsiveness of the Op Shop was 70.53% for the initial P^3C results. The results suggested a need for further investigation to find reasons for such a higher responsiveness in the Op Shop while 50.57% of the total POs of the *ACM Production System* were *late*.

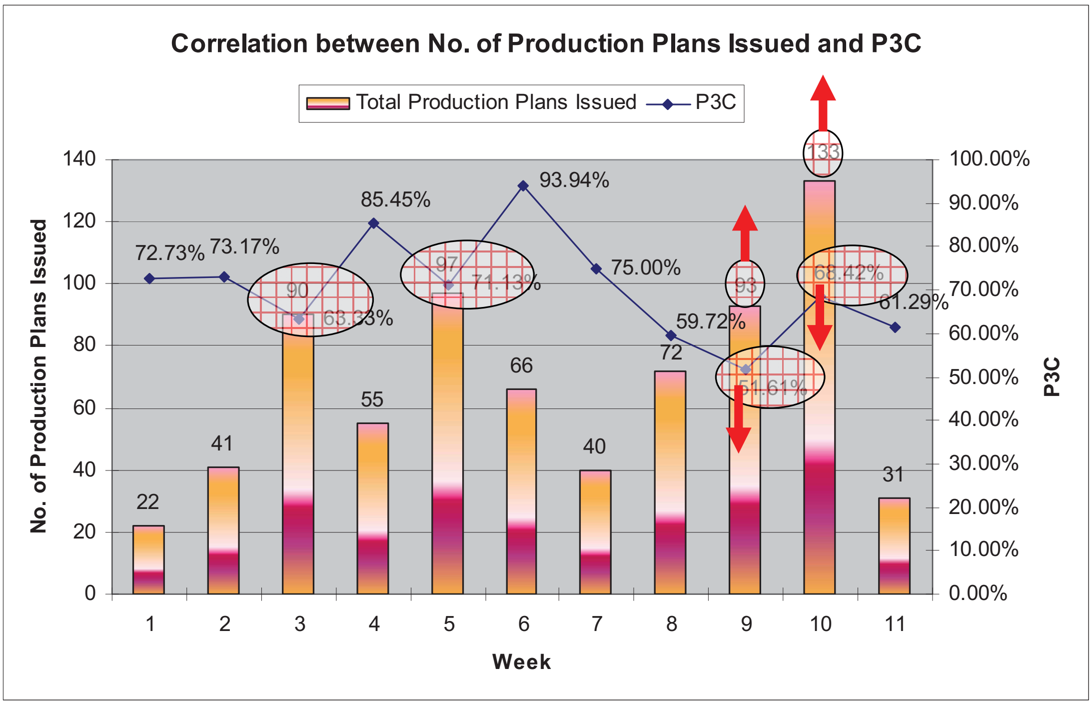


Figure 84: Correlation between POs issued and P^3C - Op Shop

Here it was considered important to conduct a further investigation of PO data in the future for certain specific weeks during which either the responsiveness was higher or lower than the average. Figure 85 shows a summary of P^3C results analysed for overall ACM and its shops. Apparently this suggests without considering shop interactions that the RM Shop has a higher responsiveness than the Op Shop and the overall ACM level.

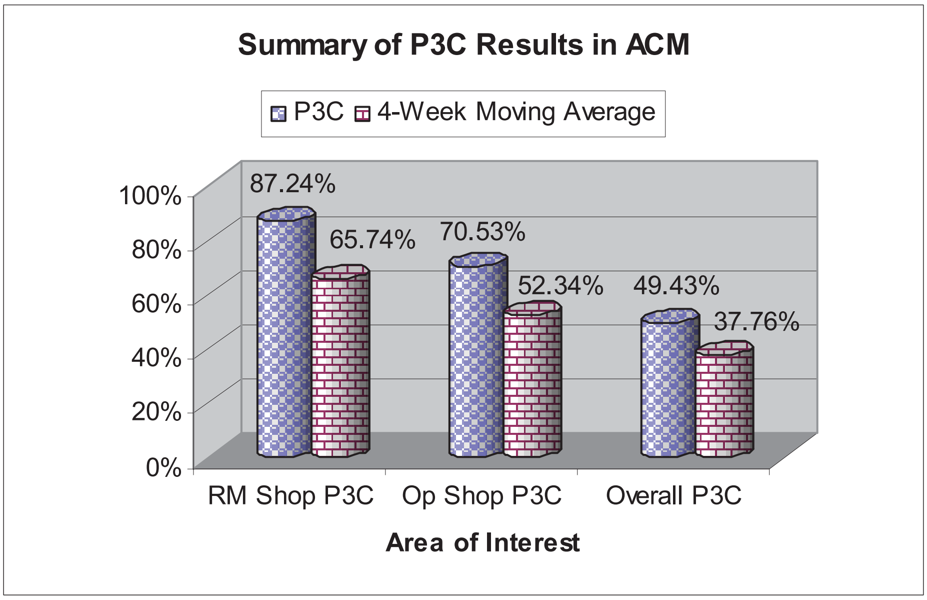


Figure 85: Summary of P^3C results in ACM

The shops may further be decomposed with respect to their resources (physical, machine, IT and human) to determine their respective P^3C levels. Decisions made on the basis of such calculations may lead to improve responsiveness. The resources may also be analysed for their efficiencies and utilization to bench mark the current state of *ACM Production System* and to inform the production planners for PPC purposes and the production managers for further improvement in the current state.

9.3.3 Stage 3: development of simulation models

Causal loop models were recoded into continuous simulation models using the model layer of the Stella® software as depicted in Figure 86. Stella® models consists of stocks, flows, converters and connectors and these general modelling constructs were used to represent different sections of the *ACM Production System,* PO inputs to them or product outputs from them, the PO data and interconnection between these. The Stella® continuous simulation tool transforms the standard modelling constructs into a set of differential equations which are solved using a numerical integration technique. The results generated from executing the causal loop model (as shown in Figure 86) are presented in Figure 87.

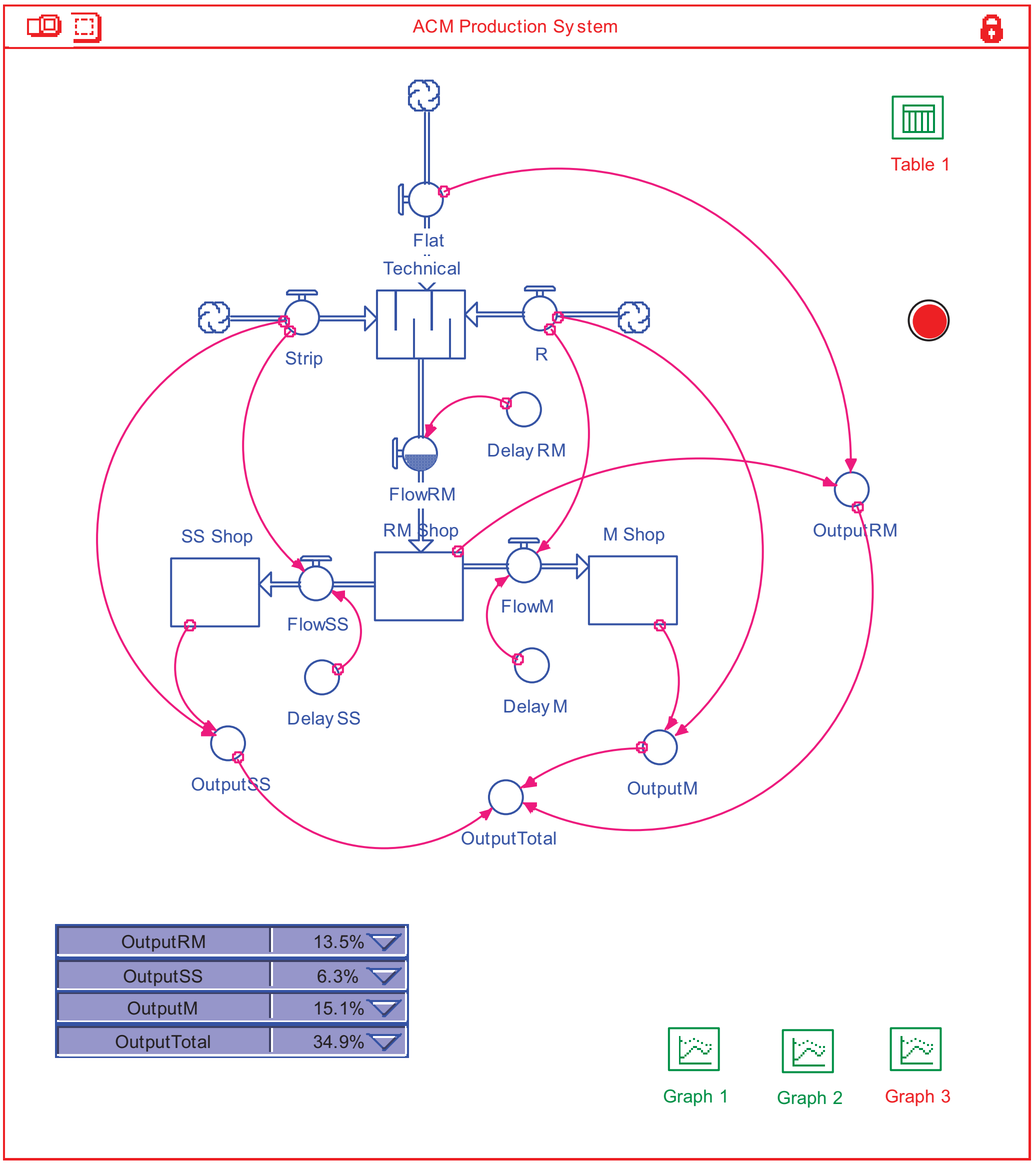


Figure 86: Dynamic causal loop model in Stella® - *ACM Production System*

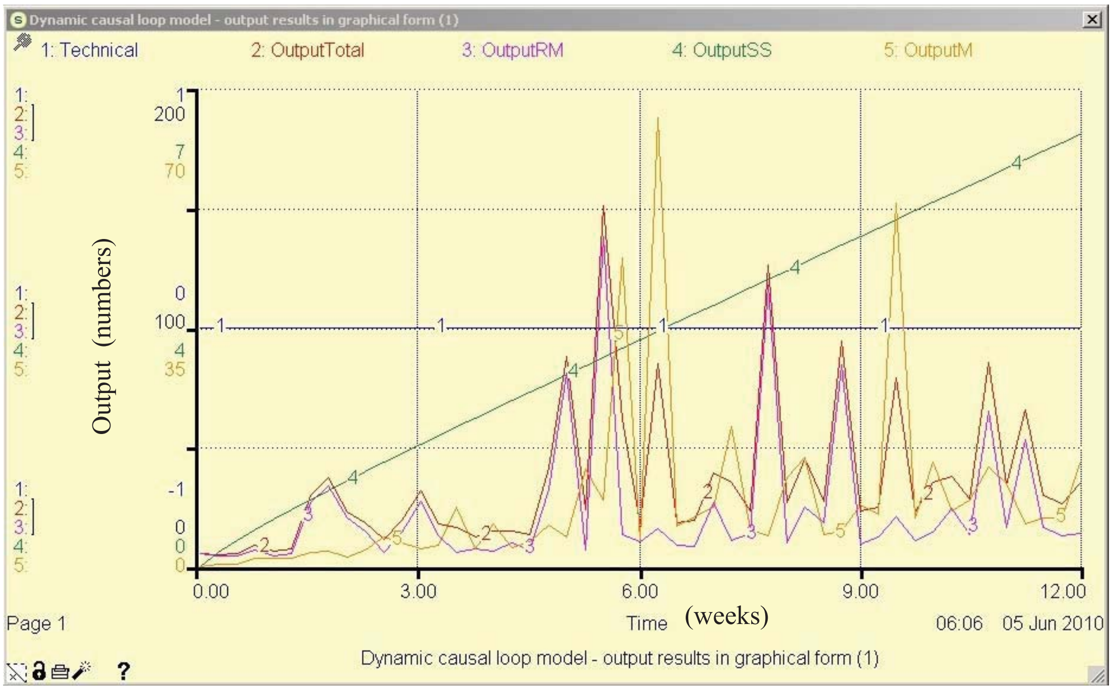


Figure 87: Dynamic causal loop model of *ACM Production System* - output results in graphical form (1)

The screen shot for the Stella® dynamic model and its results, as presented in Figure 86 and Figure 87, gave useful insights into the AS-IS configuration of the *ACM Production System,* which can be used to inform strategic (causal loop) thinking. Figure 87 shows trends of product outputs in different departments of the *ACM Production System* over the time period for which historical PO data was available to this study. The x-axis in this figure shows time in weeks while y-axis shows outputs in product numbers. The plotting lines are marked with 1 (technical department), 2 (output total), 3 (output RM Shop), 4 (output M Shop) and 5 (output M Shop) to show the relevant departments. This dynamic causal loop model was run with variable inputs for several times to interpret dynamic behaviours of the *ACM Production System.*

For further details of AS-IS configuration views, discrete event simulation models were also created using the Simul8®. One such configuration at its initial condition is presented in Figure 88. This simulation model presents the AS-IS situation of the *ACM Production System*. TO-BE simulation models and analysis shall be presented in Chapter 10.

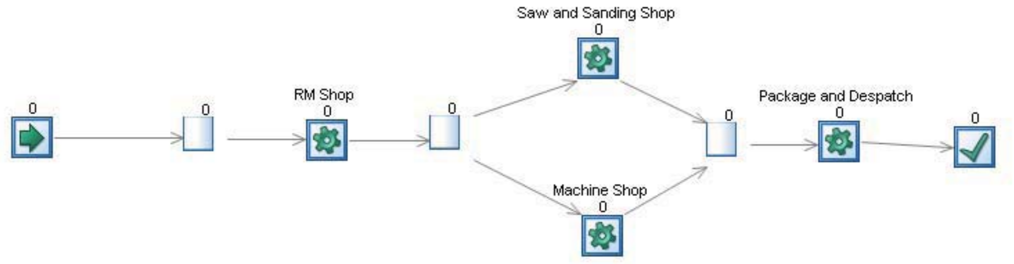


Figure 88: AS-IS simulation model (initial condition) of *ACM Production System*

9.3.4 Stage 5: modelling VVA and implementation

The following describes various types of data used for different KPIs during this case study.

- *For EM:* Actual data was captured from COs and POs of ACM, author's observations, semi structured interviews with ACM experts and researchers from MSI Research Institute and CECA;

- *For AS-IS CLM:* Actual data was gathered through company COs and POs, author's observations and semi structured interviews with ACM experts and MSI/CECA researchers during its static CLM and dynamic modelling. The data gathered from company COs and POs was also used for P^3C analysis;

- *For AS-IS SM:* Actual data was gathered through company COs and POs, author's observations on process flows, product classifications, time and resource data and MSI/CECA researchers. Simulated data was used for AS-IS resource utilisation, scheduling rules, product classifications and capacity plan (capability matrix);

- *For TO-BE SM:* Actual data was gathered through company COs and POs, author's observations on TO-BE process flows, product classifications, time and resource data, semi structured interviews with ACM experts and MSI/CECA researchers. Simulated data was used for TO-BE processing stations, times, work flows, resource utilisation, scheduling rules, product classifications and capacity plan (capability matrix).

The models presented in this case study were verified by the author. The initial models were validated by the LU research group working on this case study. This group comprised researchers from MSI Research Institute and CECA. Also the initial models and the results generated were validated and accredited by the ACM management. The ACM management was very proactive and applied partial solutions as and when presented to them provided they agreed. It is expected that the ACM management will implement the EIMA as a whole in future.

9.4 Reflections and conclusions

The following reflections and conclusions are made on the basis of ACM case study; the overall aim of which was to show another useful application of the EIMA previously presented in Chapter 7.

1) The proposed EIMA (in Chapter 7) was successfully applied in ACM Production System. During testing it proved useful in virtually reconfiguring the ME by identifying and solving production and PPC related issues.

2) The CLM of the *ACM Production System* suggested possible potential benefit to ACM from PO data analysis; including the measurement of P3C to find the responsiveness of the AS-IS PPC process. The detailed analysis helped to understand reasons for lateness.

3) Measuring and monitoring the P^3C of the AS-IS ACM PPC system proved useful and it is likely to lead to improvements in the performance of the ACM PPC process and hence to improve the responsiveness to the COs and their respective *due dates.*

4) The ΣP^3C level of the *RM Shop* was higher than that of the Op Shop even though the RM Shop was facing issues related to mandrel availability at some times. However, ΣP^3C levels were significantly lower at an overall *ACM Production System* level. This situation suggests that:

   a) The global objectives of ACM need measuring and that ΣP^3C levels should be monitored continuously for their successful and timely achievement.

b) Interactions between the *RM Shop* and *Op Shop* need attention and further improvement. The higher levels of ΣP^3C in the *RM Shop* were misleading to some extent, due to the fact that there were instances when the *RM Shop* finished work at such times that there was not sufficient time remaining for the *Op Shop* to achieve the target *due date*. This suggests further investigation into this matter and also to design a mechanism for setting *due dates* and *priorities* for all shops individually, such that global objectives can be achieved.

5) ACM is an ISO 9000:2000 certified ME (not updated to ISO 9000:2008 yet).

a) Clause 7.1 of ISO 9000:2000 standard relates to *Planning for Product Realization*. The proposed P^3C provides a planning opportunity for product realization, hence also fulfilling the respective ISO clause in addition to the present justifications.

b) Clause 8.2 of the ISO 9000:2000 standard relates to *Measurement and Monitoring*. During the ACM case study, it was proposed that the P^3C be measured and monitored for PO realization and this would also demonstrate the respective ISO clause.

c) Clause 8.5 of the ISO 9000:2000 standard relates to *Corrective and Preventive Actions*. It is suggested that reasons for exceptions to complete planned POs (rescheduling) may be traced, investigated, corrected and prevented by removing the causes which will also cover this ISO clause.

6) It was identified that time and cost were the best KPIs to consider in this case.

7) AS-IS simulation models of the *ACM Production System* are presented in this chapter which can replicate existing and predict possible future dynamic patterns of behaviour for that system.

8) Data availability was amongst one of the main limitations of this case study.:

a) Only 3-month PO data was made available. Further data gathering is necessary in order to get a clearer picture. Here it is recommended that at least one full year of PO data be gathered and analysed, so that all troughs and crests become visible especially those created seasonally or due to economic factors.

Therefore, further PO data collection is required in order to understand and predict realistic CO and PO dynamics and their impact on the responsiveness of the *ACM Production System*.

b) No data was available related to variations in the complexity level of jobs involved which could significantly affect *on-time* completion of POs.

9.5 The way forward

After this case study, the ACM management was keen to know more about future enterprise and simulation models. Chapter 10 will present future reconfigurations and analysis related to *ACM Production System*.

Chapter 10

ACM Production System: Future Reconfigurations

10.1 Motivation and introduction

Following implementation of the stepwise EIMA at ACM, the management was keen to know about possible future reconfigurations of its production system. Therefore, it was decided to look into some TO-BE model reconfigurations in this chapter that might present improved performance via the use of known PPC methods to the ACM management through quantitative analysis when using appropriate performance measures. During this TO-BE modelling exercise, the model configurations presented in the previous Chapter 9 were re-used as a basis to create future reconfigurations of the *ACM Production System*. The rest of the chapter is divided into five sections. Section 10.2 presents possible TO-BE reconfigurations of the *ACM Production System*. SM of TO-BE reconfigurations of *ACM Production System* are then illustrated in section 10.3. Section 10.4 reflects on the analysis made and draws conclusions that point to future research directions outlined in section 10.5.

10.2 Future reconfigurations of the *ACM Production System*

Based upon visits to ACM and using selected KPIs, it was identified that the *RM Shop* and the *M Shop* are both facing production challenges as shown in Figure 89.

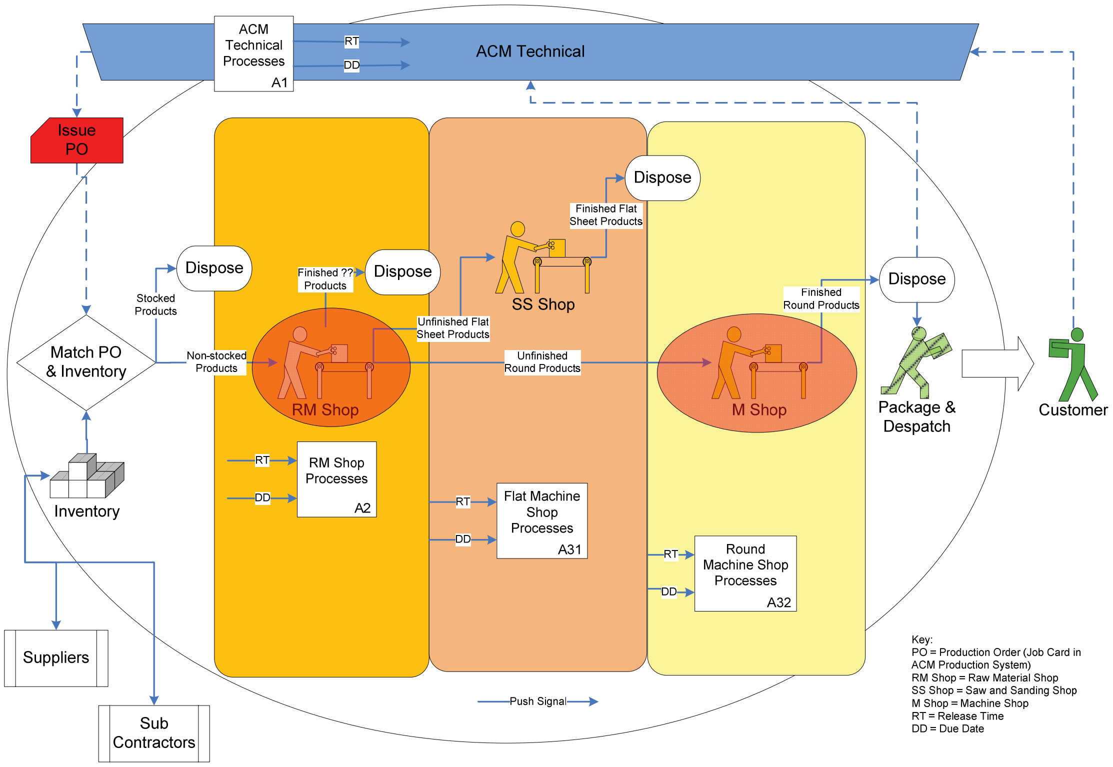


Figure 89: Identified production challenges in *ACM Production System*

TO-BE reconfigurations of the *ACM Production System* should endeavour to overcome the identified challenges and explore ways of achieving future improvement that will be discussed as follows.

10.2.1 TO-BE enterprise model reconfiguration

Based upon previous results and discussion with the ACM management it was decided to redesign the *ACM Production System*. Activity diagrams were created to initiate documentation of TO-BE enterprise model reconfigurations of the *ACM Production System*, with particular reference to CO and PO as shown in Figure 90 and Figure 91.

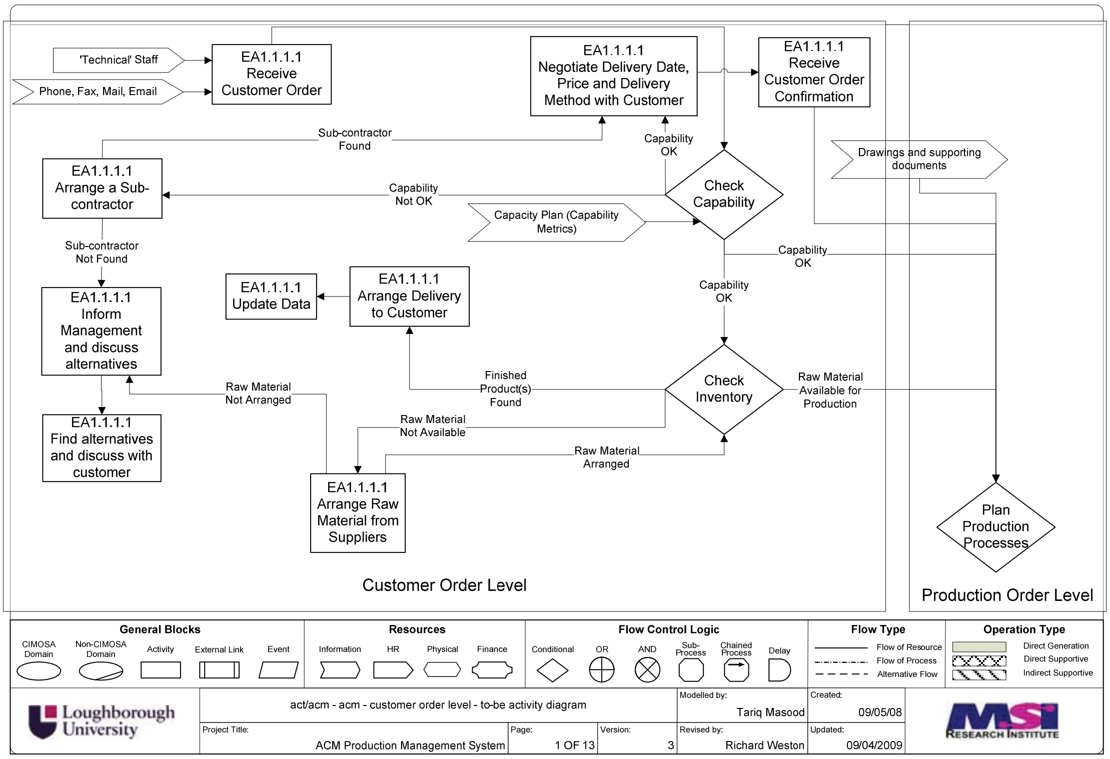


Figure 90: TO-BE activity diagram at CO level of *ACM Production System*

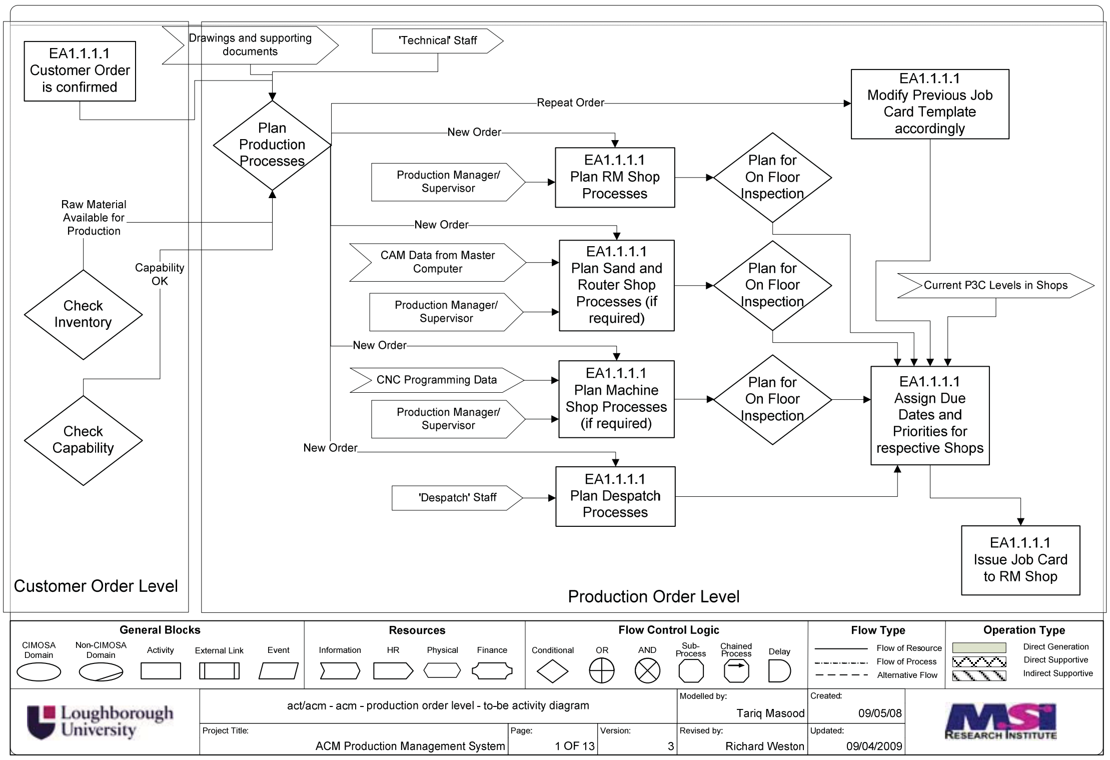


Figure 91: TO-BE activity diagram at PO level of *ACM Production System*

Figure 90 suggests a new way of processing COs centred on a planner located in the *Technical Department* of ACM. It shows EAs that should be involved in TO-BE system, including capability and inventory checks. After a CO is received, for proposed EAs related to planning of production processes are shown in detail in Figure 91. To realise the TO-BE *ACM Production System*, Figure 91 illustrates the planning processes for each shop. In addition, the assignment of *due dates* and priorities in shops is now directly linked with respective current levels of ΣP^3C. This updated information of current levels of ΣP^3C shall enable the production planner to clearly visualise the ground situation in each shop before issuing a PO to the *RM Shop*. In this case, the production planner is in a better position to decide on manageable *due dates* rather than assign unrealistic *due dates*.

10.2.2 TO-BE pull-pull (Kanban) reconfiguration

Based upon understandings gained through structured integrated modelling, data analysis and discussions with the ACM management and staff, a pull-pull (Kanban) based alternative solution was devised and is proposed as shown in Figure 92.

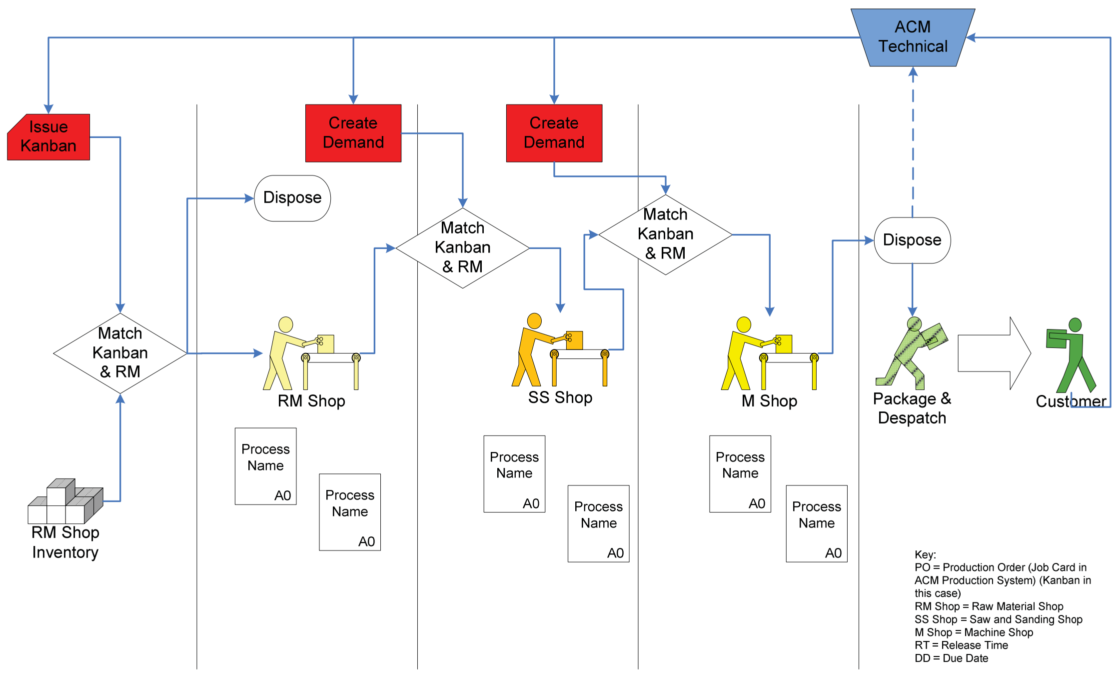


Figure 92: TO-BE pull-pull (Kanban) based *ACM Production System*

10.2.3 TO-BE hybrid push-pull reconfiguration

Based upon understandings gained through structured integrated modelling, data analysis and discussions with the factory management and staff, a hybrid push-pull based alternative solution was conceived as proposed in Figure 93.

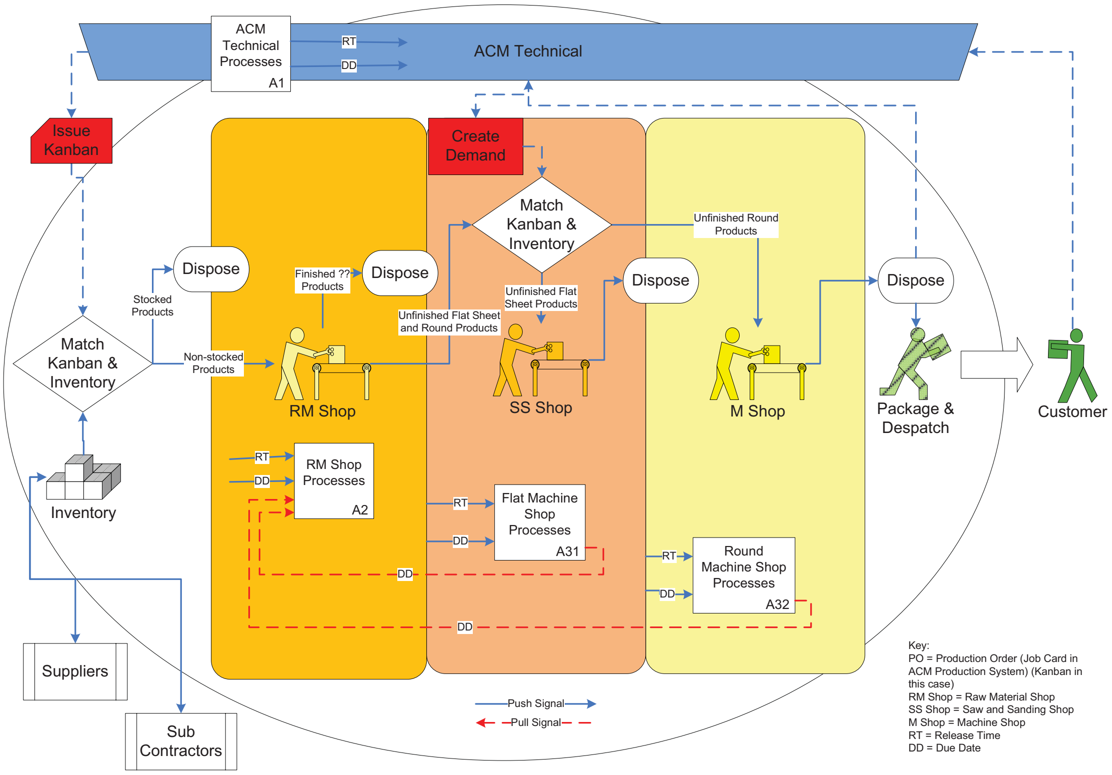


Figure 93: TO-BE hybrid push-pull *ACM Production System*

10.2.4 TO-BE reconfiguration based on CONWIP

Based upon understandings gained through structured integrated modelling, data analysis and discussions with the factory management and staff, a constant work in process (CONWIP) based future reconfiguration solution was also conceived and proposed as shown in Figure 94.

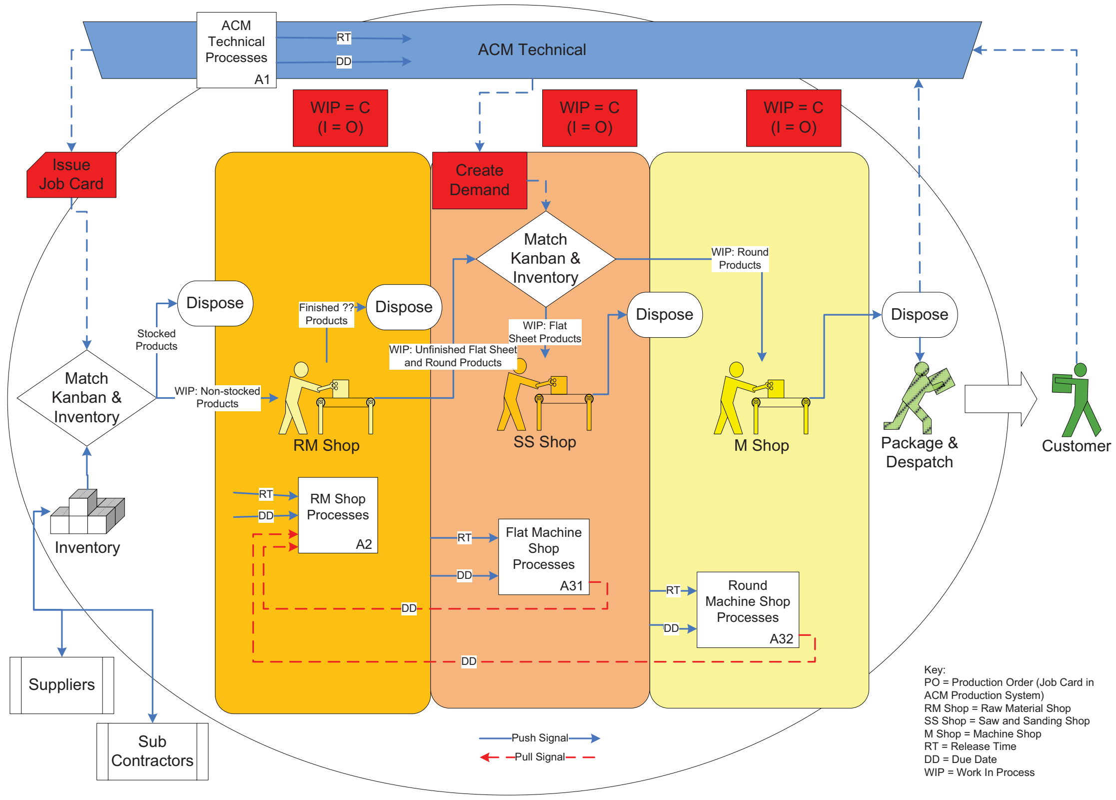


Figure 94: TO-BE CONWIP based *ACM Production System*

10.2.5 TO-BE reconfiguration based on postponement

Based upon understandings gained through structured integrated modelling, data analysis and discussions with ACM management and staff, a *Postponement* based alternative solution was also conceived as proposed in Figure 95.

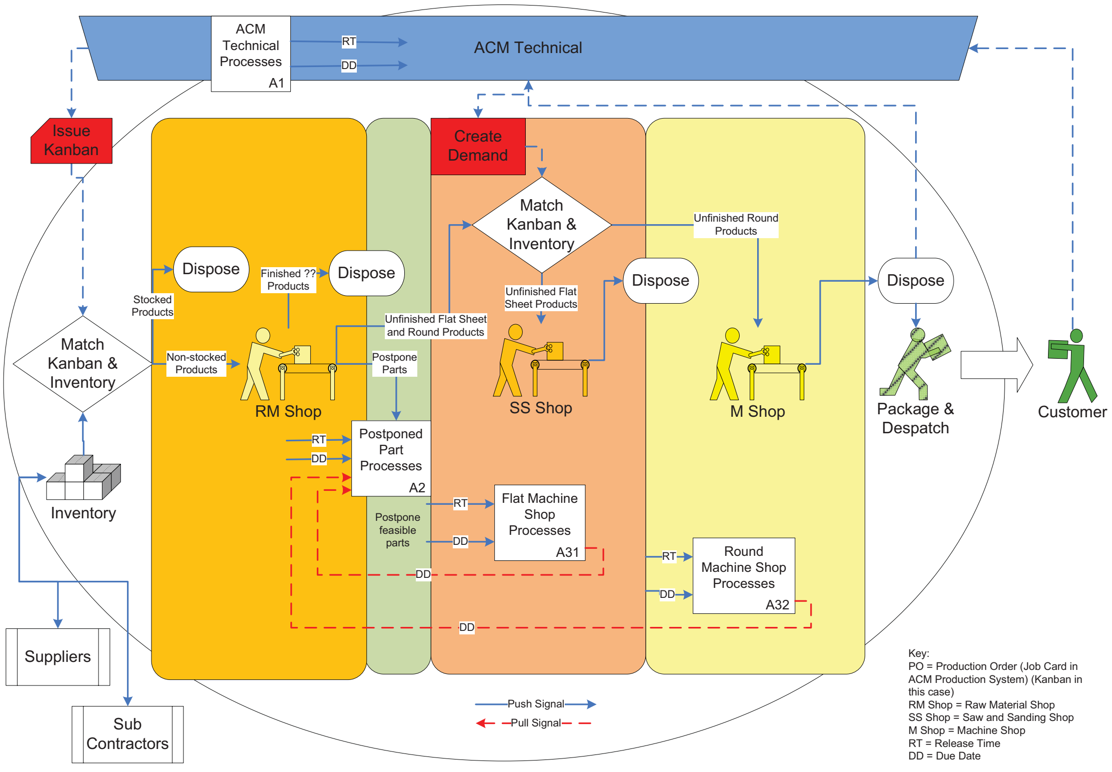


Figure 95: TO-BE Postponement based *ACM Production System*

10.2.6 TO-BE reconfiguration based on capacity planning

Capacity planning is important at the time of booking a customer order as well as while preparing a plan for a production order. The availability of an updated version of capability matrix is important as well as current state description of the resource load. The availability of such models can enable the customer interfacing department to decide whether to accept the customer order or to negotiate on suitable *due dates*.

A TO-BE capacity plan (or TO-BE capability matrix) is proposed for ACM in Table 28. This proposal was conceived on the basis of author's knowledge of the company processes and resources, with a view to informing the decision makers in the Technical Department of the company. A column of the current loading status may also be added and updated at appropriate intervals in time in order to better plan production orders and to improve negotiations with customers, when agreeing on *due dates*.

Table 28: TO-BE capacity plan (or TO-BE capability matrix) of ACM

S. No.	Product Dynamics					Work Dynamics					Company Performance Level (High, Medium, Low)	Last Updated on
	Classification	Sub-Class	Material Grades (See Appendix E for details)	Specifications Range (Min-Max)	Minimum Batch Size Required	Shop Processes	Resources					
							Physical (includes work stations and tooling)	Machine	IT based	Human (Operation Level)		
1.	Round	Bearing Plain	L7/G10	OD=80 ID=60 W or L=40-100	25	RM Shop M Shop	Mandrels Required = 1	See *	---	RM Shop = 2 Round Machine Shop = 1	High	15.11.2009
2.		Bearing Sleeve	L7/G10	OD=60 ID=50 W or L=38	10	RM Shop M Shop	Mandrels Required = 1	See *	---	RM Shop = 2 Round Machine Shop = 1	High	15.11.2009
3.		Bush	L7/G10	OD=280 ID=250 W or L=150	2	RM Shop M Shop	Mandrels Required = 1	See *	---	RM Shop = 2 Round Machine Shop = 1	High	15.11.2009
4.		Skimmed Tube	L7/G10	OD=112 ID=48 W or L=660	1	RM Shop M Shop	Mandrels Required = 1	See *	---	RM Shop = 2 Round Machine Shop = 1	High	15.11.2009

S. No.	Product Dynamics					Work Dynamics					Company Performance Level (High, Medium, Low)	Last Updated on
	Classification	Sub-Class	Material Grades (See Appendix E for details)	Specifications Range (Min-Max)	Minimum Batch Size Required	Shop Processes	Resources					
							Physical (includes work stations and tooling)	Machine	IT based	Human (Operation Level)		
5.		Wear Ring	L7/G10	OD=26 ID=22 W or L=4.2	100	RM Shop M Shop	Mandrels Required = 2	See *	---	RM Shop = 2 Round Machine Shop = 1	High	15.11.2009
6.		Washer	L4/G	OD=200 ID=152 T=3	30	RM Shop M Shop	Mandrels Required = 1	See *	---	RM Shop = 2 Round Machine Shop = 1	High	15.11.2009
7.	Flat	Pad	L4/G	T=6 W=20 L=220	100	RM Shop SS Shop	Mandrels Required = 1	Work Stations 1-3	---	RM Shop = 2	High	15.11.2009
8.		Sanded Sheet	L2 / Marine	T=16 W=600 L=1200	1	RM Shop SS Shop	Mandrels Required = 1	Work Stations 1-3	---	RM Shop = 2	Medium	15.11.2009
9.		Arm Pad	L7/G	T=12 W=50 L=100	25	RM Shop SS Shop	Mandrels Required = 1	Work Stations 1-3	---	RM Shop = 2	High	15.11.2009
10.		Disc	L4/G	T=4.5 W=30	200	RM Shop SS Shop	Mandrels Required = 1	Work Stations	---	RM Shop = 2	High	15.11.2009

S. No.	Product Dynamics					Work Dynamics					Company Performance Level (High, Medium, Low)	Last Updated on
	Classification	Sub-Class	Material Grades (See Appendix E for details)	Specifications Range (Min-Max)	Minimum Batch Size Required	Shop Processes	Resources					
							Physical (includes work stations and tooling)	Machine	IT based	Human (Operation Level)		
				L=30				1-3				
11.		Wear Pad	L3/G20	T=24.5 W=60 L=200	10	RM Shop SS Shop	Mandrels Required = 1	Work Stations 1-3	---	RM Shop = 2	High	15.11.2009
12.	Strip	Wear Strip	L14/G	T=2.42 W=14.8 L=5000	100	RM Shop SS Shop	Mandrels Required = 2	Work Stations 1-3	---	RM Shop = 2	High	15.11.2009
13.		Strip Section	L14/G	T=2.42 W=14.5 L=180	50	RM Shop SS Shop	Mandrels Required = 1	Work Stations 1-3	---	RM Shop = 2	Low	15.11.2009

OD=Outer Diameter, ID=Inner Diameter, W=Width, L=Length, T= Thickness
* CNC Horizontal Turning Machine Nos. HTM005-HTM008

10.3 Simulating TO-BE reconfigurations of the *ACM Production System*

TO-BE simulation models were developed in order to compare possible future behaviours of different configurations of the *ACM Production System*. AS-IS models were re-used to create TO-BE reconfigurations. Figure 96 shows a simulation model reconfiguration for pull (Kanban) production system. The TO-BE model was developed using Plant Simulation® simulation software tool. Figure 96 also shows sample KPI results.

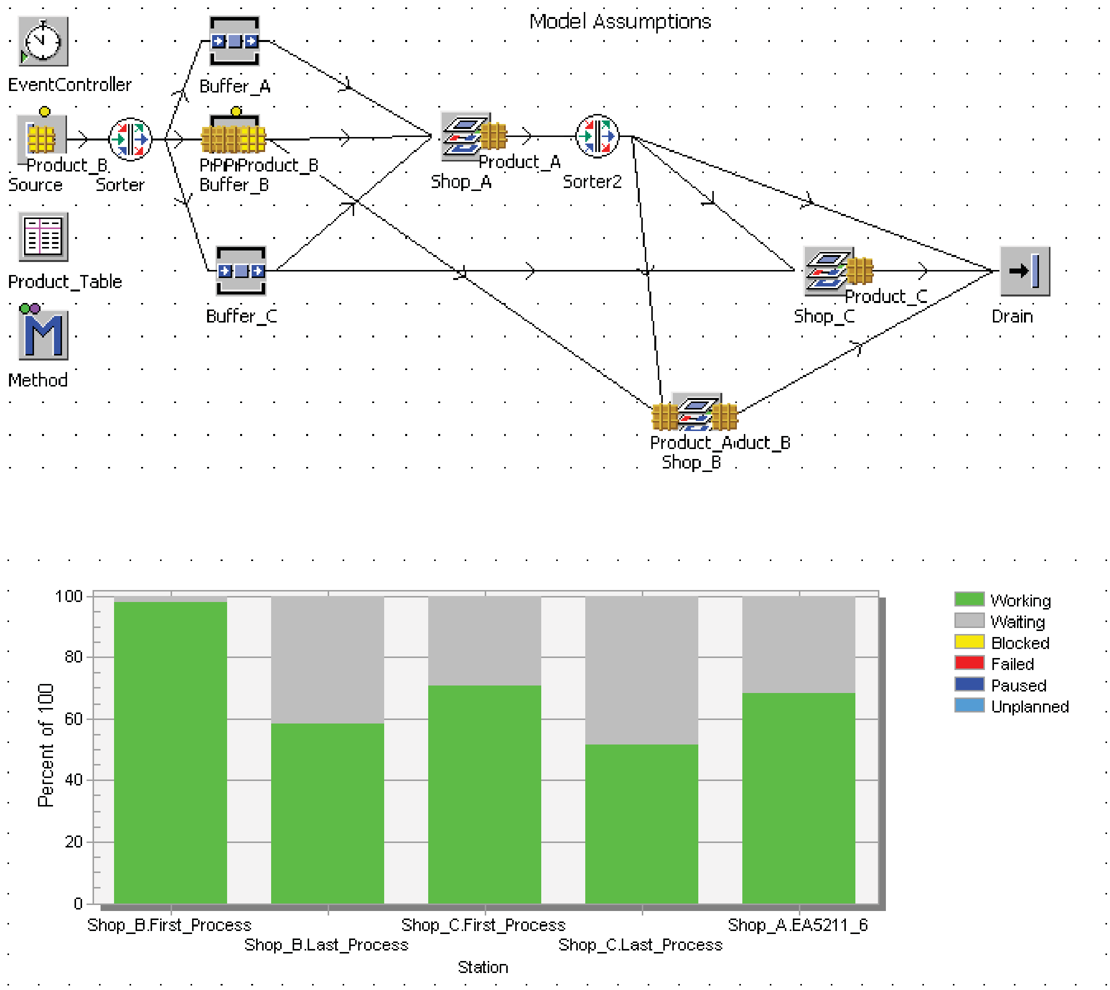


Figure 96: TO-BE simulation model for ‘pull (Kanban)’ based *ACM Production System*

TO-BE simulation model reconfiguration for RM Shop embedding pull (Kanban) based *ACM Production System* is shown along with sample KPI results in Figure 97.

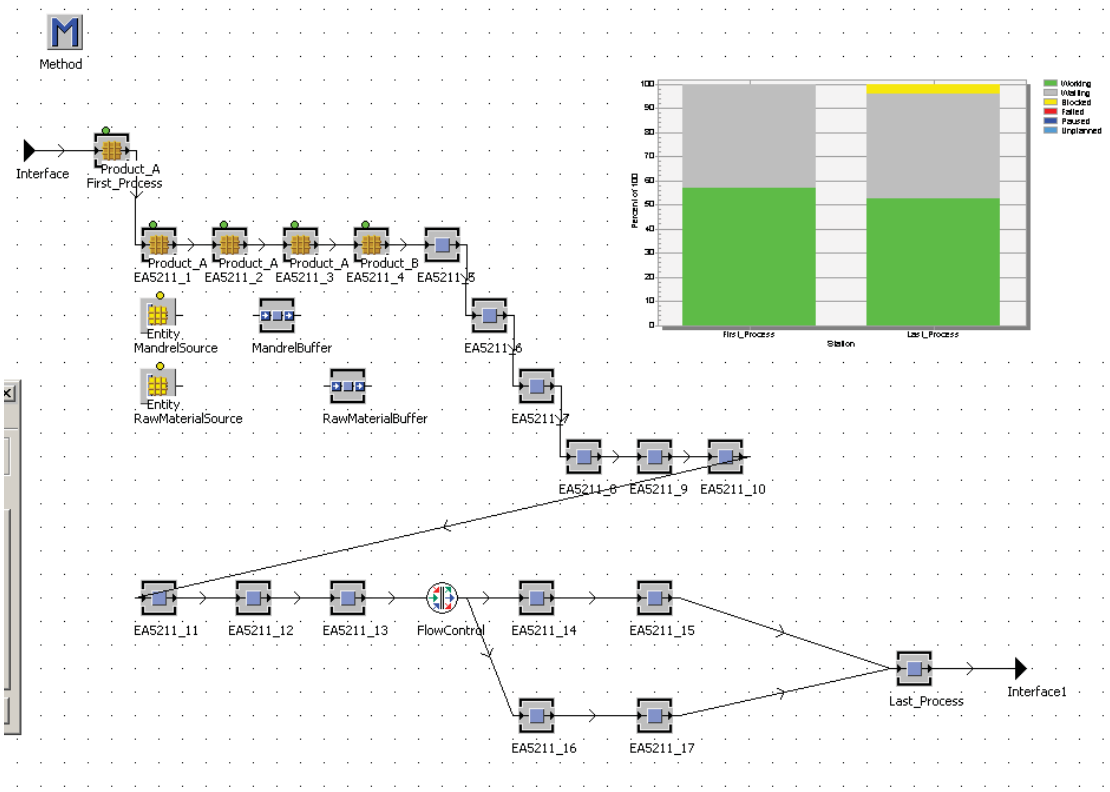
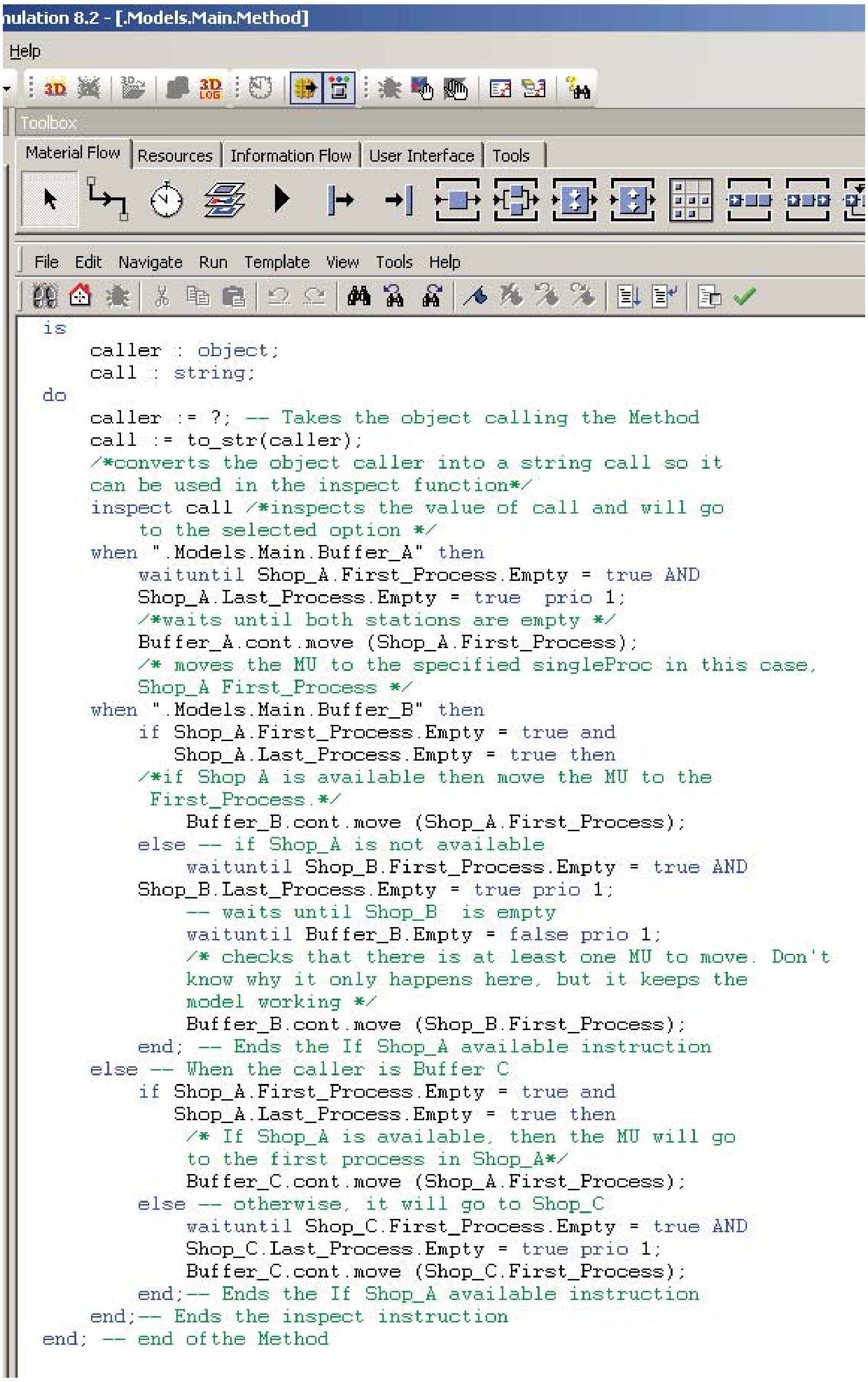


Figure 97: TO-BE RM Shop simulation model for pull (Kanban) based *ACM Production System*

Figure 98 shows a 'method' code written for TO-BE simulation model of *ACM Production System* based on the use of pull (Kanban) synchronisation. The 'method' incorporates the code that enables the simulation to run in the desired fashion.




```
is
     caller : object;
     call : string;
do
     caller := ?; -- Takes the object calling the Method
     call := to_str(caller);
     /*converts the object caller into a string call so it
     can be used in the inspect function*/
     inspect call /*inspects the value of call and will go
           to the selected option */
     when ".Models.Main.Buffer_A" then
           waituntil Shop_A.First_Process.Empty = true AND
           Shop_A.Last_Process.Empty = true  prio 1;
           /*waits until both stations are empty */
           Buffer_A.cont.move (Shop_A.First_Process);
           /* moves the MU to the specified singleProc in this case,
           Shop_A First_Process */
     when ".Models.Main.Buffer_B" then
           if Shop_A.First_Process.Empty = true and
              Shop_A.Last_Process.Empty = true then
           /*if Shop A is available then move the MU to the
            First_Process.*/
                 Buffer_B.cont.move (Shop_A.First_Process);
           else -- if Shop_A is not available
                 waituntil Shop_B.First_Process.Empty = true AND
           Shop_B.Last_Process.Empty = true prio 1;
                 -- waits until Shop_B  is empty
                 waituntil Buffer_B.Empty = false prio 1;
                 /* checks that there is at least one MU to move. Don't
                 know why it only happens here, but it keeps the
                 model working */
                 Buffer_B.cont.move (Shop_B.First_Process);
           end; -- Ends the If Shop_A available instruction
     else -- When the caller is Buffer C
           if Shop_A.First_Process.Empty = true and
              Shop_A.Last_Process.Empty = true then
                 /* If Shop_A is available, then the MU will go
                 to the first process in Shop_A*/
                 Buffer_C.cont.move (Shop_A.First_Process);
           else -- otherwise, it will go to Shop_C
                 waituntil Shop_C.First_Process.Empty = true AND
                 Shop_C.Last_Process.Empty = true prio 1;
                 Buffer_C.cont.move (Shop_C.First_Process);
           end;-- Ends the If Shop_A available instruction
     end;-- Ends the inspect instruction
end; -- end of the Method
```

Figure 98: 'Method' code for a TO-BE simulation model reconfiguration of *ACM Production System* based on pull (Kanban) synchronisation

The following assumptions were made while creating the TO-BE simulation model reconfiguration of *ACM Production System* (as shown in Figure 99).

a) processing time in all stations is 1 minute;

b) only one MU (representing POs) can be processed in a Shop at any given point in time;

c) If an MU can't go to Shop A (RM Shop), it will be directed to the relevant Shop;

d) All MUs are of an appropriate size that they can be processed with the relevant resources in the stations;

e) This model makes no use of workers;

f) Three product classifications are assumed and specific routes as shown in the model;

g) The graph plots the work and wait times of the individual processes in Shop B (SS Shop) and Shop C (M Shop). As there is no failure rate and there is no Shifts, no Failed, Paused or Unplanned time will appear in the graph;

h) Products are created utilising a *Random* strategy in the *Source*. Probability of product creation is 33% for product classification A (Flat) and B (Strip) each and 34% for product C (Round);

i) All shops contain two processes, *First* and *Last*;

j) The MU in this model represents individual POs. As noted above there are three main product classifications in the POs.

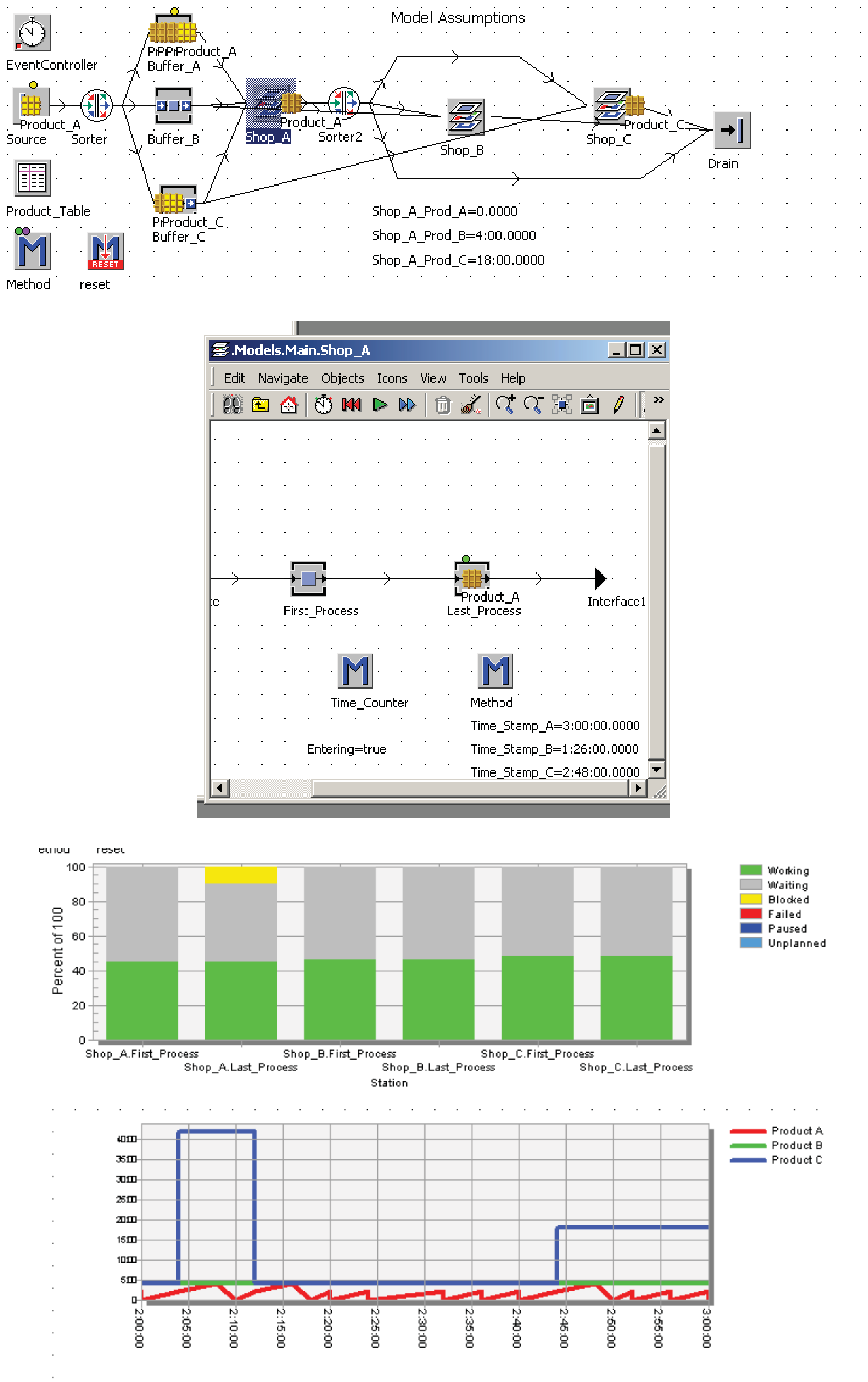


Figure 99: TO-BE simulation model reconfiguration of *ACM Production System*

Data types and VVA of TO-BE models:

The following describes various types of data that was used TO-BE modelling during this case study.

- *For TO-BE EM:* Actual data was captured from author's observations, semi structured interviews with ACM experts and researchers from MSI Research Institute and CECA. Actual and simulated data was used for interrelationships in TO-BE configurations and capacity plan (capability matrix);

- *For TO-BE SM:* Actual data was gathered through company COs and POs, author's observations on TO-BE process flows, product classifications, time and resource data, semi structured interviews with ACM experts and MSI/CECA researchers. Simulated data was used for TO-BE processing stations, times, work flows, resource utilisation, scheduling rules and product classifications.

The models presented in this case study were verified by the author. The TO-BE models were validated by the LU research group working on this case study. This group comprised researchers from MSI Research Institute and CECA. Also the initial models and the results generated were validated and accredited by the ACM management.

10.4 Reflections and conclusions

1. Candidate future (TO-BE) model reconfigurations for the *ACM Production System* are presented in this chapter, based on use of well known PPC methods including push, pull, hybrid push-pull, Kanbans and ConWIP. The application of EIMA in ACM (as presented in Chapter 9) facilitated the ME through integration of PPC methods at various modelling stages and produced such results which could prove useful to the industry decision makers. Hence it is recommended that the overall research approach be adopted by ACM for potential future use with a particular emphasis on responsiveness and PPC.

2. Decision making is distributed for pull systems, where production units can send signals to the preceding production units in order to meet the *due dates* of

POs. The preceding shop may adjust such signals within the flexibility time cushion provided by the PO planner.

3. The competence level of assessing feasible times and complexities could also affect in-time completion of POs. Hence, opportunities for improvement could include:

    a. Increasing the competence of the production planners, at company and supervisory levels;

    b. Introducing a process of interaction with the production staff when creating production plans;

    c. Creating a TO-BE capacity plan (TO-BE capability matrix) and adding estimated times for estimated amounts of material removal for example. However it should be understood that such an arrangement could only contribute partially to production problem solving because of other factors involved for example the real operational conditions of machine, operator decisions when setting feeds and speeds of CNC machines, etc.

4. TO-BE activity diagrams were developed as part of the EIMA at customer and production order levels based upon the results and discussions about the *ACM Production System*. The activity diagrams are intended to serve the purpose of explicitly describing possible improvements to PPC.

5. Figure 100 shows the overall EIMA adopted during the ACM case study and illustrated in Chapters 9 and 10.

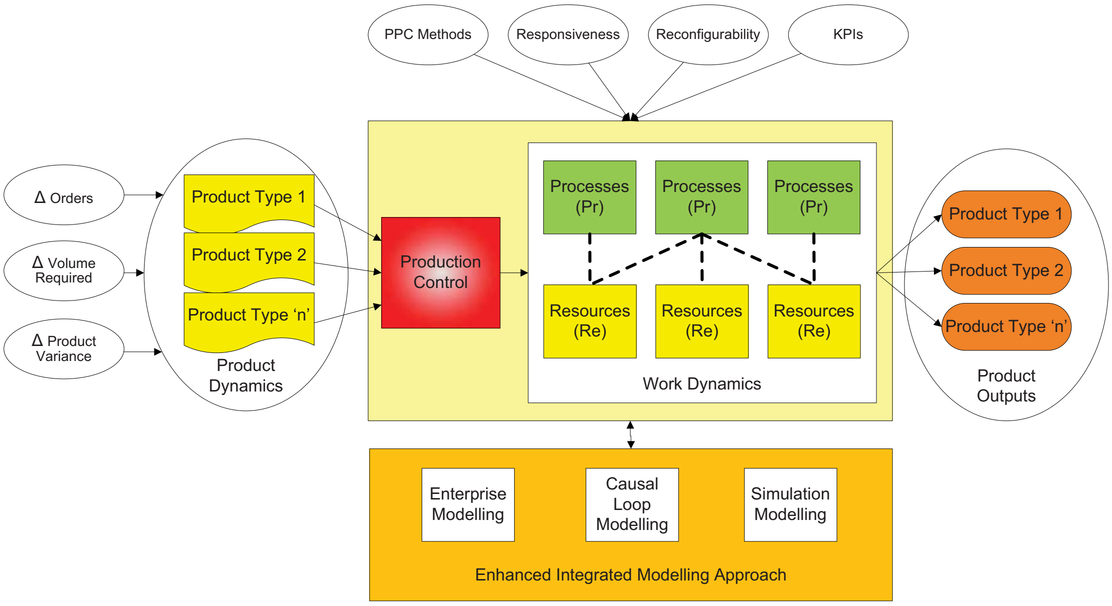


Figure 100: Overall EIMA in ACM

10.5 The way forward

Comparison of the results of the ACM case, with those from the Ford and Bradgate cases, has identified commonalities and differences. These observations are discussed in Chapter 11, as part of an overall research review and analysis of this thesis.

Chapter 11

Research Review and Analysis

11.1 Motivation and introduction

This chapter reviews and analyses the research and the industrial case studies presented in this thesis. Chapters 6, 8, 9 and 10 have already included results, analysis and discussions related to the respective case studies. This chapter reviews the overall research approach and contrasts and compares the undertaken case studies and draws out an overall analysis and discussion.

11.2 Evolution of the EIMA

Whilst methodologists and practitioners provided a vast range of methods and practical solutions, the complexity of present day business leaves ME with significant remaining problems. Modified and emerging new ways of doing business and the use of new technology has also reduced the frequency of need for a change. This induces tension between flexibility and productivity as these are not natural partners. Whenever trade-off is needed between these two different requirements this thesis explores how ‘harmony’ between the two can be improved through a new use of virtual environments in which models of production realities are used to inform ME decision making, and thereby potentially better ME action taking. The EIMA proposed and tested in this thesis was conceived from extensive review on various literature on manufacturing systems, and on ways of modelling them. Also EIMA conception was based upon industrial experience (especially from case testing IMA in Ford) and by taking into account views of related stake holders. The review of manufacturing philosophies and solutions provided in the past enabled the author to understand specific reconfigurable manufacturing paradigms and candidate PPC solutions as well as to learn about the capabilities and limitations of EMI architectures. The reference architectures namely CIMOSA, GERAM, PERA, ARIS, GRAI-GIM, IEM and IDEF were considered, by the present author, to be most important in the literature amongst others. The ISO standardised CIMOSA architecture was adopted for this research due to its advantages of generality, wide acceptance and use, and well-documented modelling concepts; to name a few. It was observed in respect of the junction of CIMOSA and PPC concepts, that there was not much written about their combined application. The field of PPC is so vast and widely tested for its classical philosophies and solutions; but would be practitioners can easily be mislead when choosing between them. Reconfigurability and responsiveness were found to be amongst major issues the present day manufacturing industry faces. Hence the general idea was formed for this research that EMI concepts should be used to facilitate PPC selection and design of related production systems with a view to achieving “flexible production”. The organisation, resource, information and function views of CIMOSA were therefore selected as the basis of EIMA for requirements definition. Following which conceptual design specification of production system solutions was to achieved through combined use of EM and CLM; to identify key issues, their effects and after effects either statically or dynamically as required. Also to enable quantitative analysis SM would be used to dynamically and virtually view likely outcomes of adopting various PPC strategies with reference to specific KPI analysis.

The application of the EIMA developed by the present author resulted in a final solution forming a specific descriptive work flow model. EIMA specifically considers configurations of Pr-Re couples and WD and helps in smoothing variations in demand levels as far as possible with selected PPC approaches. The EIMA L-Funnel, as illustrated in Figure 101, presents a right-to-left funnelling concept through which this research gained focus to reach the final EIMA.

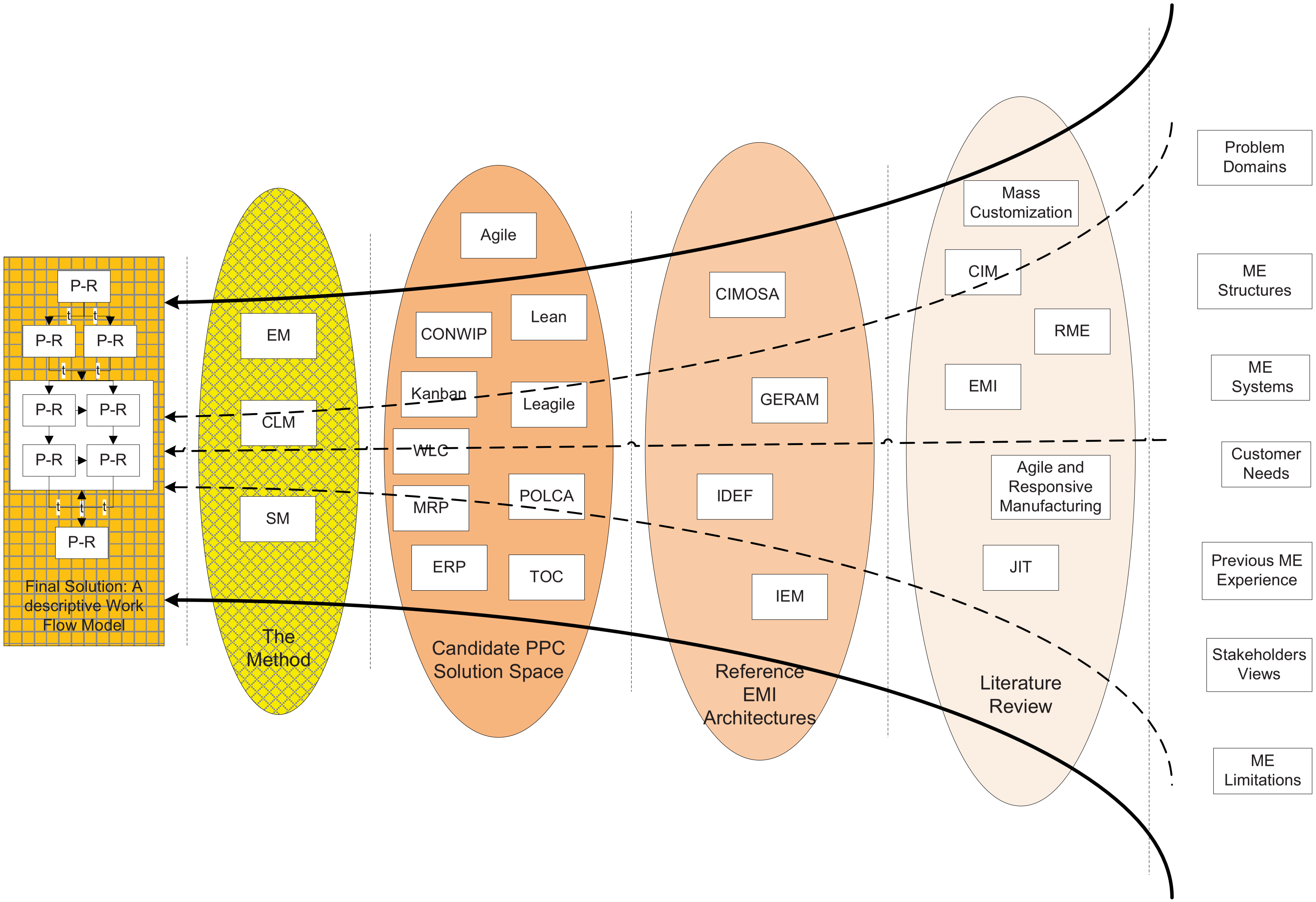


Figure 101: The EIMA L-Funnel

11.3 Comparison of the case study applications

The IMA was initially tested in Ford case by considering processes that traverse its Engineering, Pre-Production Management and New Model Launch departments. The use of IMA in the Ford case helped understand the complex AS-IS situation of the problem domain in which this company wanted to plan for a future reconfiguration of the Pre-Production Release of 2-3 vehicle models consisting of 11,000 POs within PPM department. During Ford case study, development of the enterprise models helped to understand the processes, resources and their interrelationships related to this case study. The enterprise models also provided a 'knowledge repository' in the form of a graphical 'process oriented structure'. This was designed to facilitate knowledge capture, in the form of a sequential flow of case-specific processing requirements and information needs, and an explicit definition of interactions between the process being modelled in detail and the specific environment in which that process must operate. The simulation models of the processes and resources, involved in the Ford case, quantified dynamic aspects in terms of the behaviours of a set of KPIs. This facilitated decision making on new policy changes. The Ford case has shown benefits in terms of time, resource load and cost parameters of the project based upon comparisons of AS-IS and TO-BE configurations. The TO-BE model results have shown significant reductions i.e., 15.15% reduction in project / lead time, 20.60% reduction in resource load, 9.77% reduction in cost of 'Engineers' resource and 5.35% reduction in total project cost. Hence, this exercise proved useful learning resource for the development of the IMA.

The application of the IMA in Ford case study looked into a pre-production release problem in a MTS configuration and has resulted in a way forward to conceptually designing and computer executing an improved MTO production control configuration. The knowledge gained from the Ford case study in terms of strengths and weaknesses of the IMA and its enhancement as a result (as discussed in Chapter 7) helped to apply the EIMA in Bradgate case study. The application of EIMA in Bradgate case helped understand the complex planning and control configurations needed for more than 300 product types. During this case study, the EIMA model configurations were focussed on processes that span the production and management departments. The introduction of the CLM stage during this case study helped in better understanding of impacts of change in complex manufacturing systems and therefore in designing better SM experiments.

The application of EIMA in Bradgate resulted in demonstrating its significant role to enable decision making in a responsive ME based upon virtual reconfigurations. This is true with respect to the engineering of PPC systems in MEs being representative of manufacturing responsiveness. Enterprise models, causal loop models and simulation models played key complementary roles to enable PPC decision making by using the proposed EIMA in Bradgate case. The design of a PPC system needs to cater for current and future product variance and enable new product introduction. Models created for Bradgate case study aided PPC strategy design and resultantly manufacturing responsiveness decision making in Bradgate.

The knowledge gained through Ford and Bradgate cases was applied during the application of EIMA in ACM case. It helped understand necessary complex planning and control configurations for more than 100 product types. The model reconfigurations were focussed on processes deployed in production, technical and management departments. Sets of current and future enterprise, causal loop and simulation model reconfigurations created during application of the EIMA in ACM proved useful in:

- Understanding the complex AS-IS situations of the ACM business;
- Providing useful insights to the *ACM Production System* and helping in decision making during the analytical design of the ME;
- Classifying products according to their commonalities in associated production processes and dimensional features;
- Analytically designing production planning and control system for ACM;
- Assessing current responsiveness of the production system at a given point in time through use of P^3C and improved model reconfigurations.
- Suggesting that the CLM of the *ACM Production System* held possible potential benefit to ACM from PO data analysis; including the measurement

of P^3C to find responsiveness of the AS-IS PPC process. The detailed analysis helped to understand reasons for lateness.

- Compiling a capacity plan (capability matrix) and adding estimated times for estimated amounts of material removal for example. However it should be understood that such an arrangement could only contribute partially to production problem solving because of other factors involved for example the real operational conditions of machine, operator decisions when setting feeds and speeds of CNC machines, etc.

- Developing TO-BE activity diagrams as part of the EIMA at customer and production order levels based upon the results and discussions about the *ACM Production System*. The activity diagrams are intended to serve the purpose of explicitly describing possible improvements to PPC responsiveness and future virtual reconfigurations.

Table 29 presents a cross-case comparison of IMA/EIMA industrial applications based upon observations and results of Ford, Bradgate and ACM case studies.

Table 29: Cross-case comparison of IMA/EIMA industrial applications

Context	**Ford Case Study (Pre-Production Release)**	**Bradgate Case Study (Production Release)**	**ACM Case Study (Production Release)**
CODP	MTS	MTO	ETO/MTO
Product Variance / Classification	2-3 Models	>300 Products	3 Classifications >100 Products
No. of Jobs	11,000 (in 3-month)	Unpredictable	Unpredictable
Lead Time / Throughput Time	3-month	4-weeks in-house (8-weeks customer)	Varies as agreed with customer
Departments focussed	☐ Engineering ☐ Pre-Production Management ☐ New Model Launch	☐ Production ☐ Management	☐ Production ☐ Technical ☐ Management
Problem Domains	Planning for the change (Company has full awareness of present level of KPIs)	❑ Planning for the change (Company has partial awareness of present level of KPIs) ❑ Scheduling (priorities' issues) (addition of new orders some times)	❑ Planning for the change (Company has partial awareness of present level of KPIs) ☐ Scheduling (priorities' issues) (sudden changes some times)
Adopted Approach	IMA: ☐ EM ☐ SM	EIMA: ☐ EM ☐ CLM ☐ SM	EIMA: ☐ EM ☐ CLM ☐ SM
Simulation software used	☐ Arena®	☐ Simul8®	☐ Plant Simulation® ☐ iThink®/Stella®
KPIs	☐ Lead Time ☐ Resource utilisation ☐ Cost	☐ Lead Time ☐ Resource utilisation ☐ Cost	☐ Responsiveness (P^3C) ☐ Lead Time ☐ Resource utilisation ☐ Cost
Outcomes	☐ Results of engineered model reconfigurations	☐ Results of engineered model reconfigurations ☐ Set of optional strategies and results of their virtual application ☐ Product Classification (T1-T6, C1-C8) according to the commonalities in required production processes and dimensional features.	☐ Results of engineered model reconfigurations ☐ Set of optional strategies and results of their virtual application ☐ Product Classification according to their variance over a period of time (runners, repeaters, strangers)

The EIMA (as presented in Chapter 7) was applied in the Bradgate (Chapter 8) and ACM cases (Chapters 9 and 10). Both cases have some commonalities as well as some significant differences. Table 30 summarizes key existing approaches, authors' observations and proposed strategies related to PPC for these cases.

Table 30: Summary of observations and proposed PPC hierarchy in Bradgate and ACM

Case Study	Existing PPC Hierarchy Configuration	Observations	Proposed strategies
Bradgate	No aggregate planning based on forecasting	☐ No visibility of order behaviour ☐ Slow to react	☐ Needs forecasting ☐ Historical data analysis
ACM	No aggregate planning based on forecasting	☐ No visibility of order behaviour ☐ Slow to react	☐ Needs forecasting ☐ Historical data analysis

The CODP plays an important role in determining the way a ME deals with the COs. Bradgate worked on MTO principles while ACM was an ETO/MTO in CODP terms. Table 31 shows the author's observations and propositions made to improve the CODP.

Table 31: Summary of observations and proposed CODP strategies in Bradgate and ACM

Case Study	Existing CODP Configuration	Observations	Proposed strategies
Bradgate	MTO	Majority of production starts with order arrival	❑ ATO ❑ Inclusion of Postponement theory
ACM	ETO/MTO	Majority of production starts with order arrival	❑ Identify repeat orders ❑ Prepare feasibility of starting potential repeat orders beforehand

In today's changing business environment, MEs need to be changeable in respect of their production strategies. A decision to adopting 'push' or 'pull' can make a lot of difference in terms of production lead times. Bradgate and ACM both adopt a 'push' production system and are prone to longer lead times than their management desires; as their management believe that can capture greater market share through improved reconfigurability and responsiveness levels. A hybrid ‘push-pull’ system is proposed as one of the potential future solutions in both cases. In the ACM case, ΣP^3C gave a quantitative benchmark for the state of PO responsiveness. Table 32 presents a summary of the observations and propositions regarding ‘push’ and ‘pull’ strategies in Bradgate and ACM.

Table 32: Summary of observations and proposed push/pull strategies in Bradgate and ACM

Case Study	Existing Push/Pull Configuration	Observations	Proposed strategies
Bradgate	Push system	❑ Longer lead times ❑ ΣP^3C was not measured	❑ Pull system where possible ❑ Production based upon commonality of parts ❑ Parts standardisation
ACM	Push system	❑ Longer lead time ❑ Lower ΣP^3C values (Average $\Sigma P^3C < 50\%$)	❑ Pull system where possible (e.g., M Shop Pulling from RM Shop. Pulling from M Shop is not possible at present situation).

Production scheduling was a problem in both Bradgate and ACM due to which high variety was induced in the system bottleneck. Table 33 summarizes observations and proposed production scheduling strategies for Bradgate and ACM case studies.

Table 33: Summary of observations and proposed production scheduling strategies in Bradgate and ACM

Case Study	Existing Production Scheduling Configuration	Observations	Proposed strategies
Bradgate	Accumulated order list due to logistic constraints	High variety induced in system bottleneck	Break up of job list by removing the constraint
ACM	No measurement of the COs meeting deadlines	High variety induced in system bottleneck	Measuring and monitoring average ΣP^3C values in order to achieve higher responsiveness to meet *due dates* of COs.

During the course of this research, static models were developed using MS Visio® software and dynamic models were developed using simulation software tools including Arena®, Simul8®, Plant Simulation® and iThink®/Stella®. Table 14 (as presented in Section 5.4.3) provided a comparison of the simulation tools used in this research for dynamic modelling. The understandings gained and resultant comparison drawn between these modelling tools lead to use of appropriate simulation tools in each case. The rationale for the use of different simulation software tools to undertake various case studies was:

- Changing simulation model requirements on case to case basis;
- Easier incorporation of KPIs into simulation models;
- Capabilities of the researcher and or the case study company modeller(s) to successfully model the required configurations;
- Acceptance of simulation model results by the peers;
- Availability of the software tool to the researcher and or the case study company for current research and future use.

The author and his research colleagues have successfully utilised these software tool sets in other case studies and virtual configurations prior to this research. Such interfaces enabled this author to undertake different case studies during this research so that to: (1) capture requirements data; (2) input data into models; (3) create simulation model reconfigurations to meet various specified needs while using different simulation software tools; (4) conduct various experiments based upon different virtual configurations; (5) collect results; and (6) conduct analysis of results.

The undertaken three case studies were different in context, the type of data used in them, respective variables used, choice of simulation software and case study results were different. However, it was intended to demonstrate that the application of the proposed approach was independent of the choice of simulation software. Hence, the use of three different simulation software tools provided a test of independence of the IMA/EIMA from any particular piece of software making it adaptable in at least three (or possibly more) industrial cases. Due to the nature of different businesses and specific problem domains and respective KPIs, it was difficult to compare results. The use of different simulation software tools has also resulted in an additional variability which made the comparison of case studies' results more difficult. However, the results of three case studies are partially comparable in terms of their improved time related KPIs e.g., lead time reduction in Ford and Bradgate cases and use of P^3C in ACM case to measure and monitor responsiveness.

In addition to their case specific technical requirements, Arena® was chosen in Ford case partly because the Ford modellers at other plants were already using this software tool and it would be easier for the PD Factory to establish a link with them in future. Also, the onsite engineers were familiar with this piece of software. Simul8® was chosen in Bradgate case partly because researchers (from MSI Research Institute and CECA at Loughborough University) working on Bradgate case were also using Simul8® so it was easier to discuss model inputs and results with them. Plant Simulation® was only used for advanced levels of the ACM case study during this research, i.e. where advanced controls were needed for simulation model development purposes. The choice of Plant Simulation® in this case was intended to gain more controls during simulation model creation process.

Data capturing and model VVA

While undertaking case studies, as data capturing, its representation and useful interpretation was important, the model VVA was also of significance in achieving credible results. During this research, two types of data was used: actual and simulated. The actual data was captured from the industry and accredited by the knowledge experts. The simulated data was interpreted set of information based on actual data. The data capturing methods, types and model VVA are discussed during individual case studies. With the use of SM, the actual data for TO-BE reconfigurations is validated during formal and informal discussion sessions between author and the industrial experts. Additionally, a set of validity tests for the simulation models were also conducted to validate and analyse the actual and simulated data. Table 34 summarises data types and VVA of models during case studies.

Table 34: Cross-case comparison of data types and model VVA

Case study model data types		'AS-IS' models		'TO-BE 'models		Model VVA
		Actual data	**Simulated data**	**Actual data**	**Simulated data**	
Ford case	**EM**	❑ Semi structured interviews with Ford experts; ❑ MSI/SEIC researchers	---	---	---	The verification of models was done by the author. Validation and accreditation of models was done by expert consultation which includes peers from the particular company and researchers from MSI Research Institute and CECA at Loughborough University.
	SM	❑ Author's observations (including KPI data related to time, resource load and cost); ❑ MSI Researchers	❑ Resource load based upon AS-IS resource sets and time assigned to processes with percentage availability of resource; ❑ Cost estimation based on percentage availability of resource	❑ Author's observations; ❑ MSI researchers	❑ Resource load based upon TO-BE resource sets and new time assigned to processes with percentage availability of resource; ❑ Cost estimation based on percentage availability of resource	
Bradgate case	**EM**	❑ Data collected from company COs and POs and maintained in excel database; ❑ Author's observations; ❑ Semi structured interviews with Bradgate experts	---	---	---	
	CLM	❑ The author's observations; ❑ Semi structured interviews with Bradgate experts and MSI/CECA researchers.	---	---	---	
	SM	❑ Data collected from company COs and POs and maintained in excel database; ❑ Author's observations (on process flows, product classifications, time and resource data); ❑ MSI/CECA researchers	Data related to AS-IS resource utilisation, scheduling rules and product classifications.	❑ Data collected from company COs and POs and maintained in excel database; ❑ Author's observations; ❑ Semi structured interviews with Bradgate experts; ❑ MSI/CECA researchers	Data related to TO-BE processing stations, times, work flows, resource utilisation, scheduling rules and product classifications.	

Case study model data types		'AS-IS' models		'TO-BE 'models		Model VVA
		Actual data	Simulated data	Actual data	Simulated data	
ACM case	EM	❑ Data collected from company COs and POs and maintained in excel database; ❑ Author's observations; ❑ Semi structured interviews with ACM experts	---	❑ Author's observations; ❑ Semi structured interviews with ACM experts; ❑ Data for interrelationships in TO-BE configurations and capacity plan (capability matrix)	Data for interrelationships in TO-BE configurations and capacity plan (capability matrix)	The verification of models was done by the author. Expert consultation in different cases includes peers from the particular company and researchers from MSI Research Institute and CECA at Loughborough University.
	CLM	❑ Data, collected from company COs and POs and maintained in excel database; ❑ Data was also used for P^3C analysis; ❑ The author's observations; ❑ Semi structured interviews with ACM experts and MSI/CECA researchers during static CLM stage and its dynamic model in iThink®/Stella®.	---	---	---	
	SM	❑ Data collected from company COs and POs and maintained in excel database; ❑ Author's observations (on process flows, product classifications, time and resource data); ❑ MSI/CECA researchers.	Data related to AS-IS resource utilisation, scheduling rules and product classifications.	❑ Data collected from company COs and POs and maintained in excel database; ❑ Author's observations; ❑ Semi structured interviews with ACM experts; ❑ MSI/CECA researchers.	Data related to TO-BE processing times, resource utilisation, scheduling rules and product classifications.	

Notes: * *Actual data:* Captured from industry and accredited by knowledge experts;
** *Simulated data:* Interpreted set of information based on actual data.

The application of the EIMA in the three main case studies namely Ford, Bradgate, ACM has shown their conceptual link to the CIMOSA Modelling as shown in Figure 102. A detailed discussion was made earlier in this thesis (in Sections 4.6 and 7.2) regarding CIMOSA and its different layers. The EIMA helped design the MEs by using CIMOSA modelling concepts.

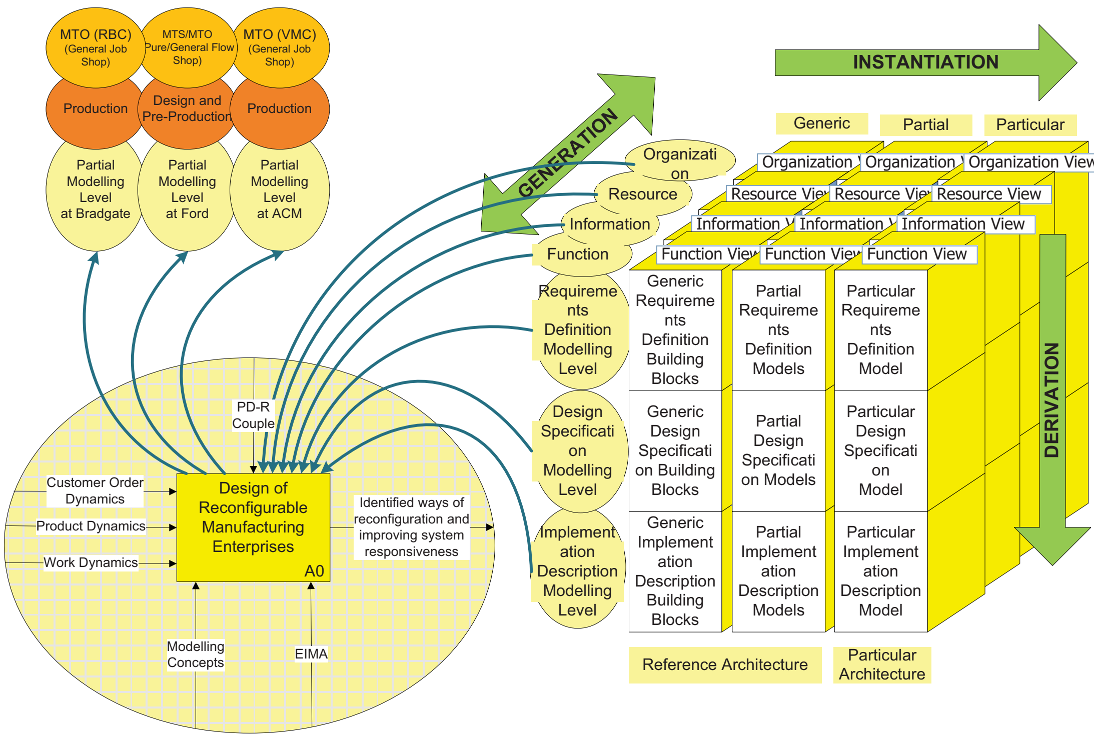


Figure 102: The CIMOSA link to EIMA and its industrial applications

11.4 Research aim and objectives: "achieved versus planned"

The research aim and objectives were set before undertaking this substantial piece of work as outlined in section 3.4. The planned research objectives are reviewed and analysed in the following to identify 'achievement versus planned' for each research task.

Research objective 1

In this research objective, it was planned to identify the research gap in literature on manufacturing system philosophies and emerging paradigms including lean, agile, mass customisation, reconfigurable manufacturing, PPC, and EMI. A literature review was carried on manufacturing system philosophies and emerging paradigms including lean, agile, mass customisation, reconfigurable manufacturing and PPC. This literature review is presented in chapter 2. The published approaches to EMI were identified and documented through detailed and specific literature review in chapter 4.

Research objective 2

In this objective, it was planned to develop a new integrated modelling approach using ISO standardised enterprise integration and modelling approaches. A new integrated modelling approach was proposed in chapter 5 which based upon detailed literature findings; along with methods and toolsets to realise it.

Research objective 3

It was planned to industrially apply and carry out proof of concept testing of the new integrated modelling approach. Exploratory case study work was carried out with an automotive industrial collaborator to model their pre-production control system. Early modelling was partly based upon data captured from the exploratory case from this automotive industry. An enhanced ISO standardised CIMOSA modelling framework and public domain process modelling tools were deployed for the purpose. The case study is presented in chapter 6.

Research objective 4

It was planned to enhance the IMA on the basis of objective 3. Structure enhancements were made to the earlier modelling activities and components of the enhanced IMA were created. The earlier modelling concepts were enriched and an EIMA was proposed in chapter 7.

Research objective 5

Industrial application of the enhanced integrated modelling approach in two different SMEs was planned in this objective. The EIMA was partially tested in two different SME cases with industrial collaborators in furniture and composite bearing manufacturing sectors. The case studies and their results are presented in chapters 8, 9 and 10.

Research objective 6

Evaluation of the proposed EIMA was planned in this objective. The developed EIMA was evaluated on the basis of its partial testing in three different industrial cases. Cross-case comparisons are made in chapter 11.

Research objectives not achieved

The presented approach has been tested in three industrial cases including automotive, furniture and composite manufacturing sectors. It still needs to be tested in different other cases for example aerospace sector to fully mature. The results are limited but not the approach.

Table 35 presents a summary of the planned and achieved research objectives.

Table 35: Research objectives: "achieved vs. planned"

Research objective No.	Planned research objectives	Achieved research objectives	Assumptions	Research objectives not achieved
1	Identification of the research gap in literature on manufacturing system philosophies and emerging paradigms including lean, agile, mass customisation, reconfigurable manufacturing, PPC, and EMI.	A literature review was carried on manufacturing system philosophies and emerging paradigms including lean, agile, mass customisation, reconfigurable manufacturing and PPC. The published approaches to EMI were identified and documented through detailed and specific literature review.	Case specific assumptions applied.	The presented approach has been tested in three industrial cases including automotive, furniture and composite manufacturing sectors. The approach still needs testing in additional industrial cases for example aerospace and other sectors to fully mature. The results are limited but not the approach.
2	Development of a new integrated modelling approach using ISO standardised enterprise integration and modelling approaches.	A new integrated modelling approach was proposed based upon detailed literature findings along with methods and toolsets to realise it.		
3	Industrial application and proof of concept testing of the new integrated modelling approach.	Exploratory case study work was carried out with an automotive industrial collaborator to model their pre-production control system. Early modelling was partly based upon data captured from the exploratory case from this automotive industry. An enhanced ISO standardised CIMOSA modelling framework and public domain process modelling tools were deployed .		
4	Enhancement of the initial IMA on the basis of objective 3.	Structure enhancements were made to the earlier modelling activities and components of an enhanced IMA were created. The earlier modelling concepts were enriched and an EIMA was proposed.		
5	Industrial application of the enhanced integrated modelling approach in two different SMEs.	The enhanced integrated modelling approach was partially tested in two different SME cases with industrial collaborators in furniture and composite bearing manufacturing sectors.		
6	Evaluation of the proposed EIMA.	The developed EIMA was evaluated on the basis of its partial testing in three different industrial cases.		

11.5 Future scope of EIMA based model reconfigurations

The EIMA was case tested through an integrated use of EM, CLM and SM configurations when considering a limited number of PPC strategies and solutions. However the usefulness of the EIMA in the cases provided an opportunity to generalise understandings about the application of the approach in respect of the following configurations: (a) MTO (VMC); (b) MTO (RBC); (c) ETO; (d) MTS; (e) General Job Shop; (f) General Flow Shop; and (g) Pure Flow Shop. Table 36 presents a future scope of EIMA based model reconfigurations. Some of the candidate PPC solution strategies have been partially tested (for example ConWIP and Kanban) in the case study model reconfigurations. The rest of the strategies still need testing in industrial applications. However, based upon the knowledge and experience gained through previous EIMA applications, it is expected that the strategies outlined in Table 36 shall be usefully applicable. It is also hoped that the model reconfigurations based upon these strategies will bring benefits to the industry by using the proposed approach.

The application and generalisation of the EIMA in three cases lead to the addition of knowledge to the following EMI reference architectures and general literature: (a) EMI; (b) CIMOSA; (c) CIM; (d) ME reconfiguration; (e) mass customisation; and (f) agile and responsive manufacturing. This generalisation of the proposed approach is elaborated by the EIMA R-Funnel shown in Figure 103. The R-Funnel is a left-to-right funnel that opens avenues of knowledge starting from the method, its industrial applications, generalisation and its additions to the literature.

Table 36: Future scope of EIMA based model reconfigurations

Candidate PPC Solution Strategies	**Core PPC 'Philosophy'**	**Push / Pull**	**Work configuration suitability**	**CODP**	**Filter / Emphasis**
Con***WIP***	HCA / HPP[28]	Hybrid	Pure Flow Shop / General Flow Shop	MTS / MTO (RBC[29])	WIP regulation
Kanban	JIT	Pull	Pure Flow Shop	MTS	Throughput control
MRP		Push	Pure Flow Shop / General Flow Shop / General Job Shop		
MRP II		Push	Pure Flow Shop / General Flow Shop / General Job Shop		
ERP		Push	Pure Flow Shop / General Flow Shop / General Job Shop	MTS / MTO (RBC) / MTO (VMC)	
TOC[30]			Pure Flow Shop / General Flow Shop / General Job Shop	MTS / MTO (RBC) / MTO (VMC)	
WLC[31]			General Flow Shop / General Job Shop	MTO (RBC) / MTO (VMC[32])	
POLCA[33]	QRM[34]	Hybrid	General Flow shop	MTO (RBC)	Resource utilization; Lead time control; Product cost control; DD control; Scrap and rework control

[28] Hierarchical Production Planning

[29] Repeat Business Customizers

[30] Theory of Constraints

[31] Workload Control

[32] Versatile Manufacturing Companies

[33] Paired cell Overlapping Loops of Cards with Authorization

[34] Quick Response Manufacturing

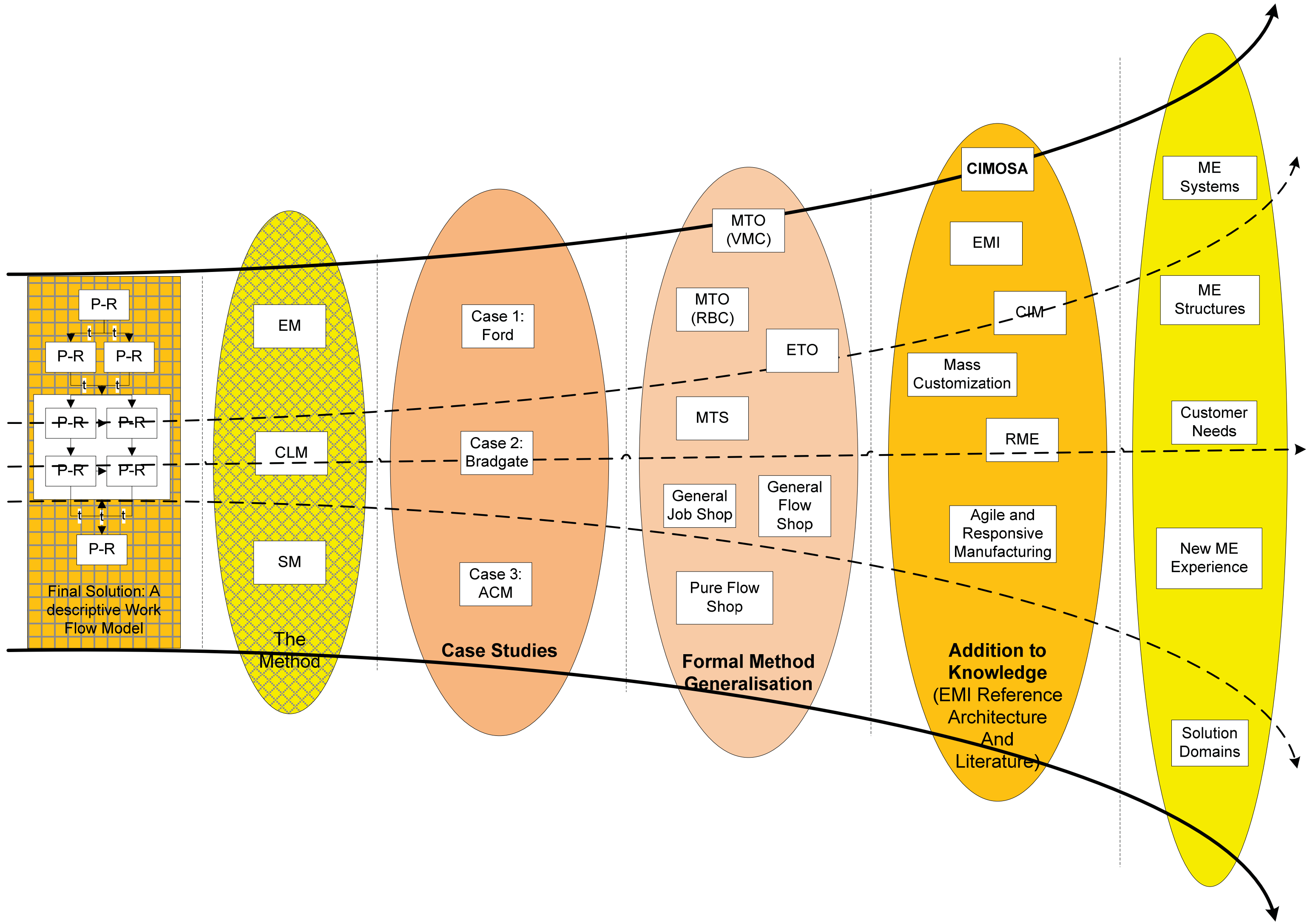
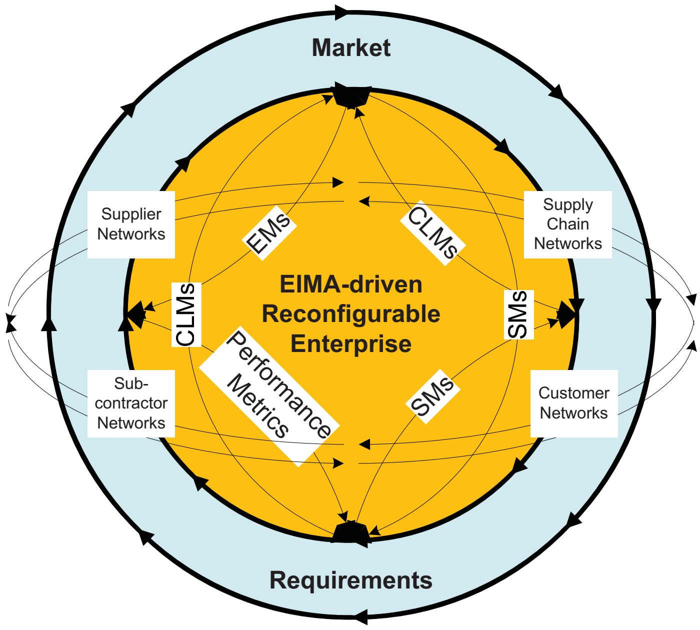


Figure 103: The EIMA R-Funnel

11.6 EIMA-driven reconfigurable enterprise

In today's hostile market driven world, MEs need to be reconfigurable and so they must carefully choose and adopt appropriate methods as part of their organisational systems. A reconfigurable and hence responsive enterprise needs to be focussed on changing market needs by applying methods that facilitate sufficient flexibility but also promote sufficient productivity. The proposed EIMA in this thesis makes use of previously proven production management and control methods as an opportunity mix. Such a production method mix is set to be modelled and virtually tested using respective models of the reality in context of the ME and its business opportunities and threats. Here focus is on a solution space where the ME can switch according to its changing needs, as markets drive it.

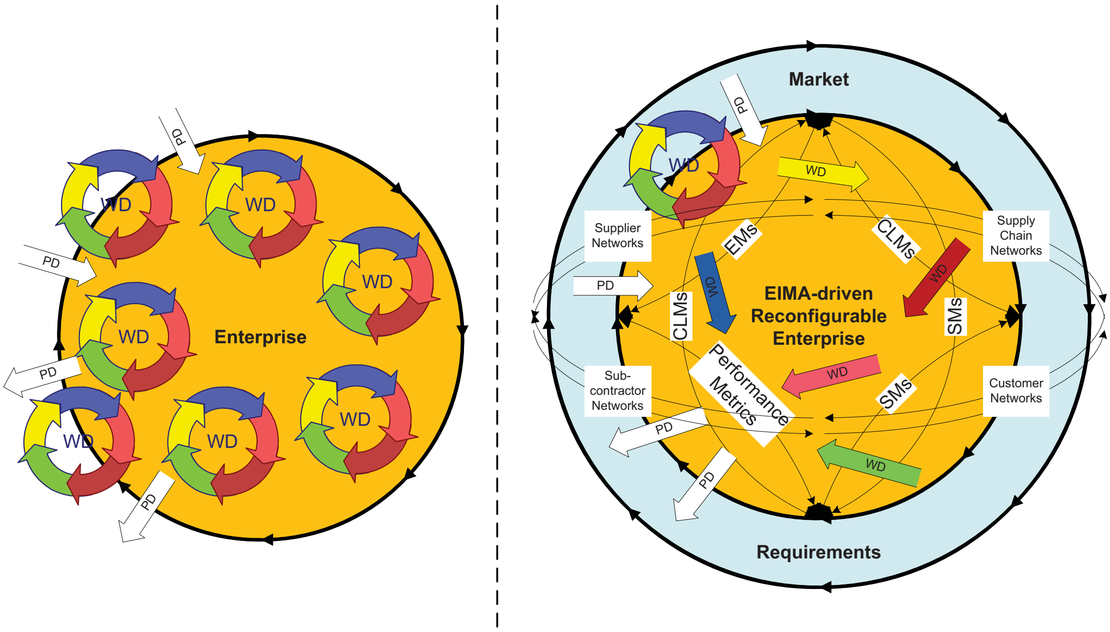
An EIMA-driven reconfigurable enterprise works in the presence of market driven forces including its supply chain network of specific supplier networks, sub-contractor networks and probably most importantly customer networks. Figure 104 elaborates the idea of the EIMA-driven reconfigurable enterprise focussed on market requirements and related customer and supply chain networks. The proposed EIMA includes use of enterprise models, causal loop models, simulation models and decisions made on the basis of enumerated KPIs. Change into TO-BE models conceptually enable the ME to be treated as being reconfigurable and responsive to market needs thus keeping it meets its intended purposes. The present thesis is focussed on internal ME processes and interactions with customers. There is still a scope for future work on remaining aspects of supply-chain networks and their impacts upon the ME's internal supply-chains.



Key:
EIMA: Enhanced Integrated Modelling Approach
EM: Enterprise Modelling
CLM: Causal Loop Modelling
SM: Simulation Modelling

Figure 104: The EIMA-driven reconfigurable enterprise

An ordinary ME may not cope with the changing demands of the market due to its inflexible organisational system structures. Such a lack of change-capability may lead to a state where a given ME cannot smooth out the product dynamics imposed upon it; hence it will fail to smoothing out demands into a suitable work dynamic which can reasonably be used as input to its Pr-Re systems. An EIMA-based reconfigurable enterprise should match its reconfigurable to market demands, especially customer demands, hence being able to maintain smooth dynamics used as input to its internal production systems. Such a so-called smooth product dynamics can be achieved with the smoothing out of work dynamic fed into Pr-Re couples. This should lead to satisfactory degree of synchronisation between the internal Pr-Re systems and the ME's external networks, including its customers. The demands of external networks and organisational internal systems, should therefore be continually monitored and changes implemented in a response to such demands as soon as possible. Figure 105 compares an inflexible enterprise with an EIMA-driven reconfigurable enterprise showing the smoothing out phenomenon of the later as an advantage for a potential success.



Key:
EIMA: Enhanced Integrated Modelling Approach
EM: Enterprise Modelling
CLM: Causal Loop Modelling
SM: Simulation Modelling
PD: Product Dynamics
WD: Work Dynamics

Figure 105: Smoothing of WD in EIMA-driven reconfigurable enterprise

11.7 Reflections and conclusions

Figure 106 shows evolution and industrial application of IMA to EIMA to reconfiguring MEs realised during this study, and its subsequent development into EIMA-2. The IMA was conceived from general and specific literature review (see Chapters 2, 3, 4 and 5). After the initial application of IMA in Ford (Chapter 6), IMA was extended to form an EIMA (Chapter 7). EIMA was then applied in both Bradgate (Chapter 8) and ACM cases (Chapters 9 and 10). The findings of three case studies and their cross-comparisons are presented in this chapter. On the basis of such findings, EIMA-2 (a future enhancement of EIMA) is conceived and proposed which is in transition phase and has not yet been fully tested. EIMA-2 shall include additional steps to EIMA based on workflow modelling.

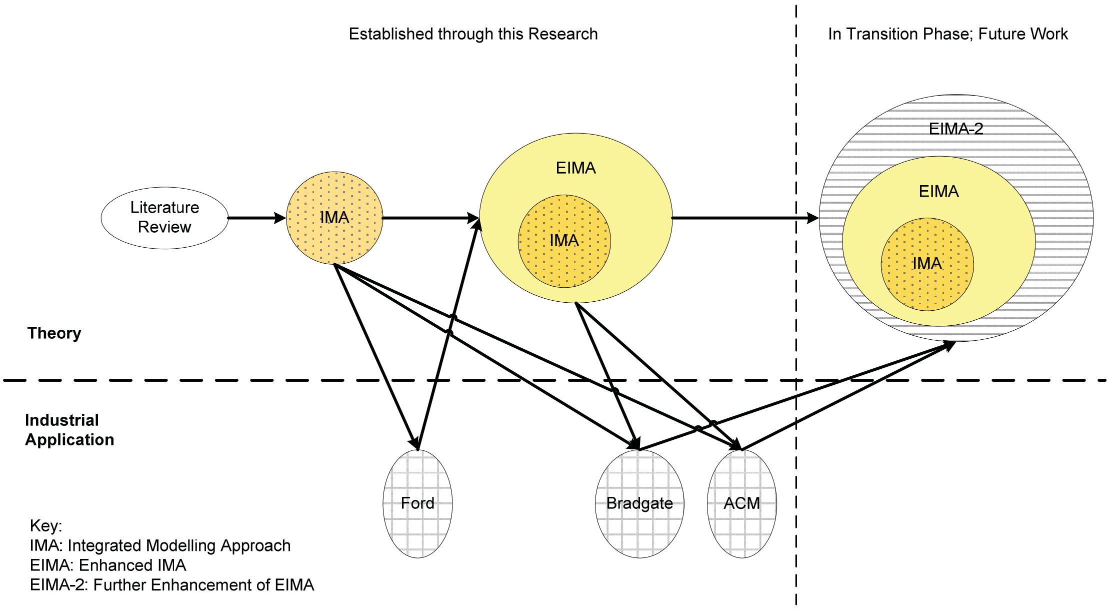


Figure 106: Evolution and industrial application of the IMA/EIMA to reconfiguring MEs

Table 37 compares the main inherent capabilities of different stages of the proposed integrated modelling approach: namely IMA; EIMA and EIMA-2.

Table 37: Main capabilities of the proposed approach

IMA (Established)	EIMA (Established)	EIMA-2 (In transition; future work
1) Structured data capture 2) Enterprise modelling 3) Simulation modelling	1) Structured data capture 2) Enterprise modelling 3) Causal loop modelling 4) Simulation modelling	1) Structured data capture 2) Enterprise modelling 3) Causal loop modelling 4) Simulation modelling 5) (Possible inclusion of) Work flow modelling

Chapter 12

Conclusions and Contributions to Knowledge

12.1 Overview of the thesis

This chapter will critically review the research presented in this thesis by: (1) concluding in terms of research objectives, assumptions and achievements; (2) contributions to knowledge; and (3) research weaknesses. Future directions for research are also discussed at the end of this chapter.

12.2 Research conclusions

The research on the analytical design and realisation of EIMA to reconfiguring MEs is presented in this thesis. The 'system' level design and realization of MEs was considered during conception and evolution of the proposed approach and via industrial testing in three different cases. The case studies were further focussed on conceptual design of pre-production management and PPC selection especially as a means to improve system responsiveness. The case studies presented new ways of addressing challenges in the design of MEs especially their PPC systems and illustrated how EIMA could be beneficial in supporting decision making. The devised research approach to analytically designing ME received positive feedback from the stakeholders during three case studies. The undertaken approach demonstrated its usefulness in terms of its benefits and potential to design reconfiguration of MEs for example in reducing lead times, costs and resource loads.

The planned research objectives are reviewed and analysed to identify 'achievement versus planned' for each research task. In research objective 1, it was planned to identify the research gap in literature on manufacturing system philosophies and emerging paradigms including lean, agile, mass customisation, reconfigurable manufacturing, PPC, and EMI. A literature review was carried on manufacturing system philosophies and emerging paradigms including lean, agile, mass customisation, reconfigurable manufacturing and PPC. This literature review is presented in chapter 2. The published approaches to EMI were identified and documented through detailed and specific literature review in chapter 4. In objective 2, it was planned to develop a new integrated modelling approach using ISO standardised enterprise integration and modelling approaches. A new integrated modelling approach was proposed in chapter 5 which based upon detailed literature findings; along with methods and toolsets to realise it. In objective 3, it was planned to industrially apply and carry out proof of concept testing of the new integrated modelling approach. Exploratory case study work was carried out with an automotive industrial collaborator to model their pre-production control system. Early modelling was partly based upon data captured from the exploratory case from this automotive industry. An enhanced ISO standardised CIMOSA modelling framework and public domain process modelling tools were deployed for the purpose. The case study is presented in chapter 6. In objective 4, it was planned to enhance the IMA on the basis of objective 3. Structure enhancements were made to the earlier modelling activities and components of the enhanced IMA were created. The earlier modelling concepts were enriched and an EIMA was proposed in chapter 7. Industrial application of the enhanced integrated modelling approach in two different SMEs was planned in objective 5. The EIMA was partially tested in two different SME cases with industrial collaborators in furniture and composite bearing manufacturing sectors. The case studies and their results are presented in chapters 8, 9 and 10. In objective 6, evaluation of the proposed EIMA was planned. The developed EIMA was evaluated on the basis of its partial testing in three different industrial cases. Cross-case comparisons are made in chapter 11. The presented approach has been tested in three industrial cases including automotive, furniture and composite manufacturing sectors. It still needs to be tested in different other cases for example aerospace sector to fully mature. The results are limited but not the approach. Table 38 critically reviews and concludes the undertaken research showing the research achievements against the planned research objectives, assumptions and the objectives not achieved during the course of this research.

Table 38: The research conclusions

<table>
<tr><th>Research objective No.</th><th>Planned research objectives</th><th>Achieved research objectives</th><th>Assumptions and research objectives not achieved</th></tr>
<tr><td>1</td><td>Identification of research gap in literature of manufacturing and EMI.</td><td>Identified research gap in literature for advanced EMI approaches and their industrial applications.</td><td rowspan="6">Assumptions:
Case specific assumptions applied.

Research objectives not achieved:
The presented approach has been tested in three industrial cases including automotive, furniture and composite manufacturing sectors. The approach still needs testing in additional industrial cases for example aerospace and other sectors to fully mature. The results are limited but not the approach.</td></tr>
<tr><td>2</td><td>Development of a new integrated modelling approach.</td><td>❑ Developed the IMA to reconfiguring MEs;
❑ Developed the MUNE.</td></tr>
<tr><td>3</td><td>Industrial application and proof of concept testing of the new integrated modelling approach.</td><td>Successfully tested IMA in an automotive case related to its pre-production management with following main achievements:
❑ Reduced lead time;
❑ Reduced cost; and
❑ Reduced resource load.</td></tr>
<tr><td>4</td><td>Enhancement of the IMA on the basis of objectives 2 and 3.</td><td>❑ Structure enhancements were made to enrich the earlier modelling activities and components of an enhanced IMA to the reconfiguration of MEs were proposed and created;
❑ Development of E-MUNE</td></tr>
<tr><td>5</td><td>Industrial application of the enhanced integrated modelling approach in two different SMEs.</td><td>The EIMA was partially tested in furniture and composite bearing manufacturing cases related to their PPC with following main achievements:
❑ Reduced lead times and related costs;
❑ Identification of P^3C in composite bearing manufacture case.</td></tr>
<tr><td>6</td><td>Evaluation of the proposed EIMA.</td><td>Cross-case industrial comparison evaluated the proposed IMA/EIMA and found benefits in its use.</td></tr>
</table>

12.3 Contributions to knowledge

The undertaken research has made significant contributions to knowledge in both academic and industrial domains. Main contributions to knowledge are presented in the following:

1. ***Development of IMA/EIMA:*** The development of IMA to reconfiguring MEs was initially based upon integrated use of EM and SM. After assessment of IMA on the basis of its industrial testing, it was enhanced to EIMA so that to introduce an additional CLM stage. The integrated use of these three

modelling stages was documented using standardised IDEF0 formalisms. The IMA/EIMA was based upon the use of ISO standardised CIMOSA concepts which are also part of GERAM. The development of IMA/EIMA is significant contribution to knowledge in terms of its benefits for example:

a. Structured way of modelling static and dynamic aspects of MEs with induced change capability and facilitation for improved decision making;

b. Structured data capturing during EM stage where the enterprise models provided a 'knowledge repository' in the form of a graphical 'process oriented structure'.;

c. Introduction of CLM stage providing rightful definition of objectives, broader situational analysis, more focussed way of looking into global objectives while considering side effects;

d. Designing a set of experiments to deploy the simulation model to address issues of concern to the organisation being studied;

e. Identification and improved design of coherent set of computer executable simulation experiments;

f. Structured way of SM analysis based upon AS-IS and TO-BE model reconfiguration KPI results;

g. Structured use of VVA stages enhancing credibility of models and hence their results;

h. Providing structured modelling output by providing additional optional stages to the initial IMA that will facilitate a set of production policy mix for better decision making;

i. An advance in the integrated modelling of MEs in terms of its integrated approach and reusable components leading to practical implementation of the approach;

j. Ability to extend reuse-able integrated ME models in a stepwise, flexible, and extendable way.

k. Reduced time and effort needed to reconfigure MEs in the event of changing requirements and conditions due to availability of knowledge in the form of reuse-able integrated models;

l. Reduced system complexity through improved system decomposition;

m. Ease of reengineering process in MEs due to availability and reuse of existing models.

2. ***Industrial application of IMA/EIMA:*** The IMA/EIMA was applied in three industrial case studies. This industrial application resulted in better ways of modelling MEs and improvement suggestions for their production systems especially related to their PPC design. The industrial case studies resulted in specific contributions to knowledge as presented below:

   a. ***Ford (automotive manufacturing) case:*** The application of IMA in Ford case study looked into a pre-production release problem in a MTS configuration and has resulted in a way forward to conceptually designing and computer executing an improved MTO production control configuration. During this case study, development of enterprise models helped to understand the processes, resources and their related interrelationships. The enterprise models were designed to facilitate knowledge capture, in the form of a sequential flow of case-specific processing requirements and information needs, and an explicit definition of interactions between the process being modelled in detail and the specific environment in which that process must operate. The simulation models of the processes and resources, involved in the Ford case, quantified dynamic aspects in terms of the behaviours of a set of KPIs. This facilitated decision making on new policy changes. The Ford case has shown benefits in terms of time, resource load and cost parameters of the project based upon comparisons of AS-IS and TO-BE configurations. The TO-BE model results have shown significant reductions i.e., 15.15% reduction in project / lead time, 20.60% reduction in resource load, 9.77% reduction in cost of 'Engineers' resource and 5.35% reduction in total project cost. Hence, this exercise proved useful learning resource for further development of the IMA.

b. ***Bradgate (furniture manufacturing) case:*** The application of EIMA in Bradgate case helped understand complex planning and control configurations needed for more than 300 product types. During this case study, the EIMA model configurations were focussed on processes that span the production and management departments. The introduction of CLM stage during this case study helped in better understanding of impacts of change in complex manufacturing systems and therefore in designing better SM experiments. The application of EIMA in Bradgate demonstrated its significant role to enable decision making in a responsive ME based upon virtual reconfigurations. This is true with respect to the engineering of PPC systems in MEs being representative of manufacturing responsiveness. Models created for Bradgate case aided PPC strategy design and resultantly manufacturing responsiveness decision making in Bradgate. The process also facilitated classification of products according to their commonalities in associated production processes and dimensional features

c. ***ACM (composite bearing manufacturing) case:*** Sets of current and future enterprise, causal loop and simulation model reconfigurations created during application of the EIMA in ACM proved useful contribution to knowledge in:

    i. Understanding the complex AS-IS situations of the ACM business including its production, technical and management departments having complex planning and control configurations for more than 100 product types.;

    ii. Providing useful insights to the *ACM Production System* and helping in decision making during analytical ME design;

iii. Classifying products according to their commonalities in associated production processes and dimensional features;

iv. Analytically designing PPC system for ACM;

v. Assessing current responsiveness of the production system at a given point in time through use of P^3C and improved model reconfigurations.

vi. Suggesting that the CLM of the *ACM Production System* held possible potential benefit to ACM from PO data analysis including measurement of P^3C to find responsiveness of the AS-IS PPC process. The detailed analysis helped to understand reasons for lateness and has a potential to be applied beyond this.

vii. Creating a capacity plan (capability matrix) and adding estimated times for estimated amounts of material removal for example. However it should be understood that such an arrangement could only contribute partially to production problem solving because of other factors involved for example the real operational conditions of machine, operator decisions when setting feeds and speeds of CNC machines, etc.

viii. Developing TO-BE activity diagrams as part of the EIMA at customer and production order levels based upon modelling results and discussions held regarding *ACM Production System*. The activity diagrams were intended to serve the purpose of explicitly describing possible improvements to PPC responsiveness and future virtual reconfigurations.

3. ***Identification and industrial application of P^3C:*** During industrial application of EIMA in composite bearing manufacturing case study, a novel KPI namely P^3C was identified and demonstrated benefits during its use. This KPI proved useful in defining current levels of responsiveness when redesigning the ME. It is believed that it is the first time that P^3C has been defined and case tested in a manufacturing / production environment. The identification and industrial

application of the P^3C is significant in virtually reconfiguring the ME while contributing to knowledge in following ways:

a. The CLM of the *ACM Production System* demonstrated benefits from PO data analysis including measurement of P^3C to find responsiveness of the AS-IS PPC process. The detailed analysis helped to understand reasons for lateness.

b. Measuring and monitoring the P^3C of the AS-IS ACM PPC system proved useful and it is likely to lead to improvements in the performance of the ACM PPC process and hence to improve the responsiveness to fulfil the CO *due dates*. The P^3C values can also be used for possible future responsiveness monitoring purposes.

c. The analysis of ΣP^3C levels of different departments of *ACM Production System* helped in finding causal relationships of different production issues.

d. P^3C is also aligned with few of ISO 9000:2000 clauses.

   i. Clause 7.1 of ISO 9000:2000 standard relates to *Planning for Product Realization*. P^3C provides a planning opportunity for product realization, hence also fulfilling the respective ISO clause in addition to the present justifications.

   ii. Clause 8.2 of the ISO 9000:2000 standard relates to *Measurement and Monitoring*. Measuring and monitoring of P^3C for PO realization is also aligned to demonstrate production related measuring and monitoring of the respective ISO clause.

   iii. Clause 8.5 of the ISO 9000:2000 standard relates to *Corrective and Preventive Actions*. Based upon P^3C analysis, reasons for exceptions to complete planned POs (rescheduling) may be traced, investigated, corrected and prevented by removing the causes which will also cover this ISO clause.

4. ***Development of MUNE/E-MUNE:*** The development of the IMA facilitated to develop MUNE. Subsequently, the EIMA helped to develop E-MUNE which is an enabler of reconfigurability and responsiveness. The MUNE/E-MUNE is significant contribution to knowledge in terms of its:

    a. modelling views including enterprise modelling, causal loop modelling, simulation modelling, product dynamics, customer order decoupling point, work dynamic (Pr-Re couple), production policy mix, solution space, performance metrics and enhanced data capturing;

    b. modelling levels (generic, partial and particular); and

    c. production management levels.

12.4 Research weakness

The case testing of the IMA/EIMA in three different industries exhibited involvement of the real stakeholders in this research study. The involvement of the stakeholders was however limited. The author was involved in the Ford case study during the initial phase, in the Bradgate case during initial and middle phases, and in the ACM case during middle and near final phases. During all these phases, the stakeholders gave feedback on the research work while verifying, validating and accrediting the static and dynamic models. This research was conducted for the benefit of the stakeholders and even though it was successfully applied in three case studies, it has certain weaknesses and risks. The following identified weaknesses may hinder the development and wider application of this research:

1. ***Partial industrial testing:*** The EIMA was partially tested in three different case studies. Therefore, the results of the analytical ME design in different environments may prove to be undesired.

c) ***Limited availability of data:*** There were limitations to data availability due to which the results might be limited but not the approach which has shown its benefits. For instance in the ACM case the P^3C results were based on PO data available only for three months. Had the provided PO data been available for a greater length of time, the results would have proven more useful. Here it is recommended that at least one full year of PO data be gathered and analysed in future, so that all troughs and crests become visible especially those created seasonally or due to economic factors. Also, no data was available related to variations in the complexity level of jobs involved which could significantly affect *on-time* completion of POs. Therefore, further PO data collection is required in order to understand and predict realistic CO and PO dynamics and their impact on the responsiveness of the *ACM Production System*.

12.5 Scope of future research and recommendations

The contribution to knowledge from the undertaken research is reported in this chapter. Based upon its demonstrated benefits, the following further research is recommended.

1. ***Further application of EIMA:*** Further application of EIMA in additional case studies while concentrating on various PPC concepts and configurations may be useful to realise the potential benefits of the proposed approach. The approach may also be implemented in different industrial segments for example cash flow management.

2. ***Industrial testing with increased availability of data:*** The proposed approach may be industrially tested with increased data availability. Data to be used should cover seasonal troughs and crests to give full results.

3. ***Extension of EIMA to workflow modelling:*** Future work on Workflow Modelling in order to look for possible interplay between EM, CLM, SM and workflow modelling may prove an enhancement and extension to the EIMA. It may contribute towards the implementation layer of EIMA to reconfiguring MEs. The author's initial work on extending EIMA to workflow modelling (named as EIMA-2) in the Bradgate case is included as Appendix F.

4. ***Wireless integrated manufacturing system (WIMS):*** Technology can be developed that facilitates the updating of integrated models so that distributed decision making can be enabled (Masood 2006a). The updating mechanism is an important aspect in making models live and responsive to the needs of MEs. In order to take responsive decisions in MEs it is necessary to develop means of updating distributed model fragments (i.e., so that updated model elements can be available at near point of use by relevant ME personnel),

where possible by using existing and emerging IT techniques (Masood 2006a). Application of the EIMA with use of emerging technologies for updating mechanisms may prove a ground breaking idea in the reconfiguration of MEs. Two important emerging technologies that may be used are: (a) wireless/mobile technologies (including but not limited to the use of PDA[35]); and (b) advanced forms of RFID[36]. The author first conceived the *WIMS (Wireless Integrated Manufacturing System)* idea to use emerging technologies for updating models during Feb/March 2006 and presented it to Prof Richard Weston in the form of an initial concept report (Masood 2006b). The author further developed the *WIMS* idea in addition to the main aim and objectives of the research until his first year PhD viva conducted by Dr Andrew West[37] in June 2006 (Masood 2006a). It was then decided to first apply EIMA in industry and then continue further work on *WIMS* idea. Now that the EIMA has been successfully applied in three main case studies, it deems fit to further carry on the postponed *WIMS* work which may bring even greater industrial benefits in terms of reconfigurability and responsiveness. Use of such technologies may also prove useful in updating live models (or their identified segments) that may possibly be part of a broader model driven manufacturing execution system. Such a manufacturing execution system may take signals from distributed control system of MEs. In this regard, future work may include: (a) development of high technology applications for mobile devices; and (b) their testing and application in industrial environments.

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[36] Radio Frequency Identification

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Weston, R.H., R. Zhen, J.O. Ajaefobi, A. Rahimifard, A. Guerrero, T. Masood, B. Wahid and C. Ding (2007). Simulating dynamic behaviours in manufacturing organisations. International Conference on Industrial Engineering & Systems Management (IESM 2007), May 30 - June 2, Beijing.

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Appendix A: List of Author's Selected Publications during PhD

A.1 Journal Papers

1. **Masood, T.** and R.H. Weston (2010). "An integrated modelling approach in support of next generation reconfigurable manufacturing systems." International Journal of Computer Aided Engineering and Technology: Accepted July 2009, In press. URL: http://www.inderscience.com/browse/index.php?journalCODE=ijcaet

2. **Masood, T.**, R.H. Weston and A. Rahimifard (2010). "A computer integrated unified modelling approach to responsive manufacturing." International Journal of Industrial and Systems Engineering 5(3): 287-312, March. DOI: 10.1504/IJISE.2010.031962, URL: http://www.inderscience.com/search/index.php?action=record&rec_id=31962&prevQuery=&ps=10&m=or

3. Zhen, M., **T. Masood**, A. Rahimifard and R.H. Weston (2009). "A structured modelling approach to simulating dynamic behaviours in complex organisations." Production Planning & Control – The Management of Operations 20(6): 496-509, September. DOI: 10.1080/09537280902938597, URL: http://www.informaworld.com/smpp/content~content=a913809540~db=all~jumptype=rss

4. Rashid, S., **T. Masood** and R.H. Weston (2009). "Unified modelling in support of organisation design and change." Proc. of the Instn. of Mech. Engrs., Part B: Journal of Engineering Manufacture 223(8): 1055-1079. DOI:

10.1243/09544054JEM1181, URL: http://journals.pepublishing.com/content/u124718126272657/

5. Wahid, B.M., J.O. Ajaefobi, K. Agyapong-Kodua, **T. Masood** and R.H. Weston (2009). "Enterprise Modelling in support of methods based engineering: lean implementation in an SME bearing manufacturer." Selected for publication in Special Issue of extended versions of papers from ICMR-2008. International Journal of Manufacturing Research Submitted (August 2009). URL: http://www.inderscience.com/browse/index.php?journalCODE=ijmr

6. **Masood, T.** and R.H. Weston (2010). "Enhanced integrated modelling approach to reconfiguring manufacturing enterprises." MSI Research Institute, Loughborough University, UK May 2010, Unpublished.

7. **Masood, T.** and R.H. Weston (2010). "Reconfigurable manufacturing design: a case of pre-production control in automotive industry." MSI Research Institute, Loughborough University, UK April 2010, Unpublished.

8. **Masood, T.** and R.H. Weston (2009). "Enhanced integrated modelling approach to reconfiguring manufacturing enterprises: a case of SME bearing manufacturer." MSI Research Institute, Loughborough University, UK June 2009, Unpublished.

9. **Masood, T.** and R.H. Weston (2009). "Redesigning manufacturing enterprises for improved responsiveness: towards measuring and monitoring percent of production plan complete." MSI Research Institute, Loughborough University, UK November 2009, Unpublished.

10. **Masood, T.** and R.H. Weston (2009). "An integrated production control modelling simulator for next generation change capable small and medium enterprises." MSI Research Institute, Loughborough University, UK March 2009, Unpublished.

A.2 Conference Papers

11. Wahid, B.M., J.O. Ajaefobi, K. Agyapong-Kodua, **T. Masood** and R.H. Weston (2008). "Enterprise Modelling in support of methods based engineering: lean implementation in an SME bearing manufacturer." Proc. of International Conference on Manufacturing Research (ICMR), Brunel University, UK, Pp. 391-402, September 9-11. URL: http://www.brunel.ac.uk/338/conferences1/ICMR08/ICMRAcceptedAbstracts2.pdf

12. **Masood, T.** and R.H. Weston (2008). "An integrated model driven approach in support of next generation reconfigurable manufacturing systems." Proc. of 4th Virtual International Conference on Intelligent Production Machines and Systems (I*PROMS), The Internet (Organised by Cardiff University), UK, July 1-14. URL: http://conference.iproms.org/conference/download/4000/101

13. **Masood, T.** and R.H. Weston (2008). "Reconfigurable manufacturing systems: Integrated modelling approach in support of PPC strategy realisation in an SME." Proc. of 4th Virtual International Conference on Intelligent Production Machines and Systems (I*PROMS), The Internet (Organised by Cardiff University), UK, July 1-14. URL: http://conference.iproms.org/

14. **Masood, T.**, A. Rahimifard and R.H. Weston (2007). "A Computer Executable Modelling Approach to Engineering Production Planning and Control Systems in Dynamic Manufacturing Organisations." Proc. of 4th International Conference on Responsive Manufacturing (ICRM 2007), Nottingham, UK, September 17-19.

15. Weston, R.H., M. Zhen, J.O. Ajaefobi, A. Rahimifard, A. Guerrero, **T. Masood**, B. Wahid and C. Ding (2007). "Simulating Dynamic Behaviours in Manufacturing Organisations." Proc. of International Conference on Industrial Engineering & Systems Management (IESM-2007), Beijing, China, May 30-June 2.

16. Weston, R.H., M. Zhen, A. Rahimifard, J.O. Ajaefobi, C. Ding, A. Guerrero, B. Wahid and **T. Masood** (2006). "Simulation Model Interoperability in Support of Complex Organisation Design and Change." Proc. of European

Simulation and Modelling Conference (ESM-2006), Toulouse, France, October 23-25. URL: http://www.eurosis.org/conf/esm/esm2006/prelprog.html

A.3 Internal Reports

17. **Masood, T.** and R.H. Weston (2009). "Redesigning Manufacturing Systems for Responsiveness – Towards Measuring and Monitoring Performance Metrics in ACM." MSI Research Institute, Loughborough University, UK, January.

18. Ajaefobi, J.O., B.M. Wahid, **T. Masood**, K. Agyapong-Kodua and R.H. Weston (2007). "Preliminary 5S Audit Report of ACM Bearings Ltd." MSI Research Institute and CECA, Loughborough University, UK, October 22.

19. **Masood, T.** (2007). "A Model-driven Approach to Engineering Production Planning and Control Systems in Dynamic Manufacturing Organisations." Internal Report, MSI Research Institute, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, UK, July.

20. **Masood, T.** (2006). "Configurable and Interoperable Manufacturing Systems." Internal Report, MSI Research Institute, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, UK, June.

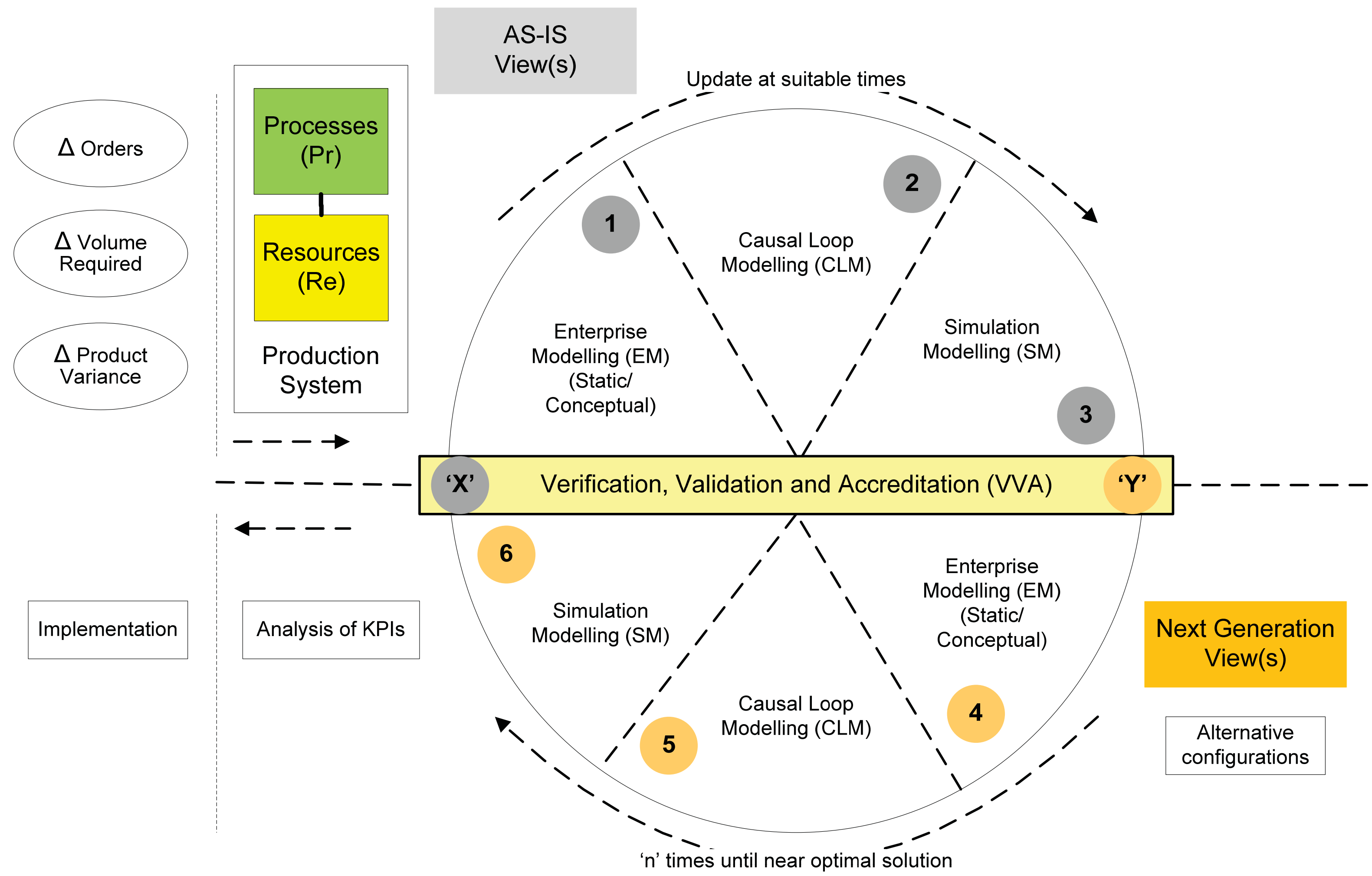
21. **Masood, T.** (2006). "Role of Wireless Technologies and Information Systems in Integration of Manufacturing Enterprises." Internal Concept Report, MSI Research Institute, Loughborough University, UK, March 27.

22. Rahimifard, A. and **T. Masood** (2006). "Bradgate Assembly Production System." Internal Project Report, MSI Research Institute, Loughborough University, UK, March.

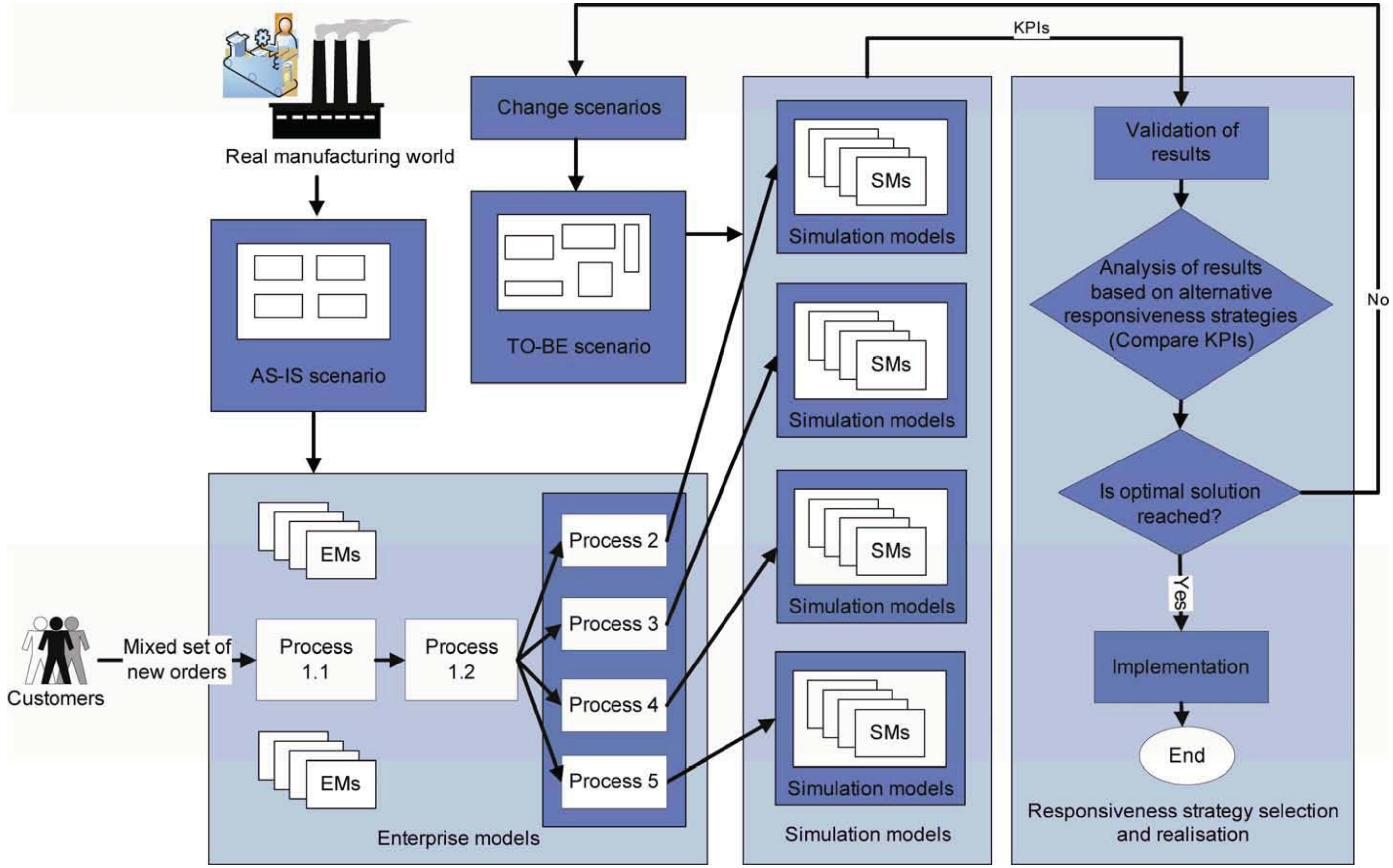
23. Rahimifard, A. and **T. Masood** (2006). "Ford PD Factory Production Release Process Decomposition." Internal Project Report, MSI Research Institute, Loughborough University, UK, January.

Appendix B: IMA/EIMA Extension

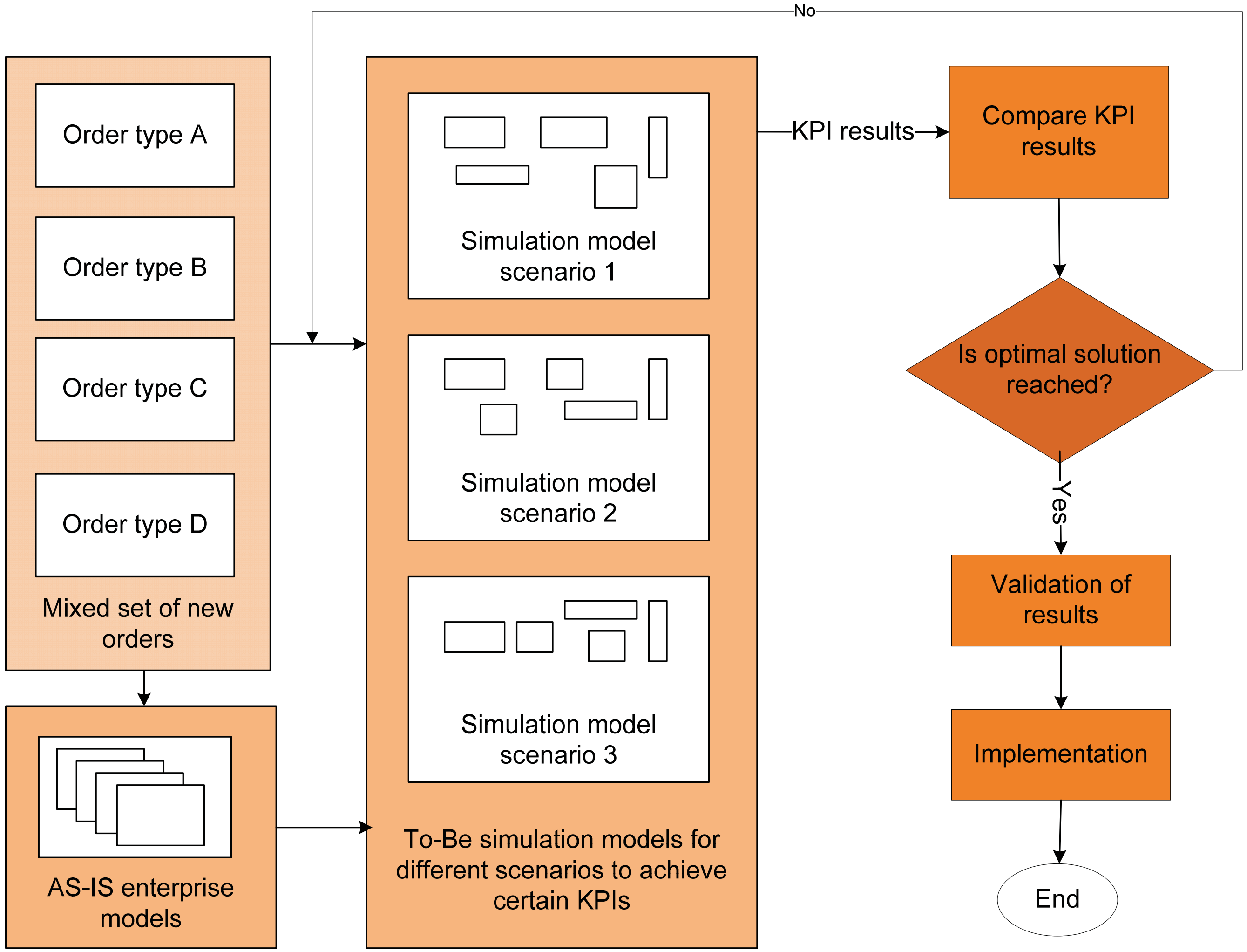
This appendix includes published versions of the IMA/EIMA.



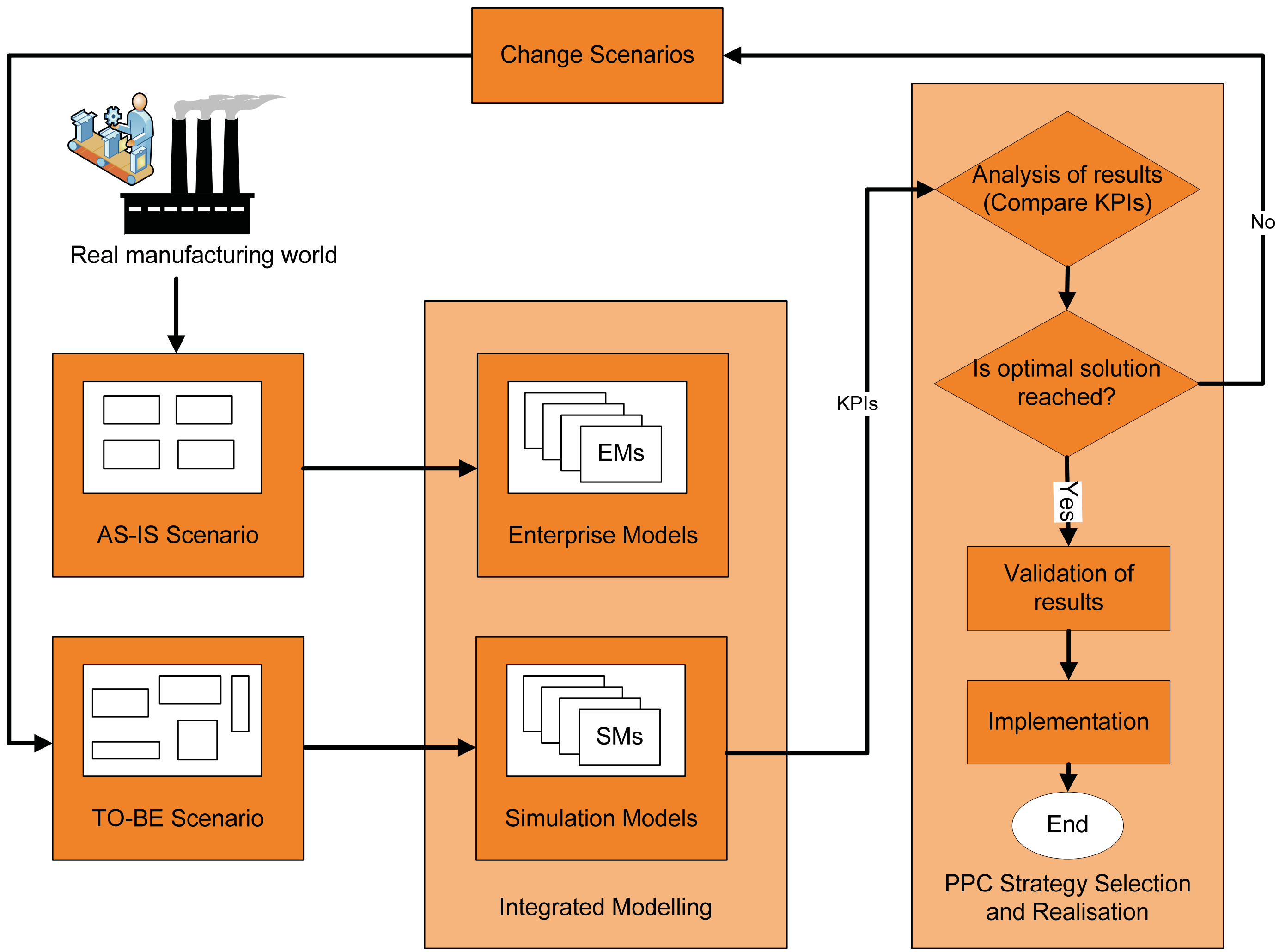
Figures 22a and 56a (Published Version): The EIMA in support of next generation reconfigurable manufacturing systems (Masood et al. 2010b)



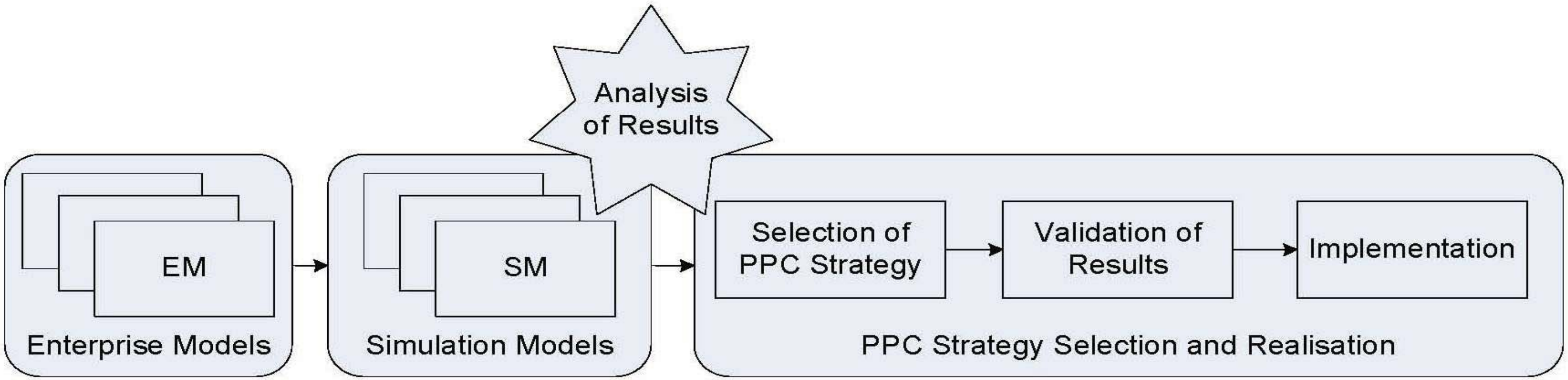
Figures 22b and 56b (Published Version): The IMA in support of responsive manufacturing (Masood et al. 2010a)



Figures 22c and 56c (Published Version): The IMA in support of reconfigurable manufacturing systems (Masood et al. 2008a)



Figures 22d and 56d (Published Version): The Change-capable IMA in support of PPC strategy realisation (Masood et al. 2008b)



Figures 22e and 56e (Published Version): The IMA in support of PPC strategy selection (Masood et al. 2007)

Appendix F: Draft Paper on EIMA-2 (IPCMS) featuring Bradgate Case
(2009: MSI Research Institute, Unpublished)

This appendix includes the following unpublished work from the undertaken research:

Masood, T. and R. Weston (2009). "An integrated production control modelling simulator for next generation change capable small and medium enterprises" MSI Research Institute March 2009, Unpublished.

An Integrated Production Control Modelling Simulator for Next Generation Change Capable Small and Medium Enterprises

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Abstract

Today's small and medium enterprises (SMEs) are prone to the challenges of globalization, shortened lead times, shortened product life cycles, and many others that resulted in imposing much more pressures on next generation SMEs to be change capable. Manufacturing has seen a range of paradigms in recent decades viz: lean manufacturing, agile manufacturing, mass production, continuous improvement, group technology, intelligent manufacturing systems, computer integrated manufacturing and reconfigurable manufacturing systems. The modelling and integration of enterprises remained a difficult task in most of he manufacturing hypotheses especially in the context of production control which plays a key role in resolving complexities of scheduling production orders according to the feasible processes and available resources. Such complexities of production control may be decomposed by adopting a model driven approach in which these could be easier to solve. Previous model driven approaches demonstrated combined use of computer integrated manufacturing open system architecture (CIMOSA) and Petri nets to model workflows based upon processes and resources. Linking 'role-dynamic producer unit (DPU)' couple to 'process-resource' couple is an emerging concept. An integrated production control modelling simulator (IPCMS) is presented for next generation change capable small and medium enterprises. The IPCMS is based upon 'flexibly integrated' use of static CIMOSA enterprise models (EMs), causal loop models (CLMs), simulation models (SMs) and WfMC based workflow models (WfMs). The IPCMS is applied in an industrial case to partially test the integrated production control modelling approach. In this specific case, static enterprise models in the form of DPU states have been used along with Petri net models to predict dynamic behaviours of a selection of productivity characteristics of DPUs during enterprise design analysis stage of IPCMS. The paper also reflects upon future research

directions in the form of more case applications of role-DPU couples in order to better understand their behaviours and mapping on to 'process-resource' couples.

Keywords:
Enterprise design and change, process-resource couple, role, dynamic producer unit (DPU), static modelling, causal loop modelling, simulation modelling, work flow modelling, integrated production control, CIMOSA, Petri net.

1. Motivation and Requirement

Today's SMEs are prone to the challenges of globalization, shortened lead times, shortened product life cycles, and many others that resulted in imposing much more pressures on next generation SMEs to be change capable. The manufacturing has seen a range of paradigms in recent decades viz: lean manufacturing, agile manufacturing, mass production, continuous improvement, group technology (GT), intelligent manufacturing systems (IMS), computer integrated manufacturing (CIM) and reconfigurable manufacturing systems (RMS) (Kusiak and He 1998; Backhouse and Burns 1999; Sullivan, McDonald et al. 2002; Masood and Weston 2008). The modelling and integration of enterprises remained a difficult task in most of he manufacturing hypotheses especially in the context of production control which plays a key role in resolving complexities of scheduling production orders according to the feasible processes and available resources. Such complexities of production control may be decomposed by adopting a model driven approach in which these could be easier to solve.

To address enterprise modelling and integration problems, several methods or reference architectures have been proposed in previous two decades as a result of world leading consortia and multi-regional research team work for computer integrated manufacturing viz: CIMOSA (ESPRIT Consortium AMICE 1993; Vernadat 1996), GRAI-GIM (Chen and Doumeingts 1996), IEM, IDEF (Mayer 1991), PERA (Williams 1996) and GERAM (Bernus and Nemes 1996; IFIP - IFAC Task Force 1999). CIMOSA has been central to most of the state of the art approaches used by viz: Monfared (Monfared 2000), Chatha (Chatha 2004), Weston et al (Weston., K. A.Chatha et al. 2004; Weston, Zhen et al. 2006; Weston, Zhen et al. 2007), Rahimifard and Weston (Rahimifard and Weston 2007), Masood et al

(Masood, Rahimifard et al. 2007; Masood and Weston 2008; Masood and Weston 2008; Masood, Rahimifard et al. Accepted Aug 2008). Previous model driven approaches also demonstrated combined use of either IDEF or CIMOSA with Petri nets to model workflows based upon processes and resources (Kim, Yim et al. 2001; Dong and Chen 2005). On the basis of University-Industrial research work of MSI Research Institute spread over two decades, the researchers developed to use the concepts of CIMOSA, 'process-resource' couples and then 'role' and 'DPU'. There is a requirement to case test the emerging concept of 'role-DPU' couple.

This paper describes how: (1) integrated production control models of different compositions of candidate 'role-DPU' couples can be created using Petri net simulation modelling tool; and (2) simulation experiments can be designed, firstly to gain useful insights by replicating existing (as-is) SME production control system behaviours and secondly predicting SME behaviours of possible future (to-be) 'role-DPU' compositions and their 'productivity' and 'changeability' characters. An integrated production control modelling simulator (IPCMS) for next generation change capable SMEs is presented in this paper. The IPCMS is based upon 'flexibly integrated' use of static enterprise models, causal loop models and simulation models. The IPCMS is applied in an industrial case to partially test the integrated production control modelling approach. In this specific case, enterprise static models in the form of DPU states have been used along with Petri Net simulation models to predict the dynamic behaviours of some productivity characteristics of DPUs during enterprise design analysis stage of IPCMS. The paper also reflects upon future research directions in the form of more case applications of role-DPU couples in order to better understand their behaviours and mapping on to 'process-resource' couples.

The remaining paper is divided in 5 sections. Section 2 explains next generation change capability, DPU paradigm and state of the art in combined use of CIMOSA and Petri nets. It also identifies research gap and highlights the need for an integrated production control modelling (IPCM) approach. The IPCMA is proposed in section 3. Sections 4 and 5 are based on an industrial case study of a make-to-order (MTO) manufacturing SME in order to develop, enhance and apply the IPCM approach/simulator. Conclusions and future research directions are outlined in section 6 followed by a list of references.

2. Next generation change capability requirement and DPU paradigm

Researchers at MSI Research Institute conceived and developed the idea of 'role' and 'dynamic producer unit (DPU)' couples during many University-Industrial projects spread over two decades. The 'role' and DPU modelling concepts enhanced the utility of enterprise models (EMs) and their connectivity with dynamic models of concern (Weston, Zhen et al. 2006). The DPUs have productivity, changeability and self characters and its different configurations are subject to work loads. Figure 1 shows the DPU paradigm (Weston, Zhen et al. 2006).

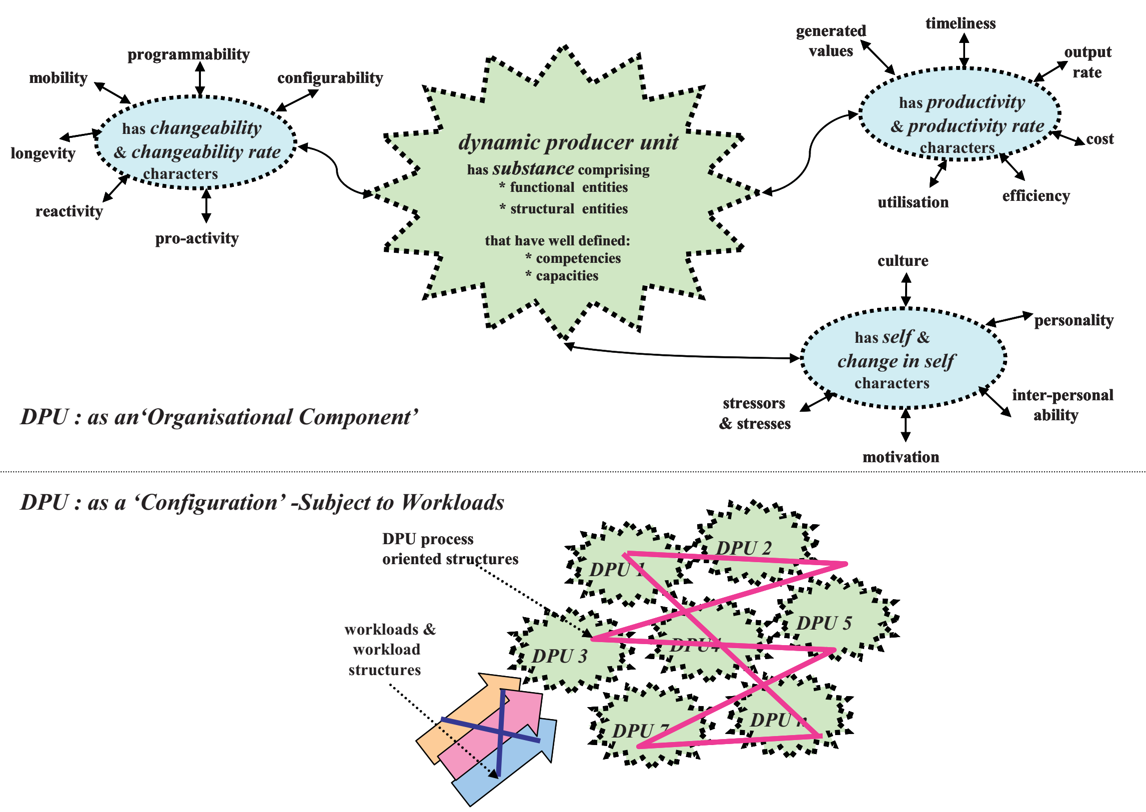


Figure 1: The DPU concept (Weston, Zhen et al. 2006)

Weston et al (2008) further elaborated the DPU paradigm by giving detailed views on DPU, its link with organisational design and benefits (Weston, Rahimifard et al. Accepted Nov 2008). The reusable DPU system components form basis of this process-oriented approach to achieve system composition. The following ME design and change principles are linked with the DPU paradigm (Weston, Rahimifard et al. Accepted Nov 2008):

(1) Processes are decomposed into viable roles that DPUs can realise

(2) DPUs are reconfigurable resources that can realise defined roles

(3) DPUs can be reprogrammable resources
(4) DPUs can be reconfigured or recomposable into higher level DPUs hence also catering for highly capable DPUs
(5) DPUs can be attributed to one or more roles, therefore requiring scheduling for the assignment of roles.

Conceptual view of a new process oriented system decomposition approach using the DPU concept includes stages: (1) requirements capture of ME processes with well defined roles, (2) conceptual design of ME components (DPUs) and DPU compositions as example candidate holders of roles and (3) implementation description of actual ME human and technical resources assigned to roles (Weston, Rahimifard et al. Accepted Nov 2008). Three main classes are used to quantify the DPUs namely (1) productivity characters, (2) changeability characters and (3) self characters as also shown in Figure 2 (Weston, Rahimifard et al. Accepted Nov 2008). Ding and Weston (2007) demonstrated, through a role based modelling approach, how performance is affected by different role decompositions and resourcing policies (Ding and Weston 2007).

Petri nets are very popular and powerful models for representation and analysis of systems that exhibit concurrency, parallelism, synchronization, non-determinism and resource sharing features (Dong and Chen 2005). Petri nets were used in two VOICE projects resulting in the development of McCIM, the first online implementation of CIMOSA, during AMICE and ESPRIT projects to prototype model-based operations and monitoring of two industrial partners, Renault and Elval (Didic 1993). MSI Research Institute developed a formal systems engineering workbench named SEW-OSA[1] that combined CIMOSA, generalized stochastic time Petri nets, predicate-action Petri nets, object oriented design and the services of the CIM-BIOSYS[2] integrating infrastructure to support system integration projects (Wilson, Aguiar et al. 1999). Sternemann et al (1999) demonstrated use of generic timed Petri nets based on CIMOSA design and implementation levels for process modelling in Daimler-Benz car production application concluding that if the process simulation models describe the

[1] Systems Engineering Workbench – Open Systems Architecture developed at MSI Research Institute

[2] CIM Building Integrated Open SYStems developed at MSI Research Institute

authentic enterprise state, alternatives can be compared and evaluated (Sternemann, Didic et al. 1999). Dong and Chen (2001) presented a systematic methodology for modelling and analysis of manufacturing supply chain business processes using CIMOSA behaviour rules and object oriented predicate/transition nets (Dong and Chen 2001). Cheng and Popov (2004) demonstrated application of process-based and object-oriented techniques for internet-enabled extended manufacturing enterprise modelling by using CIMOSA and object and place/transition Petri nets to develop an Object Petri Model Java application (Cheng and Popov 2004). Structured business modelling processes are very important for management of today's dynamically changing and complex business processes. Present business process reengineering and workflow tools do not provide an effective approach to design a structured business process (Dong and Chen 2005). Derks and Weston (2005) extensively reviewed sales-order-processing characteristics in assemble-to-order and make-to-stock companies and presented exception modelling approach using CIMSOA, WfMC[3], and Petri nets thereby identifying future need to adopt workflow simulation approaches (Derks and Weston 2005). Wong et al (2007) demonstrated useful integration of CIMOSA and high-level coloured Petri Net modelling techniques in the postal process using hierarchical dispatching rules and identified future scope of representation, understanding, and analysis of the process structural design, planning and scheduling tasks (Wong, Parkin et al. 2007).

The foregoing discussion shows that PN modelling has been successfully used with CIMOSA. Hence PN modelling could also be used in combination with CIMOSA and DPU paradigms. As DPUs can be attributed one or more roles, therefore scheduling is required for role assignments. Therefore, an integrated modelling approach is required to be adopted keeping in mind production control issues.

3. The Integrated Production Control Modelling Approach (IPCMA)

The IPCMA is conceived and developed during two EPSRC projects titled "unified modelling of complex systems – to facilitate ongoing organisation design and change" (grant no. EP/D05821X/1) and "study of the interplay between role dynamics and organisational performance" (grant no. GR/S64950/01). The IPCMA aims to develop

[3] The Workflow Management Coalition

and use enterprise, causal loop and simulation modelling techniques to support change capability in next generation SMEs. There has been limited development in the domain of model integration. Since integration and reuse of models is of paramount concern during the design and re-design phases of processes and products, this approach explores the integration of EM, CLM, SM and WfM in reconfigurable and responsive manufacturing systems with particular emphasis on production control. Figure 2 illustrates the IPCMA.

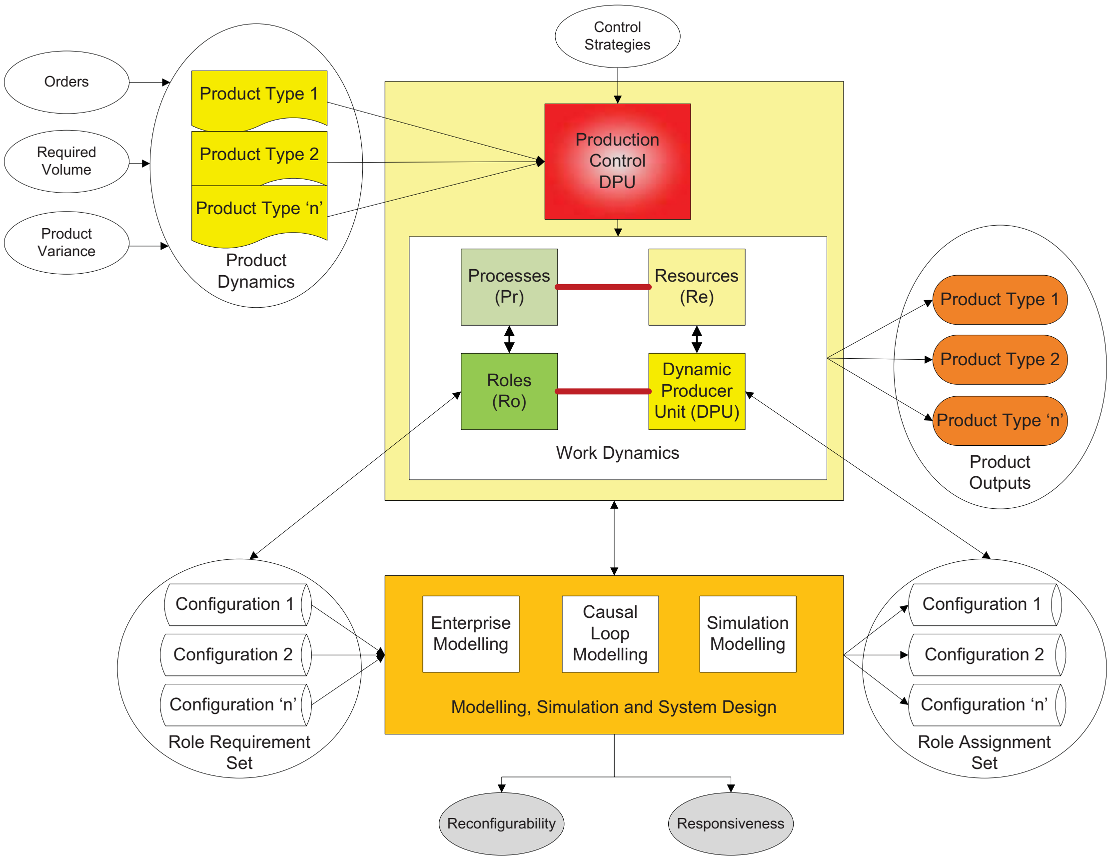


Figure 2: The IPCMA

This new integral approach to production control in reconfigurable and responsive manufacturing environments is developed with the net effect of improving modelling approaches whilst providing integration of EM with CLM, SM and WfM techniques. This research work aims to explore a number of problems associated with current industry requirements, modelling technology, organisation design and process execution. It assumes that there is a need for a process orientation while designing present day change capable SMEs and that integrated production control modelling in support of organisation design and enactment can play a key role to satisfy the need. Hence, the overall aim of this research is to develop a model-based integrated production control environment, which lends structure and support to organisation design and enactment. The scope of research capable of accomplishing the needs include (1) understanding the nature and role of production control processes in manufacturing organisations; (2) process modelling within the broader context of enterprise static, causal loop and simulation modelling (3) integration of modelling techniques and (4) application of the IPCMA in a MTO manufacturing SME. Prime deliverables of this research are centred on:

> (1) modelling both human and technical resources as DPUs along with systematic methods of assigning DPUs to well defined process-oriented roles. The IPCMA shall include modelling stages, concepts and methods for capturing aspects of organisations, techniques and tools that can be deployed to develop integrated models of processes and roles;
>
> (2) an integrated modelling framework and modelling concepts that describes those production control aspects of an enterprise that need to be understood and captured while modelling processes and roles as DPUs so that these can be reused in future to deliver a step change in the 'flexibly integrated' use of leading edge virtual engineering (VE) tools.

As change-capability is essential characteristic for an enterprise to sustain in today's competitive environment, the models for such systems should also be transformable, reconfigurable and interoperable. It is not feasible in such environments that manufacturing systems adhere to products due to shorter life cycles and frequency of change; therefore, supportive modelling techniques are sought for reconfiguration and interoperation of the systems.

Different roles, models, and systems within an organisation have different requirements of information, the impact of these on modelling related information will also be explored e.g.; strategists and appropriate performance measurement requirements. Decision support will be strengthened by integration of EM and SM techniques, widening the scope for optimisation of the systems for quantifiable parameters.

The research aims to create model driven prototype reconfigurable manufacturing system which address production control problems of the industrial collaborator which in this case is a MTO manufacturing SME. The simulation and design of different system configurations shall follow evaluating the pros' and cons' of the ideas developed. *The fundamental question that this research aims to answer is that how 'role' and 'DPU' ideas can partially be applied in a manufacturing SME to enable change capability in terms of reconfigurability and responsiveness on the basis of a robust integrated model driven production control system.* Figure 3 shows IPCMA/IPCMS research inputs and deliverables.

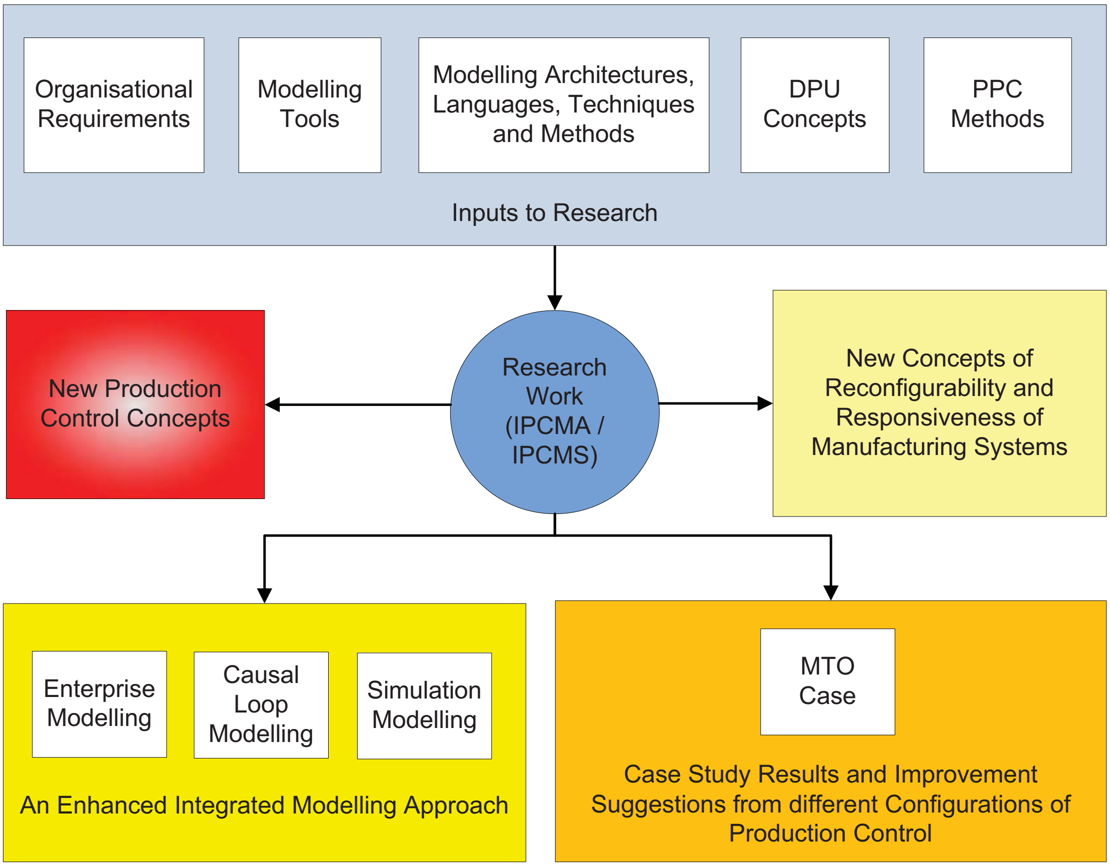


Figure 3: IPCMA/IPCMS research inputs and deliverables

A prototype IPCM Simulator (of the proposed IPCMA) is presented in Figure 5 and shall be tested in production control environment of the industrial case. The IPCMS works on industrial case data which is input to develop AS-IS enterprise models and AS-IS simulation models. The IPCMS works on EITHER/OR conditions in order to decide the path to follow. The path is decided by the industrial knowledge holder depending upon the need of the industry. The Figure 4 also shows alternative starred (1* to 6*) paths of the IPCMS either to go through CLMs or directly to future To-BE SMs.

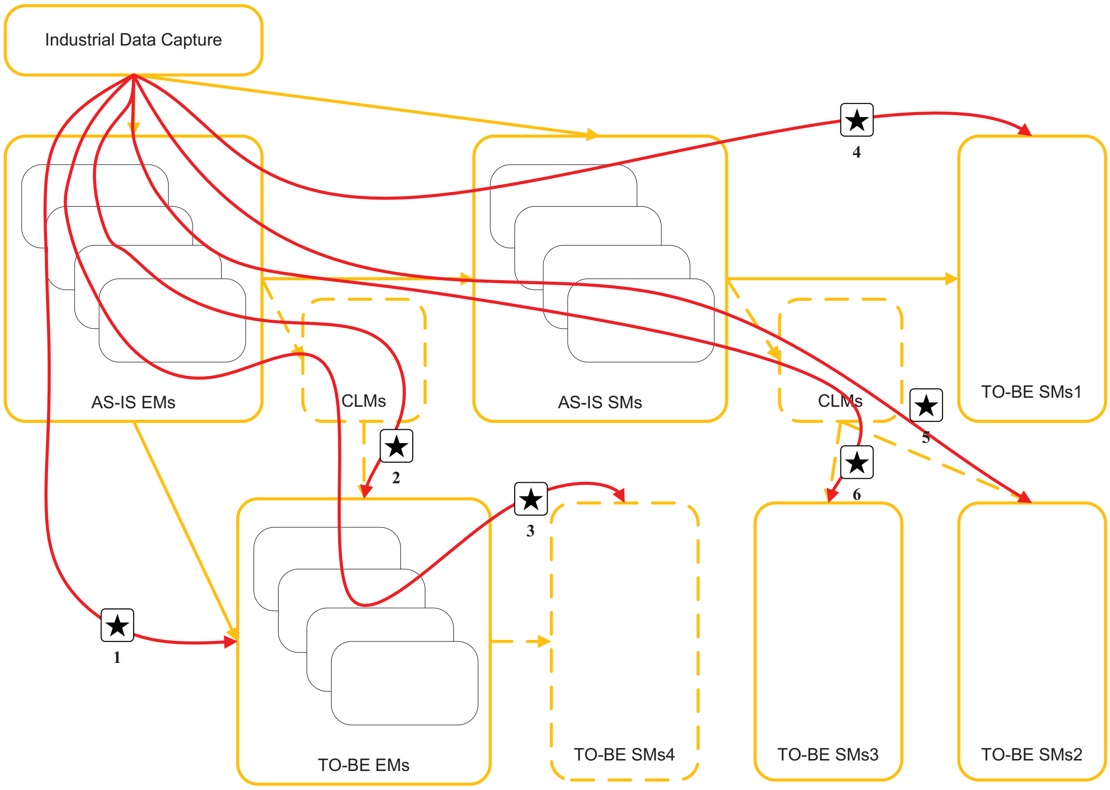


Figure 4: The IPCMS and its alternative starred paths

The IPCMS makes use of candidate reference architectures, methods or concepts to be used viz: CIMOSA, DPU, production control methods, etc. Candidate tools or templates that may be used to apply IPCMA include data capturing templates, CIMOSA based static modelling templates developed in MS Power Point® or MS Visio®, dynamic simulation models developed in Plant Simulation®, Simul8®, Arena®, iThink®, or Visual Object Net ++ (VON++). Table 1 presents mapping of candidate IPCMA/IPCMS stages to CIMOSA and DPU paradigms.

Table 1: Mapping of IPCMA/IPCMS on CIMOSA and DPU

CIMOSA (Process-Resource)	**DPU (Role-DPU)**	**IPCMA/IPCMS (Process-Resource) (Role-DPU)**
Level 1: Requirements definition modelling level (generic, partial and particular)	Stage 1: Requirements capture	Stage 1: Capture industrial data
Level 2: Design specification modelling level (generic, partial and particular)	Stage 2: Conceptual design	Stage 2A: Develop static role-DPU models Stage 2B: Validate static models Stage 3A: Develop as-is dynamic PN models for production control policies Stage 3B: Validate as-is dynamic PN models for production control policies Stage 4: Develop causal loop models (if and where required) Stage 5: Develop to-be dynamic PN models for production control policies Stage 6: Enterprise design analysis Stage 7A: Develop work flow models Stage 7B: Validate work flow models
Level 3: Implementation description modelling level (generic, partial and particular)	Stage 3: Implementation description	Stage 7: Implementation of finalised production control policies

The IPCMA/IPCMS is complemented by DPU performance indicators (DPIs) especially related to productivity, reconfigurability and responsiveness. Identification of DPIs is important part of the IPCMA as key decisions depend upon comparisons of as-is and to-be values of chosen set of DPIs. The DPIs may vary depending on a particular set of experiment configurations. However, a list is presented in the subscript which is not exhaustive:

- DPIs (Productivity) viz: efficiency, utilisation, work rate, generated values, cost, timeliness, quality;

- DPIs (Changeability) viz: programmability, configurability, mobility, longevity, reactivity, pro-activity;
- DPIs (Self) viz: personality, inter-personal ability, culture, motivation, stressors and stresses.

4. Industrial Case of a Manufacturing SME

An industrial case study of a make-to-order SME has been undertaken to apply the IPCMA/IPCMS. The case study SME (referred to as ABC) employs circa 50 people in UK to make around 350 high quality pine furniture product types. Its main product range includes tables, cabinets, beds, wardrobes and other furniture items that are designed for both house hold and business users. Previously, application of a number of alternative production control strategies has been investigated in order to improve responsiveness of ABC to rapidly changing market demands (Masood, Rahimifard et al. 2007; Masood and Weston 2008; Masood and Weston 2008; Masood, Rahimifard et al. Accepted Aug 2008). The previous work applied integrated modelling approaches mainly based upon ‘process-resource’ couples. Enterprise and simulation models of ABC’s business processes, (human and technical) resource systems and dynamic patterns of multi-product workflows have been created and reused with the aim of enhancing responsiveness and reconfigurability.

Machining, assembly, spraying and finishing are the main production processes involved in ABC’s furniture manufacturing. The current production control system of ABC makes groupings of customer orders based upon logistical criteria related to customers categorized by UK location. ABC compiles orders received from customers on weekly basis. The production starts with the issuance of a production order (known as ‘sales order picking list’ in ABC) to the assembly shop. The production order is then reviewed by the assembly shop coordinator who generates a ‘machine shop production order’ that requests needed parts from machine shop. The job list of the machine shop is regularly updated and priorities are set in order to maintain smooth running of the assembly shop. The production order is then moved through the assembly shop after receiving parts to be assembled from the machine shop where assembly processes are carried out.

The assembly department of ABC mainly consists of two sections, namely, table assembly and cabinet assembly sections. Each section has its own work organisation, but there are commonalities in production control approach. This section briefly explains related issues for table assembly section which is the focus of this paper and the overall assembly production planning system. The assembly area (and in effect the table assembly section) works on a 'real-time scheduling' approach where there is no frozen schedule and the question of 'what-to-do next' is attempted every time a job is finished based on the current status of ever changing job list, level of resources and due dates. The (human) resources are almost fully floating across different sections, sometimes even across departments. Assembly area has three production supervisors, one being the overall assembly coordinator, the other two being the respective section sub-supervisors for table assembly and cabinet assembly sections. The picking list is received from customer order processing department twice a week by the assembly coordinator. Then he prepares 'partial picking' lists by highlighting the relevant furniture items for each assembly area and pass it to the work benches. Every time a workbench finishes a job the next job is picked from the highlighted list according to earliest due date (EDD) and minimum setup time (MST) sequencing rules. The similar items are grouped together and some items are made in batches to save the setup time if they are in the same delivery run. Figure 5 shows DPU configurations of table assembly in ABC industrial case.

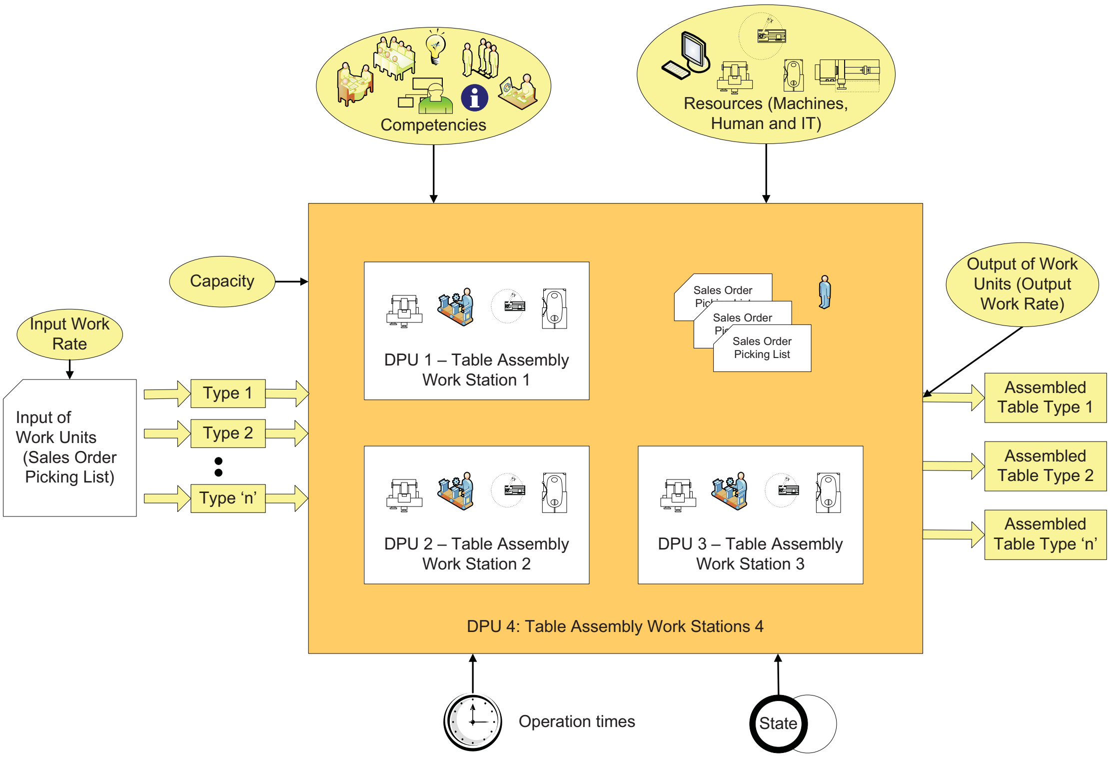


Figure 5: DPU table assembly configurations in ABC industrial case

There were no forecasting methods being adopted by ABC and product demands were unpredictable with a high variety of more than 300 products containing both less frequent and highly demanded products during certain periods which were unknown.

5. Use of IPCM Simulator in the Industrial Case

This section describes case study modelling in ABC using IPCM Simulator. While translating the process-resource couple into role-DPU couple, the relationships of (1) processes to their required roles and (2) resources to their DPUs are also very important. During stage 1, the IPCMS conceives the role requirements from their related process-oriented roles and static enterprise models are developed especially of DPU states. During stage 2, the EITHER/OR information from static models especially of DPU states and their precedence relationships are fed into simulation models (in this case Petri Net models) to observe the dynamic behaviours of the role-DPU couples already translated from process-resource couples. The results from this stage and characteristics of dynamic DPU states provides a basis of stage 3 of IPCMS where enterprise design analysis is performed to predict the dynamic behaviours of role-DPU couple. Such enterprise design analysis may include productivity analysis, configurability analysis and cost-benefit analysis to name a few. The outcomes of such an analysis provides a basis for role assignment to process-oriented roles. Figure 6 shows an IPCM Simulator proposed for the undertaken ABC industrial case.

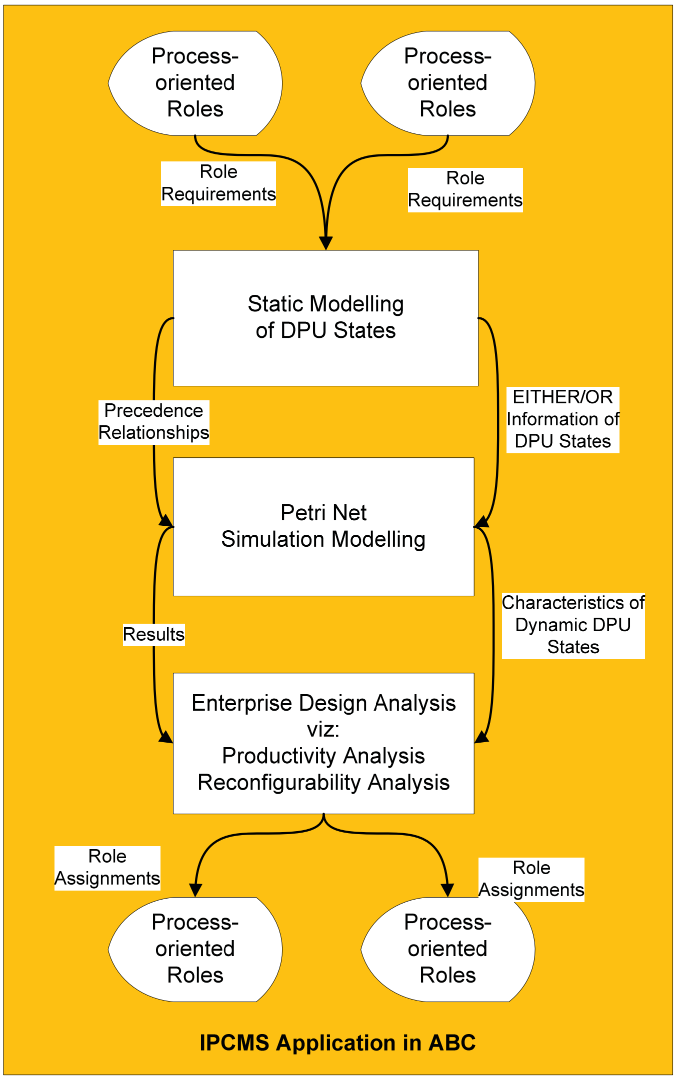


Figure 6: IPCM Simulator stages during application of IPCMA in ABC

The following will stepwise explain the application of IPCMS in ABC industrial case.

Stage 1: Development of CIMOSA based static enterprise models

Data was collected during a number of visits to the company and while a number of issues were discussed with company management, supervisors and operators. Following which enterprise models of the make to order processes of ABC were created and validated by the company managers. Previous publications of the present authors have described in some detail the way CIMOSA diagrams populated to create the enterprise models of ABC (Masood, Rahimifard et al. 2007; Masood and Weston 2008; Masood and Weston 2008; Masood, Rahimifard et al. Accepted Aug 2008). This industrial case study focuses on improving best practice production control in the company and when so doing to consider other possible production control configurations that might enhance the profitability of ABC. An enterprise model of DPU states of a production order in ABC industrial case is shown in Figure 7.

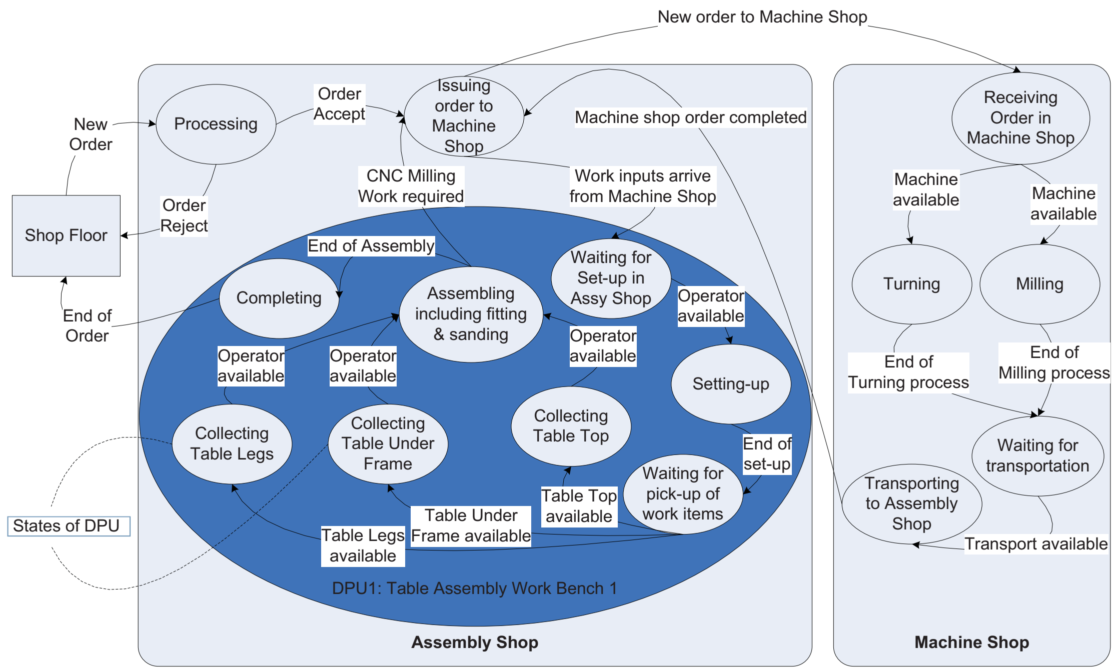
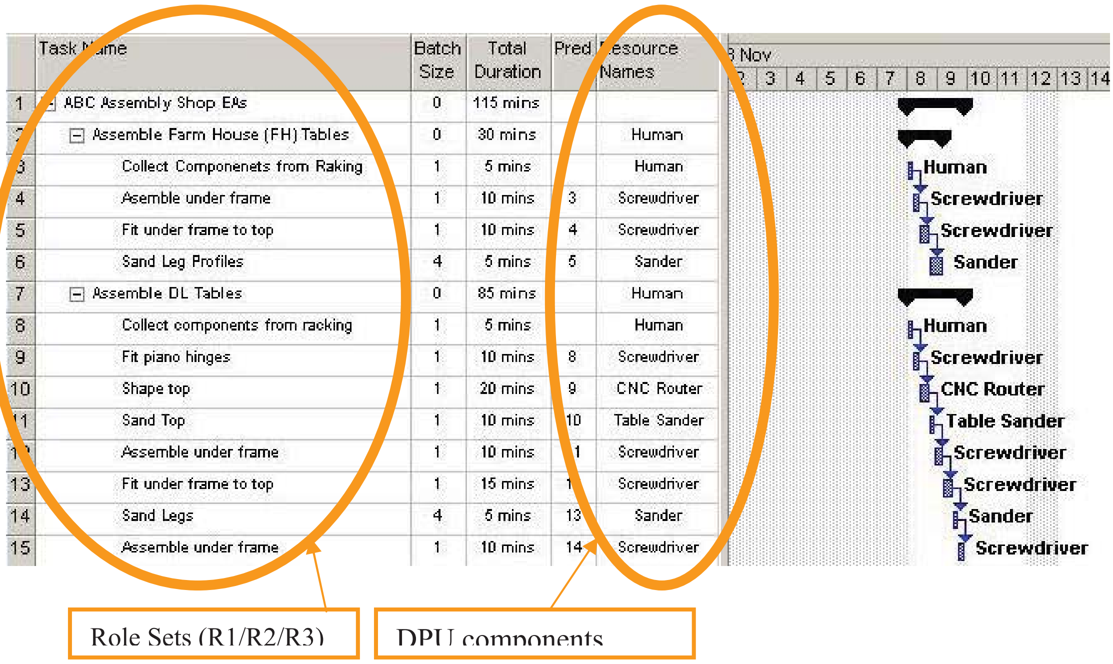


Figure 7: An enterprise model of DPU states of ABC table production order (also showing interaction between machine shop and assembly shop)

The following process-oriented role sets have been identified during assembly of tables: (1) R1 = R2 = R3 = collecting, fitting, sanding, shaping, assembling and (2) R4 = coordinating, supervising, arranging material, collecting, fitting, sanding, shaping, assembling. Figure 8 shows role sets and DPU components during table assembly in ABC also including details of the task name, batch sizes, process duration, predecessors, resources name or type and a Gantt chart regarding the execution of roles.



	Task Name	Batch Size	Total Duration	Pred	Resource Names
1	ABC Assembly Shop EAs	0	115 mins		
2	Assemble Farm House (FH) Tables	0	30 mins		Human
3	Collect Componenets from Raking	1	5 mins		Human
4	Asemble under frame	1	10 mins	3	Screwdriver
5	Fit under frame to top	1	10 mins	4	Screwdriver
6	Sand Leg Profiles	4	5 mins	5	Sander
7	Assemble DL Tables	0	85 mins		Human
8	Collect components from racking	1	5 mins		Human
9	Fit piano hinges	1	10 mins	8	Screwdriver
10	Shape top	1	20 mins	9	CNC Router
11	Sand Top	1	10 mins	10	Table Sander
12	Assemble under frame	1	10 mins	1	Screwdriver
13	Fit under frame to top	1	15 mins	1	Screwdriver
14	Sand Legs	4	5 mins	13	Sander
15	Assemble under frame	1	10 mins	14	Screwdriver

Figure 8: Role sets and DPU components during table assembly in ABC

Stage 2: Development of Petri net models

General purpose PN models of make to order ABC production processes were built on the basis of foregoing analysis. Here a PN simulation software (namely Visual Object Net ++ (VON++)) has been chosen to dynamically show the behaviours of various role-DPU states that takes place during production and assembly of tables. VON++ was developed by Dr Reiner Drath and his team of the Department of Automatic Control at Illemnau University of Technology, Illemnau, Germany. It is an innovative PC based Petri net CAE tool that supports mixed continuous and discrete event Petri nets. The benefits of using VON++ include easy designing, quick simulation and simple documentation of hybrid Petri nets. It is available free of charge at http://www.systemtechnik.tu-ilmenau.de/~drath/visual_E.htm. An as-is PN model of DPU states during table assembly is developed and is shown in Figure 9. The PN model is general purpose in that it facilitates experimentation (with respect to needed roles), enabling impact analysis of changes to scheduling and work organisation policies. A set of PN modelling experiments were designed and carried out so as to test effects of production control policy change on ‘lead times’, ‘inventory levels’, ‘bottlenecks’, ‘resource utilisation’, ‘value generation’ and ‘process costs’.

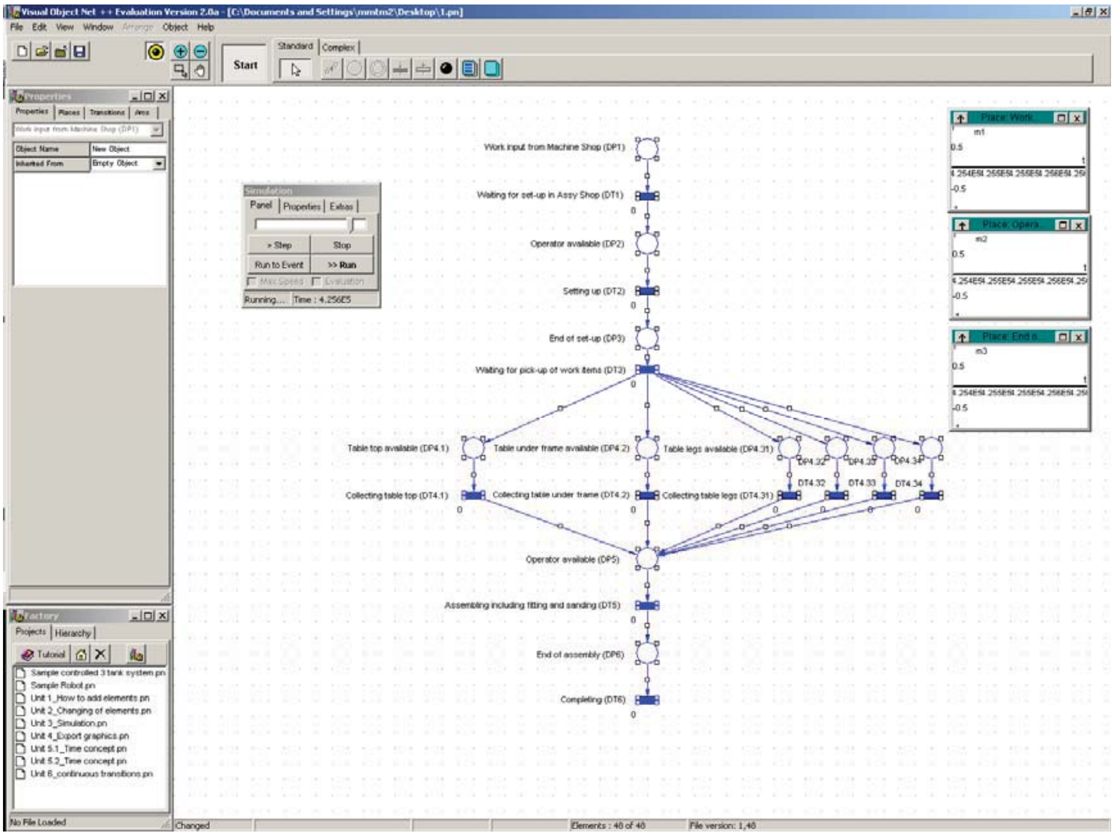


Figure 9: PN simulation model of DPU states of ABC table production in VON++

The PN model helped to understand dynamically the behaviours of role-DPU couple in table assembly. To realise changeability in ABC, a to-be configuration was conceived in which the table assembly orders are routed through a production control DPU. The to-be conceptual model incorporates a MTS/ATO hybrid manufacturing system. It is assumed in the to-be PN models that the products are grouped on the basis of their related process oriented roles, process times and DPUs. Figure 10 illustrates the conceptual base model of the to-be table assembly system.

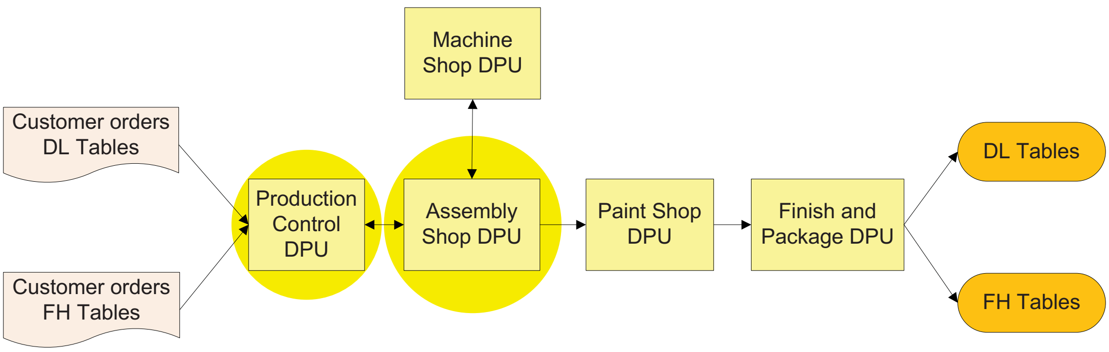


Figure 10: Conceptual base model of the to-be production control of table assembly

Validation of the static CIMOSA models and dynamic PN models up to an acceptable level of accuracy is important. The DPIs of the model needs to be compared with the operation of the real system or the performance of the designed to-be systems to build confidence in results. It is important to note that the model may only be 'valid for the purpose'. In reality, it may not be possible to validate fully a model of a real system (Robinson 1997; Sargent 2005; Sargent 2007; Monfared, West et al. 2008). The validation method of Robinson (1997) are adopted here that generally follows the method suggested by (i.e., validation of static model, data, codes, and black box approaches).

Stage 3: Enterprise design analysis

While performing enterprise design analysis, a number of potential production control policies and configurations are considered within the virtual environment. Such parametric changes to the initial model generated 'to-be' configurations where potential benefits are predicted and measured through DPIs especially related to productivity and configurability. The following DPIs are identified as being of major interest to ABC: (1) throughput time (lead time), (2) cost, (3) utilisation of resources and (4) work in progress (WIP) levels. The throughput time or lead time is one of the most frequently used KPI and has been used in this case as a major comparator. While comparing push and pull systems during previous ABC case study, Masood et al. (2008) identified that (a) production based upon commonality of parts may reduce lead times of products and (b) standardisation of parts may lead to enhance the responsiveness for the customer orders and reduce lead times (Masood, Rahimifard et al. Accepted Aug 2008). During a lean implementation project in a SME bearing manufacturing company, Wahid et al (2008) identified that cost may be used as a performance parameter (Wahid, Ajaefobi et al. 2008). Hence, Cost is also a prime KPI on which alternative production policies are decided. The assignment of resources to work within the assembly section can be optimised for process improvements. The WIP levels play an important role in determining the amount of inventories held in a manufacturing business.

On the basis of the foregoing enterprise design analysis, an innovative 'role-DPU' table is proposed to be used by next generation SMEs to help better plan and control production. An exemplary 'role-DPU' table is presented in Table 2.

Table 2: 'Role-DPU' table

	DPU1	DPU2	DPU3	DPU4	DPU5	DPU6	DPU7	…	DPU 'n'
R1									
R2	☑	☑				☑			☑
R3	☑			☑					
R4		☑					☑		☑
R5				☑					
R6		☑				☑			☑
R7	☑								
…				☑			☑		
R 'n'								☑	

(R=Role)

The 'role-DPU' table is based upon process related roles and (human, machine and IT) resource related DPUs and could help in planning capacity as well as schedule production orders. The input to this table is a role requirement set while output is a role assignment set. DPU examples may be taken from Figure 5.

The case study has shown how the IPCMA/IPCMS has benefited the ABC to: (1) better understand 'role-DPU' couple; (2) better respond to the rapidly changing customer demands by applying the CIMOSA based particular level of the modelling approach for production control strategy selection and realisation; (3) integrally use EM, CLM, SM and WfM techniques that helped to gain an in-depth understanding about ABC's current production strategies, their shortcomings and possible ways of achieving improvements; (4) have an innovative option to use 'role-DPU' table to better plan and control production.

6. Conclusions and Future Research Directions

The paper presents an industrial case study to partially case test role and DPU paradigms. IPCMA/IPCMS is conceived to be adopted for the purpose and is mainly based upon integrated use of enterprise modelling, causal loop modelling and simulation modelling stages in production control. The application of the IPCMA/

customised IPCM Simulator in a MTO manufacturing SME helped redesign the production control strategy decision making to achieve change capability especially in terms of reconfigurability and responsiveness. The IPCMA/IPCMS may be tested in other MTO manufacturing SMEs for more complex situations than ABC industrial case. It may be worth applying the proposed strategies of ABC case in other (1) SME configurations e.g., engineer to order (ETO) job shop environment, (2) production control strategies e.g., Kanban, ConWIP, postponement. This research may also lead to the use and updating of integrated production control models in order to enable next generation change capable SMEs.

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