CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgement, footnotes, or in reference, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a higher degree.

…………………………. (Signed)

…………………………. (Date)

Role Based Modelling in Support of Configurable Manufacturing System Design

by

CHENGHUA DING

A Doctoral Thesis
Submitted in Partial Fulfilment of the Requirements
for the award of

Doctor of Philosophy
of
Loughborough University

February 2010

Wolfson School of Mechanical & Manufacturing Engineering
Loughborough University

Loughborough UK, 2010

Acknowledgement

I would like express my gratitude to the following people and organisations:

This is dedicated to my dearest parents: 丁佰昌 (Baichang DING) and 程月琴 (Yueqing CHENG) for their love, support and care, which always around me and giving me strength to overcome any difficulties, even though they are thousands of miles away.

My most sincerely gratitude to Professor Richard Weston, my supervisor of research, for his continuous splendid guidance derived from his extensive and intensive knowledge, with amazing encouragement, inspiration, motivation, support and help throughout the period. Indeed, this work would not have been successfully completed without most essential directions from him.

I sincerely acknowledge the research colleagues of Manufacturing System Integration (MSI) Research Institute in Wolfson School, for their kind help, support and encouragement. I would like to thank especially Dr. R.P.Monfared, Dr. A. Rahimifard, Revd Dr. J.O. Ajaefobi and Dr. K.A.Chatha who gave me valuable suggestions and guidance. Mrs M.E. Carden and Mrs S. Beaumont also deserve special thanks for their kind help.

I would like also to express my deep thanks to colleague including Mr. B.M. Wahid, Mr. A.Guerrero, Dr. J.Darlington, Dr. R.Darlington and Dr. A.J.Norward, at the Centre of Excellence in Customised Assembly, for their kind help and contribution to my research.

Last but not least, my thanks to all the people who helped, supported, caring, encouraged me in many different ways from time to time, you have all contributed to achieving my objectives.

Abstract

Business environments, in which any modern Manufacturing Enterprise (ME) operates, have grown significantly in complexity and are changing faster than ever before. It follows that designing a flexible manufacturing system to achieve a set of strategic objectives involves making a series of complex decisions over time. Therefore manufacturing industry needs improved knowledge about likely impacts of making different types of change in MEs and improved modelling approaches that are capable of providing a systematic way of modelling change impacts in complex business processes; prior to risky and costly change implementation projects. An ability to simulate the execution of process instances is also needed to control, animate and monitor simulated flows of multiple products through business processes; and thereby to assess impacts of dynamic distributions and assignments of multiple resource types during any given time period. Further more this kind of modelling capability needs to be integrated into a single modelling framework so as to improve its flexibility and change coordination. Such a modelling capability and framework should help MEs to achieve successfully business process re-engineering, continuous performance development and enterprise re-design.

This thesis reports on the development of new modelling constructs and their innovative application when used together with multiple existing modelling approaches. This enables human and technical resource systems to be described, specified and modelled coherently and explicitly. In turn this has been shown to improve the design of flexible, configurable and re-usable manufacturing resource systems, capable of supporting decision making in agile manufacturing systems. A newly conceived and developed Role-Based Modelling Methodology (R-BMM) was proposed during this research study. Also the R-BMM was implemented and tested by using it together with three existing modelling approaches namely (1) extended Enterprise Modelling, (2) dynamic Causal Loop Diagramming and (3) Discrete Event Simulation Modelling (via software PlantSimulation ®). Thereby these three distinct modelling techniques were deployed in a new and coherent way.

The new R-BMM approach to modelling manufacturing systems was designed to facilitate: (1) Graphical Representation (2) Explicit Specification and (3) Implementation Description of Resource systems. Essentially the approach enables a match between suitable human and technical resource systems and well defined models of processes and workflows. Enterprise Modelling is used to explicitly define functional and flexibility competencies that need to be possessed by suitable role holders. Causal Loop Diagramming is used to reason about dependencies between different role attributes. The approach was targeted at the design and application of simulation models that enable relative performance comparisons (such as work throughput, lead-time and process costs) to be made and to show how performance is affected by different role decompositions and resourcing policies. The different modelling techniques are deployed via a stepwise application of the R-BMM approach.

Two main case studies were carried out to facilitate methodology testing and methodology development. The chosen case company possessed manufacturing characteristics required to facilitate testing and development; in terms of significant complexity and change with respect to its products and their needed processing structures and resource systems. The first case study was mainly designed to illustrate an application, and benefits arising from application, of the new modelling approach. This provided both qualitative and quantitative results analysis and evaluation. Then with a view to reflecting on modelling methodology testing and to address a wider scope manufacturing problem, the second case study was designed and applied at a different level of abstraction, to further test and verify the suitability and re-usability of the methodology.

Through conceiving the new R-BMM approach, to create, analyse and assess the utility of sets of models, this research has proposed and tested enhancements to current means of realising reconfigurable and flexible production systems.

Key words: Role based modelling; Enterprise modelling; Simulation modelling; Configurable system design; Modelling integration.

TABLE OF CONTENTS

Declaration of originality

Title page

Acknowledgement **I**

Abstract **II**

Contents pages **IV**

Index of figures **X**

Index of tables **XII**

Index of Abbreviation **XIV**

Chapter 1 The Needs For Complex Manufacturing Resource Systems **1-10**

1.1 Current Manufacturing Enterprises Feature **1**

1.2 Change Requirements to Manufacturing System **2**

1.2.1 Typical ME processes characteristics and resource requirements 3

1.2.2 The need for systemically structured process and resource system change 4

1.2.3 Requirements of complex manufacturing resource systems 5

1.2.3.1 Functional requirement 5

1.2.3.2 Decomposition requirement 5

1.2.3.3 Inherent need to handle multiple resource system types 6

1.2.3.4 Requirement of resource system integration and alignment to process definitions. 6

1.2.3.5 Organisational requirement 6

1.3 Requirement for Knowledge Sharing and Re-use **6**

1.4 Requirements to Model Aspects of Integration **8**

1.5 Problems and Opportunities within ME Process-resource System Design, Modelling and Integration **9**

Chapter 2 Literature Review **11-37**

2.1 Manufacturing Enterprise Flexibility **11**

2.1.1 Understanding of flexibility 11

2.1.2 Manufacturing flexibility 11

2.2 System Thinking and Engineering **12**

2.2.1 Concept of system thinking 12

2.2.2 Systems engineering (SE) 13

2.3	**Enterprise Engineering, Modelling and Integration**	**15**
2.3.1	Enterprise engineering	15
2.3.2	Enterprise modelling	16
2.3.3	Enterprise integration	17
2.3.4	Standards related to enterprise engineering, modelling and integration	18
2.3.5	Enterprise modelling and integration tools	19
2.3.5.1	*Structured Analysis and Design Technique(SADT)*	*19*
2.3.5.2	*The IDEF Suit of Methods*	*20*
2.3.5.3	*The IEM Approach*	*20*
2.3.5.4	*Open Systems Architecture for CIM Systems (CIMOSA)*	*20*
2.3.5.5	*GIM-GRAI Integrated Methodology*	*21*
2.3.5.6	*Architecture of Integrated Information Systems (ARIS)*	*21*
2.3.5.7	*Purdue Enterprise Reference Architecture (PERA)*	*22*
2.4	**Human System, Modelling and Role Concepts**	**22**
2.4.1	Human system and modelling	22
2.4.2	Role concepts and its modelling	23
2.4.2.1	*Role concept early origin into literature*	*23*
2.4.2.2	*Role of human in relation to their competency*	*24*
2.4.2.3	*Modelling roles and competencies*	*25*
2.5	**Dynamic and Simulation Modelling**	**27**
2.5.1	Dynamic simulation construction	27
2.5.2	Discrete Event Simulation	28
2.5.3	Basic differences between discrete event & continuous simulation models	29
2.5.4	Simulation software tools	30
2.6	**Workflow Modelling and Management**	**32**
2.6.1	Fundamental concepts and structure	32
2.6.2	Workflow and BPM	32
2.6.3	Modelling tools and techniques	33
2.7	**Component and Component Based Modelling**	**35**
2.7.1	Definition of “component”	35
2.7.2	Understanding of “component architecture”	36
2.7.3	Component modelling technology and their commercial implementation	36

Chapter 3 Literature Analysis **37-42**

3.1	**Literature Review Summary**	**38**
3.2	**Gap Analysis to Literature**	**39**
3.2.1	Regarding human and technical system modelling in support of process improvement	39

3.2.2 Regarding dynamic and simulation modelling in support of resource systems 39
3.2.3 Regarding the integrated use of models of processes, roles and resource systems 40
3.3 Research Aims and Objectives 40
3.4 Scope of Research 41
3.5 Research Methodology Used 41

Chapter 4 Research Design 43-54
4.1 New Modelling Methodology Development Principles 43
4.2 Detailed Analysis of Candidate Modelling Tools 44
4.2.1 CIMOSA modelling as tool of decomposition to handle complexity 45
4.2.2 Modelling 'Roles' and 'Competencies' of resource Systems 47
4.2.3 Dynamic and simulation modelling tool selection 48
4.3 Key Features of New Methodology Development 49
4.3.1 Requirements and solutions decoupling 49
4.3.2 Top-down and bottom-up mechanism usage 49
4.3.3 Visualisation for the new model approach 50
4.4 Research Approach Deployment 51
4.4.1 Research methods adopted during the research 51
4.4.2 Comprehensive research achievement plan 52
4.5 Research Novelty Expected to be Delivered 54

Chapter 5 Enterprise Modelling Approach 55-67
5.1 Introduction to The Case Study Company 55
5.1.1 Choice of the case study company 55
5.1.2 Products and essential operations 56
5.1.3 Targeted modelling domain in FFL 56
5.2 CIMOSA Based Decomposition and Modelling 57
5.2.1 Top level context diagram 57
5.2.2 Top level interaction diagram 58
5.2.3 Structure diagram of a selected domain process 59
5.2.4 Sub-Level interaction diagrams 60
5.3 Deployment of Control Logic in CIMOSA Model Diagrams 61
5.4 Value Stream Classification to Processes 63
5.5 New EM Template to Combine Modelling Development 65
5.5.1 Catalogue of building blocks 65
5.5.2 Illustration of new template implementation 65
5.6 Chapter Conclusion 67

Chapter 6 Role based conceptual modelling and system configuration 68-89

6.1 General Principles to Role Concepts Definition 68

6.2 Role Based Modelling Concepts 69

6.2.1 Role and its requirements 70

6.2.2 Role holder 71

6.2.3 Competency 71

6.3 Role Based Modelling Methodology Framework 72

6.4 Role Based Modelling Methodology Development 74

6.4.1 Role Identification (ST1) 74

6.4.2 Role & Competency Requirement Specification (ST2) 75

6.4.2.1 CIMOSA FO and FE link to role and competency 75

6.4.2.2 Competency classification 76

6.4.3 Competency Possessed Specification, for Candidate Role Holders (ST3) 78

6.4.4 Planning the Role Assignment to Role Holders (ST4) 79

6.4.5 Role-based Behaviour Modelling (ST5) & Specification of Multiple Role-based Interoperation (ST6) 80

6.4.5.1 Measurement 1: Achievement rate 80

6.4.5.2 Measurement 2: Relative ratio of effective time and waste time 80

6.4.5.3 Measurement 3: Relative ratio of value adding and cost 81

6.4.6 Role-based Production System Development (ST7) 81

6.5 Case Study Application and testing of the R-BMM 82

6.5.1 Role Identification 82

6.5.2 Competency Requirement Specification 84

6.5.3 Competency Possession Specification by Investigating Resource System 84

6.5.4 Role Assignment for Assumed Static Scenario 87

6.5.5 Discussion of Role Potential from Case Study 88

6.6 Conclusion of the Chapter 89

Chapter 7 Dynamic Simulation and Role Performance Modelling 90-116

7.1 Necessity to Model Dynamic Behaviours 90

7.2 Causal Loop Dynamic Analysis 91

7.2.1 Segments of the CLM diagram and links to role modelling stages 91

7.2.2 CLM’s causal impact analysis to R-BMM entities’ dynamics 93

7.3 Simulation Modelling Software 95

7.4 Simulation Model Experimental Design 96

7.4.1 Change Dynamics in Table Assembly Realisation System 97

7.4.2 Dynamic Scenario Instance Matrix for Experimental Input Design 98

7.4.3 Experimental Design of the FFL Table Assembly Simulation Model 99

7.4.3.1 Product historical data review *100*
7.4.3.2 Scenario set 1 (‘As Is’ Production System) *101*
7.4.3.3 Scenario set 2 (‘As Is’ Production System) *102*
7.4.3.4 Scenario set 3: (To-Be production system redesign 1) *102*
7.4.3.5 Scenario 4: (To-Be production system redesign 2) *104*
7.4.4 Scenario Design Link to CLM 104
7.4.5 Expected Simulation Results 104
7.5 Creating Simulation Models of FFL Table Assembly 105
7.5.1 Model Construction 105
7.5.2 External Data Input Interpretation and Parameter Configuration 108
7.5.2.1 Work item entry specification information *108*
7.5.2.2 Active resources involved *108*
7.6 Model Execution and Results Analysis 109
7.6.1 Simulation Model Execution and Results Explanation 110
7.6.2 Analysis of Multi-role Inter-operation 112
7.7 Production System Optimisation Through Role Re-design 113
7.7.1 Role re-design in FFL Table Assembly Section 113
7.7.2 Table Assembly System Re-design 114
7.8 Summary of the simulation modelling work 115

Chapter 8 Research Reflection and Extension 117-129
8.1 Research Reflection 117
8.1.1 Reflection Discussion 119
8.1.2 Costs Trail in the Case Study 120
8.2 Reusability Test of the New Methodology 121
8.3 Research Development 126
8.3.1 Role Categories to Support Role Identification 126
8.3.2 Improved Modelling of Resource Components – Role holder link to DPU concepts 127
8.3.3 Computerised Model Building & Model Development 128

Chapter 9 Research Conclusion and Further Development 130-137
9.1 Complying With the Research Development Plan 130
9.2 Main Practice Approaches in Case Studies 130
9.3 Main Outcomes from the Modelling Methodology Development 131
9.4 Research Novelty and Contributions to Knowledge 133
9.5 Weakness of Current Research Progress 134
9.5.1 Methodology Weaknesses Observed. 134

9.5.2 Constraints on Methodology Implementation in the Case Study Work 134

9.6 Future Research Development 135

9.6.1 Develop Better Computerised Model Building Environment 135

9.6.2 Wider Industrial Application 136

Reference 137

Appendix

Appendix I Comparison of Enterprise Modelling Approaches

Appendix II Examples of CIMOSA Model Diagrams with improved logic control and model template

Appendix III Flow Control Logic specification template

Appendix IV Role based resource system design case study tables

Appendix V Plant Simulation Experimental Design Scenario Set

Appendix VI Plant Simulation model results

Appendix VII Conference Paper at ICIEA2007

Appendix VIII Conference paper at DET09

Index of Figures

Figure 2.1.	The system engineering process	14
Figure 2.2.	Development and Operational Systems	14
Figure 2.3.	Enterprise engineering main components	16
Figure 2.4.	Structural relation among Personality, Position and Role	25
Figure 2.5.	Role analysis building up for series of activities	25
Figure 2.6.	Competency cube	26
Figure 2.7.	Dynamic interaction within a system	27
Figure 2.8.	Key stages used in Discrete Event Simulation(DES)	28
Figure 2.9.	Interpretation to three different elements to Discrete Event Simulation	29
Figure 2.10.	Evolution of Workflow & BPM	33
Figure 3.1	Research scope illustration	41
Figure 4.1	CIMOSA model framework	45
Figure 4.2	Hierarchical CIMOSA model demonstration	46
Figure 4.3	Gradual research achievement plan map	53
Figure 5.1	Overall order fulfilment process	56
Figure 5.2	Multi-flow network within production process scope	57
Figure 5.3	Top level context diagram in FFL	57
Figure 5.4	Top Level Interaction Diagram in case scenario	58
Figure 5.5	Structure diagram of selected domain process(DP7)	59
Figure 5.6	Sub-Interaction Diagram to ‘Produce & Deliver Furniture’ DP	60
Figure 5.7	Assembly Process Activity Diagram within Production DP	61
Figure 5.8	General Workflow diagram with process classified in FFL	64
Figure 5.9	Improved building blocks in CIMOSA model diagram template	65
Figure 5.10	Operation type categorised activity diagram with logic control nodes	66
Figure 6.1	Key concepts and aspect of Role based modelling entities	70
Figure 6.2	Main development stages of role modelling development	72
Figure 6.3	Role based modelling methodology development and application steps	74
Figure 6.4	Competency type distribution at incremental levels	76
Figure 6.5	Role Identification from the FFL assembly activity diagram	83
Figure 6.6	Role dependencies within targeted process area	83
Figure 7.1	Causal loop dynamics analysis with role modelling concepts	92
Figure 7.2	Snapshot of Plant Simulation software interface	96
Figure 7.3	Change dynamics types within product realisation system	97

Figure 7.4	Table family products in experiment scenario	100
Figure 7.5	Table assembly section simulation model layout	105
Figure 7.6	Preparation frame	106
Figure 7.7	TopMaker frame	107
Figure 7.8	Pedestal Frame	107
Figure 7.9	Delivery Frame	107
Figure 7.10	Illustration of data input: receiving parts – Preparation Role	108
Figure 7.11	Example of resource specification	109
Figure 7.12	Example of operation data input – the TopMaker role	109
Figure 7.13	Snapshot to model simulation execution	110
Figure 7.14	Role re-design of the table assembly process	114
Figure 8.1.	Research reflection format	117
Figure 8.2.	Research Reflection Summary	118
Figure 8.3.	General modelling scope of the second case study	122
Figure 8.4.	Inter-relationship impact of R-BMM and its application	126
Figure 8.5.	Proposed role type category and example roles	127
Figure 8.6.	Conceiving of DPU combined use in R-BMM as role holder	127
Figure 8.7.	Computerised CIMOSA building tool snapshot (in developing)	129
Figure 9.1	Enhanced modelling approach for future industrial application	137

Index of Tables

Table 1.1	Gradual trends impacting on present day organisations	1
Table 1.2	Descriptions of knowledge perspectives	7
Table 2.1.	The definitions of sub-constructs of manufacturing flexibility	12
Table 2.2.	Three elements to Discrete Event Simulation	29
Table 2.3.	Discrete event simulation execution manner	29
Table 2.4.	Basic concepts difference for discrete and continuous simulation model	30
Table 2.5.	Comparison of current main commercial component model tool	37
Table 4.1	Comparison between SIMUL8 and Plant Simulation	48
Table 4.2	The Methodology adopted during this Research	51
Table 5.1	Flow Control Logic (FCL) node list	62
Table 5.2	Sub-Process Node(SP) specification table in BP723	66
Table 5.3	AND Node(AN) specification table in BP723	67
Table 6.1.	Competency Type incremental classification	76
Table 6.2.	Competency Criticality Level classification	77
Table 6.3.	Specified competency collection list template	77
Table 6.4.	Competency applicability among resource	78
Table 6.5.	Planning template of role assignment to candidate role holder resource	79
Table 6.6	Competency requirements specification (partial)	84
Table 6.7	Competency possession distribution among resources (partial)	85
Table 6.8	Skill level related to applicable competency	85
Table 6.9	Resource evaluation as candidate role holders (R1)	86
Table 6.10	Resource evaluation as candidate role holders (R3)	87
Table 6.11	Resource evaluation as candidate role holders (R6)	87
Table 6.12	Role assignment and resource allocation (Single scenario)	88
Table 7.1	Variable experiment change matrix template	99
Table 7.2	Experimental Scenario Set 1	101
Table 7.3	Experimental Scenario Set 2	102
Table 7.4	Experimental Scenario Set 3	103
Table 7.5	Experimental Scenario 4	104
Table 7.6	Main building block with customised icons in the model	106
Table 7.7	Building blocks link to R-BMM entities	106
Table 7.8	Assembled table and value generation within 3 month	110
Table 7.9	Resources utilisation percentage (Scenario 2-3b, As-Is)	111

Table 7.10	Resources utilisation percentage (Scenario 3-4, To-Be)	111
Table 7.11	Paradigm of value added and cost comparison in simulation	112
Table 7.12	Assembled table and value generation within 3 month (re-designed)	115
Table 7.13	Resources utilisation percentage (re-designed)	115
Table 7.14	Value added and cost comparison in simulation (re-designed)	115
Table 8.1	FFL second case study summary	123
Table 8.2	Terminology explained: an example DPU description card	128
Table 9.1	Main concepts and methodology achievement	132

Index of Abbreviation

ACT – ACTivity diagram (of CIMOSA RPM's approach)

ARIS – Architecture for integrated Information Systems

AGV – Automated Guided Vehicle

BP – Business Process

BPM – Business Process Management

BPR – Business Process Reengineering

CIM – Computer Integrated Manufacture

CIMOSA – Computer Integrated Manufacture Open System Architecture

CLM – Causal Loop Modelling

CTX – ConTeXt diagram (of CIMOSA RPM's approach)

DES – Discrete Event Simulation

DM – DoMain

DL – Drop Leaf (one table family in case study furniture company)

DP – Domain Process

DPU – Dynamic Producer Unit

EA – Enterprise Activity

EAI – Enterprise Application Integration

EAU – Engine Assembly Unit

EM – Enterprise Modelling (Plural MEs)

EMEIS – Enterprise Model Execution and Integration Services

EMI – Enterprise Modelling and Integration

FCL – Flow Control Logic

FFL – Fixed Furniture Limited (Referred name of case study furniture company)

FMS – Flexible Manufacturing Systems

GIM – GRAI Integrated Methodology

GRAI - Graphe `a R`esultats et Activit´es Interli´es

ICAM – Integrated Computer-Aided Manufacturing

IDEF - ICAM DEFinition Languages

IEM – Integrated Enterprise Modelling

INT – INTeraction diagram (of CIMOSA RPM's approach)

J2EE– Java 2 platform Enterprise Edition

JIT – Just In Time

KADS – Knowledge Analysis and Design Support

MANDATE – MANufacturing management Data Exchange

ME – Manufacturing Enterprise

OSI – Open System Interconnection

PERA – Purdue Enterprise Reference Architecture

R-BMM – Role Based Modelling Methodology

RPM – R.P.Monfared ‘s CIMOSA modelling diagram approach

SADT – Structured Analysis and Design Technique

SE – Systems Engineering

SM – Simulation Modelling

STEP – Standard for the Exchange of Product model data

STR – STRucture diagram (of CIMOSA RPM’s approach)

UI – User Interface

UML – Unified Modelling Language

WfMC – The Workflow Management Coalition

CHAPTER 1

The Needs For Complex Manufacturing Resource Systems

During recent decades, globalisation has changed our socioeconomic world. Since the late 1990's the business environment has been progressively grown in complexity and become less certain than ever before. This has impacted significantly on the way that Manufacturing Enterprises (MEs) operate and compete. In general MEs themselves are complex entities: designed, operated, managed and changed by people; to realise people requirements, aspirations and desires; by deploying people and technological resources in systematic, timely and innovative ways so as to generate competitive behaviours. Because typically MEs have multi-purposes and multiple stakeholders it is difficult to decide how best to develop the social and technological systems they deploy and it is difficult to change them rapidly and in ways that enhance overall ME competitive behaviours.

1.1 CURRENT MANUFACTURING ENTERPRISES FEATURE

Manufacturing 2020 Programme [www.foresight.gov.uk] analysed the globalisation phenomenon and observed and recommended that tools need to be developed that enable real time modelling and decision-making within companies that can be shared with customers and suppliers within related value chains. Similarly, agile, lean, and remote manufacturing philosophies, technologies and systems need to be developed to enhance the performance of manufacturing processes.

Hammer and Champy (1993) observed three driving forces behind ongoing radical change, namely:

1. customers who can now be very diverse, segmented, and are expectant of consultation;
2. competition that has intensified to meet the needs of customers in every niche; and
3. change that has become pervasive, persistent, faster and in some markets a pre-requisite.

In our everyday lives most of us have felt consequences from those forces. In combination these forces are impacting on present day organisations leading to: globalisation; increased competition; greater customisation; increased need to respond to ethical and moral issues and new legislations; reduced lead-times; and reduced total cost. These kinds of phenomenon are listed in Table 1.1.

Table 1.1 Gradual trends impacting on present day organisations

Stage	Trends	Philosophical catalogue	description
1	Globalisation	Ontology	Globalisation existing as inevitable phenomena, is a general trend
2	Increased competition	Epistemology	Brings both opportunity & challenge, people must be aware of intense business competition

3a	Customisation	Methodology	Satisfy the diversity of individual customer requirements
	Increase responsiveness to new ethical & moral issues and legislations		Effectively deal with ethical & moral issues and legislation in wider cross cultural social-economic environment
3b	Reduce lead-times		Need to reduce lead-time and total cost, target higher customer satisfaction and profitability
	Reduce total cost		
4	Develop overall business performance to survive	Consequence	Facing 1, having awareness to 2, find solutions to achieve 3, leading to higher performance to survive and become competition winner.

Such trends have directly led to some essential impacts on current MEs. One prime impact chain has led to increased ME competition on the basis of (1) providing custom products and services and this has resulted in a significant increase in product variety and significantly shorter product lifetimes. (2) While MEs must drive down product costs and profit margins, for reasons that include: lower cost labour may be deployed (e.g. via suitable location of manufacturing facilities) and because new materials and technologies can create smaller, lighter, easier to produce and hence cheaper products. This has induced a need for MEs to focus on core competencies and to partner with other MEs that have complementary competencies, in order to realise customer facing products and services, with competitive functionality, cost and timeliness. These trends are changing the composition of MEs. Dedicated and fixed production lines are being replaced by more “agile” or “flexible” resource systems. High stock levels are being reduced by using methods and techniques like “Lean” and Just-In-Time (JIT): computer-based systems have supported most manufacturing procedure [Hayes, et al 1988]. These changes have largely been in response to the increasing need for companies to become competitive; not only in terms of cost, but also with regard to quality and responsiveness to customers [Storey, 1994 and Crainer, 1996]. Such developments figured appropriate and effective use of advanced manufacturing technology; which in turn needs new knowledge about how they can be successfully adopted into manufacturing enterprises.

1.2 CHANGE REQUIREMENTS TO MANUFACTURING SYSTEM

It was realised during the 1970s that designing a manufacturing system to achieve a set of strategic objectives of a ME involves a series of complex decisions made over time [Hayes and Wheelwright, 1979]. To achieve this in a way that supports a ME’s high-level objectives and requires an understanding of how detailed design issues affect interactions among various components of a manufacturing system. In practice, designing the details of manufacturing systems (including aspects such as equipment design and specification, layout, manual and automatic work content, material information flow, etc.) that is supportive of a ME’s business strategy has proven to be a difficult challenge. Manufacturing systems are complex entities involving many interactive elements, it can be difficult to understand the impact of detailed deficiencies and to change the performance of a manufacturing system as a whole. In order to establish an effective manufacturing strategy in today’s turbulent environment, ideally MEs continuously need to be re-optimised concerning their process-resource system composition and structures, so that they form an integral part of an entire logistical chain of suppliers, production processes, distribution and servicing functions.

1.2.1 Typical ME processes characteristics and resource requirements

Processes are an abstract conceptualisation rather than reality [Chatha,2003]. Processes have a defined beginning, body of execution and end within a finite life span; processing structure can be relatively stable with many similar process instants realised over long time frames [Poli,2004]. Weston [1999] explains that relatively 'endurable' proprieties of process networks can naturally conceptualise and specify enterprise activity requirements with a re-usable form; and that resource systems are needed to 'realise' those requirements within time, cost, flexibility and robustness constraints. Resource systems are composed of combinations of people, machines and support computer hardware and software. Functional abilities of technical resource systems (i.e. machines and software) that can be brought to bear on processing requirements are often referred to as their 'capabilities'. Whilst functional abilities of human systems (i.e. teams, groups of people or individuals) are normally characterized in terms of the 'competences' they possess [Vernadat,1996]. Resource system organisation is achieved via 'structures' such as methods, project plans, procedures, product structures, work lists, process routes, workflow specifications business rules, state transition descriptions. Some of these structures may be relatively constant (or enduring) other structures many change frequently over time. Significant benefit can be gained by developing and reusing separate models of (1) processes and (2) candidate resource systems, with abilities to realise processes [Vernadat,1996]. It's important to conceptualises such a separation in MEs where processes and resource systems often have distinctive life times and change requirements. For example, the introduction of a new production philosophy may require a once only restructuring and re-engineering of enterprise activities, but various alternative resource system's instances may need to be deployed many times during the useful lifetime of the restructured process. Where products themselves have significantly distinctive processing requirement, distinctive process instance flows may need to be created. New and existing process flows may share common product realizing activities, but to meet different products requirements these activities may need to be physically or logically linked differently; requiring so called generate distinctive 'physical flows' (e.g. of materials and products) and 'logical flows' (e.g. of information and control). Essentially these kinds of organisation structure can be viewed as being both process and product oriented, so that a variety of product applications can be specified and realised in quantities, and by due dates, required by customers. Economies of scope may come primarily from using a common resource set to realise sequential and concurrent instances of multiple process flows; as such a requirement increases in general so will opportunities to cost-effectively utilise available resource system capacity. But the down side of realising economies of scope is that it introduces increasing organisational complexity concerns.

1.2.2 The need for systemically structured process and resource system change

Implicit within the foregoing discussion is the notion that formalising any change realisation to ME processes and resource systems itself requires procedures and set of instructions [Weston, 1999]. General steps which can be used in this respect can include (1) change in process design (i.e. modify the composition and structures binding ME activities and process segments); (2) change in resource system assignment being based on existing process structure definitions (As-Is basis); (3) modified process conceiving resource system comparative testing; (4) then verify and finalise changed process-resource system association. But in general such steps constitute complex requirements because changing one ME process can have causal impacts on other ME processes and their underlying systems. In addition, generally this necessitates the involvement of a number of change actors (personnel in most cases) with sufficient collective competency to conceive, specify and implement needed compositional and structural change, to avoid problems or failure due to ad-hoc change implementation. So that they accomplish their tasks in an ordered, timely and effective manner, generally change actors will benefit from deploying suitable personal productivity and group productivity tools. However, complex causal dependencies exist between ‘design variables’ (all those involved elements during process change process design), and this illustrates why in reality every ME is a unique, complex entity which typically is subjected to ongoing change processes. That said, some aspects of ME processes are relatively enduring (i.e. can be considered to be static over the timeframe of concern to a given change process and set of change actors), whereas other aspects are dynamic in that they demonstrate ongoing changes in state (and associated state transitions) over the timeframe of concern (where the concerned dynamic behaviours may or may not be of a predictable nature). It follows that large scale change processes will typically be decomposed into a number of more limited scope change processes, instants of which may be resourced via suitable change actors, structures and tools to cater for change to short term operational needs. Whereas other change process segments will be matched to tactical and strategic change requirements, timeframes and frequencies. In general any change process will have an implicit requirement to conceive needed changes, specify ways in which the changes can be realised and implemented as required. Some forms of ME resource system are inherently change capable [Harrison et al. 2001] and this can facilitate implementation of process change. For example, some aspects of programmable machines (such as a robot or CNC machine) can be changed readily. This will be the case should specified changes be within the envelope of reachable states and state transitions that correspond to that machine’s capabilities. Similarly people and teams possess competency and capacity to achieve some kinds of activity and behaviour, e.g. to accomplish tasks. Human centred resource systems can reflect on the activities they perform and typically can gain new insights and competencies (e.g. knowledge and skills) over time. However the use of a change capable resource (such as a person or robot) rather than a highly specialized resource (such as a special purpose machine) may lead to inferior runtime performance of a process (in terms of lead time, cost and robustness. There needs therefore to be means to predict whether such a ‘change capable resource’ is also ‘performance acceptable’ (i.e. can deliver required operation performance with pre-defined specific levels even when changes are made. Thus it is necessary to know the consequence of any process or resource change on its related ME processes environment.

1.2.3 Requirements of complex manufacturing resource systems

Potentially well-conceived process-oriented views of MEs can be used by process and production system engineers to improve their current practice as they specify, design and sanction human and technical resource system change. However this potential can only be realized with sufficient understanding and clear identification of current resource system needs.

1.2.3.1 Functional requirement

Required functional capabilities of candidate systems can be deduced from knowledge about the various types and instances of process that MEs deploy; as they conduct business in a profitable and sustainable manner. In theory MEs seek competitiveness by deploying systems that closely match their specific processing needs. There is evident commonality of purpose and function between types and instances of processes used by MEs. One clear unifying need is for systems that structure and co-ordinate the way in which grouped people and technical resources accomplish various types of enterprise activity. There are many types of possible enterprise activity and many kinds of dependency between activities. Hence an extremely wide range of functionalities need to be provided by ME human and technical resource systems at large: albeit that any specific vending of such systems can focus attention on satisfying requirements of selected subsets of enterprise activities.

1.2.3.2 Decomposition requirement

It follows that a rational basis is needed to decompose general ME requirements into classes of ME system with defined specific requirements that can be readily selected and tailored to specific ME needs; prior to change implementation. In addition, Sackett & Fan [1989] stated that the decomposition and identification of a system goal is not a static problem: it concerns decision making to achieve system goals change with time.

1.2.3.3 Inherent need to handle multiple resource system types

It can be deduced that it is impractical to suppose that a single, universal ME system could be designed to systemise all needed classes of ME process types and instance; covering all variable ME activities and their dependencies. Implicitly therefore there arises a need to conceive, develop and systematically use multiple resource types. System composition and system behaviours can be programmed to handle anticipated changes or to reactively modify responses to unanticipated changes in business requirements and environmental conditions.

1.2.3.4 Requirement of resource system integration and alignment to process definitions.

ME resource systems should enable dependencies between concurrently executing threads of ME processes to be realised, underpinned and maintained. In so doing ME systems should enable necessary material and product flows, information and control flows, and exception flows to be overlaid onto selected sets of enterprise activities. By such means people, machines and software applications responsible for realising activities should work in a systematic and effective manner. Within each ME case more than one human and technical system will need to interoperate to realise all needed ME processes. If any given set of ME systems that need to interoperate are derived from a common system decomposition, in principle their interoperation should be more effective and readily achieved.

1.2.3.5 Organisational requirement

All the above complex requirements from functional, structural and integration aspects essentially require ME process and resource system elements to be organised appropriately, and adjust their organisation accordingly when change occurs, so that process integration and system interoperation are appropriately enabled and do not overly constrain interworking in a specific ME by imposing inappropriate organisational boundary conditions.

1.3 REQUIREMENT FOR KNOWLEDGE SHARING AND RE-USE

For MEs to remain productive and effective, in general they are concerned as being dynamic process-resource hybrid systems. People need to be involved in designing and changing organisations as decision makers and decision actors. This is because (1) necessary understandings and knowledge about what can and cannot be done is normally distributed amongst different knowledge holders, (2) various personnel will normally have different responsibility for, and hence need to ‘buy into’, identified changes, and (3) because a range of business, managerial, technical and social skills are needed to realise organisational change on any significant scale.

The above knowledge-intensive-needs in MEs includes: knowledge gathering, design, developing, testing, deploying, maintaining, project coordinating and management. As an ME grows in size and complexity it becomes less likely that the members involved in a single ME resource system will possess all the knowledge necessary for the aforementioned requirement, This underlies the need for knowledge sharing support to enable the resource system (especially the related staff as human resource) to (1) identify the specific requirements of the system segments for which they have concern; (2) capture non-externalised knowledge about resource elements; (3) bring together knowledge from distributed sources to form a repository of organisational knowledge (group knowledge of knowledge library); (4) effectively share domain expertise between diverse teams across process and value streams; (5) retain knowledge that would otherwise be lost due to the loss of experienced staff; and (6) improve the use and dissemination of organisational knowledge.

Schreiber et. al (1999) summarised knowledge into seven different perspectives which need to be shared as Common Knowledge Analysis and Design Support (KADS), as seen Table 1.2, which represents a collection of knowledge, to support knowledge based system development.

Table 1.2 Descriptions of knowledge perspectives

Perspective	Description
What	knowledge encompasses concepts, physical objects and states. It also includes knowledge about classifications or categorizations of those states.
How	Knowledge about actions or events. It includes knowledge about which actions are required if certain events occur,
which	actions will achieve certain states and the required or preferred ordering of actions.
When	actions or events happen, or should happen; it is knowledge about the controls needed on timing and ordering of events.
Who	The agents (human or automated) who carry out each action, and their capabilities and authority to carry out particular actions.
Where	Where knowledge is needed and where its comes from communication and input/output knowledge.
Why	Rationale: reasons, arguments, empirical studies and justifications for things that are done and the way they are done

(Source: Schreiber, 1999)

The above classified description of knowledge management implies the necessity for organisations:

- to be able to capture and represent their knowledge assets;
- to share and re-use their knowledge for differing applications and differing users;
- this implies making knowledge available where it is needed within the organization;
- to create a culture that encourages knowledge sharing and re-use.

Modelling, as an abstraction of reality, can also be considered as one type of documentation of knowledge. Thus knowledge sharing and re-use can be considered from a modelling point of view as being concerned about: (1) Re-usability of models: where models developed to analyse ME cases in some particular area may deploy a model structure which could be used in other cases and areas; (2)

Re-usability of modelling methodology: such as where the methodology is deployed and/or developed during model generation, could be imported and transferred for other models building in similar cases and areas and (3) re-usability of tools: where a suitable tool could widely be used.

1.4 REQUIREMENTS TO MODEL ASPECTS OF INTEGRATION

The complexities of the modern enterprises, and the challenging environment in which enterprises exist, demands a new type of engineering professional. Enterprises are just like any other complex system that can be engineered systematically [Bernus et al, 1996 (Source: Bernus & Nemes, 1996)]. With these requirements in mind, the Society for Enterprise Engineering [SEE, 2004] defined enterprise engineering as "that body of knowledge, principles, and practices having to do with the analysis, design, implementation and operation of an enterprise".

Enterprise engineering can be split into Enterprise Modelling (EM) and Enterprise Integration (EI) where EM is considered as a pre-requisite to aid EI [Bernus et al, 1996, Aguair & Weston, 1995]. EM was defined as 'the set of activities, methods, and tools related to developing models for various aspects of an enterprise [AMICE,1993]. It aims to provide a set of common languages to describe various aspects of the enterprise at different abstraction levels (e.g. business level, engineering level or operational level) and from different perspectives (e.g. function view, information view or organisation view) [Vernadat, 1996]. Currently, there is an increasing need in manufacturing industry for sound and precise techniques for enterprise modelling and capitalisation of acquired experience and know-how. To improve this, the Enterprise Modelling domain therefore seeks to provide a set of common tools to describe the enterprise at different levels of abstraction; and as such to provide a basis for business process re-engineering.

Integration has always intrigued scientists and practitioners in trying to improve systems through cooperation of related elements. Very different meanings have been associated with the word integration ranging from social sciences to system sciences, and from cultural to economic systems integration. But the basic goal is always the same, i.e., to improve the overall system efficiency by linking its elements by means of communication networks. Thereby obtaining a higher responsiveness and effectiveness of the whole system compared with the isolated operation of its components. More modern evolution of the meaning of enterprise integration, refers to the fact that integration is always a matter of networks. More specifically, Williams (1998) defined enterprise integration as "The coordination of the operation of all elements of the enterprise working together in order to achieve the optimal fulfillment of the mission of that enterprise as defined by enterprise management".

The primary reason for the limited success of comprehensive enterprise modelling and analysis methods on a large industrial scales is that these methods are generally very elaborate and require significant skill and expertise to be used effectively. They operate on very intricate models of the enterprise being analysed. Such models require specific formats and use technical jargon hardly comprehensible to the non-initiated. In addition, the dichotomy between the models created for analysis and the actual enterprises they represent has promoted the impression that enterprise analysis is complex, time consuming, and prohibitively expensive. This perception is reinforced by the following characteristics of today's modelling and analysis efforts:

- Enterprise analysis efforts are analyst-dependent. To produce executable models, most enterprise analysis methods rely heavily on a group of experts with considerable knowledge and experience in the domain-specific modelling and analysis tools and methods.
- Enterprise analysis involves time- and communication-intensive activities. The communication between the domain experts who possess in-depth knowledge of the enterprise to be analyzed and the analysts who are experts in their particular modelling and analysis methods is probably the most critical part of the enterprise analyses effort. A significant amount of the effort spent is not reusable. The knowledge that is transferred from domain experts to an analyst is mostly an ad hoc one and is seldom possible to reuse in other analysis efforts of a different nature.
- Decision-makers are not in control of the enterprise analysis effort. The prevailing approach used to model and analyze a particular problem of the enterprise depends on the knowledge and experience of the analyst and is not easily understandable to the decision-maker. These four characteristics are often viewed by decision-makers as significant, if not insurmountable, obstacles that are far too costly to overcome. Therefore, a major challenge MEs face is to increase the use of enterprise analysis methods in businesses and organizations through the provision of tools and methods that will address their changing needs without the need to make disproportionate investments in so doing.

1.5 PROBLEMS AND OPPORTUNITIES WITHIN ME PROCESS-RESOURCE SYSTEM DESIGN, MODELLING AND INTEGRATION

From a business perspective, although many companies and their senior management boards have been widely aware of critical needs to re-design their organisations and to re-organise their business operations, they have very little idea about what exactly they need to do. In many organisations causal impacts between product, process and resource elements may not be widely understood; nor how this bears relation to the operations that form value-chains [Mintzberg & Heyden, 1999]. Traditional organisation charts do not detail process roles and interaction between customers, people and other resources and many company employees may be unaware of the network of processes involved in realising products, and how many different types of flows of products, resources, cost, data and information pass through the entire enterprise. Hence, there is a need to develop new approaches that make those understandings more explicit so that improved decision making can be made in organisations at large.

From a methodology perspective, it is observed that today's enterprise engineering and modelling should benefit from a number of different modelling approaches. Within the enterprise modelling field, many theoretical approaches and commercial software tools have been developed. Many of them are based on different principles or consider similar problems from different viewpoints. They may also focus on and enable different techniques. On their own many of these modelling approaches have a specific and limited deployment area. This panorama leads to the necessity to deploy a number of complementary modelling approaches when solving complex organisation re-engineering problems. Often off-the-shelf enterprise modelling systems, cannot satisfactorily support the overall working of an organisation because: (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 systems (based on different architectural styles) are implemented in different parts of the organisation [Weston, 1999]. In order to model the various parts of an enterprise properly, the use of a set of complementary modelling tools needs to conform them to a common architecture. Also related organisation design practice should define or refine, conform to, and possibly develop, such an architecture. Hence a true picture of the design and working of an organisation should include specified requirements of the systems that will be built to support the working of the organisation.

From a technical perspective before any grouping of modelling techniques can be utilised effectively to life-cycle engineer MEs, exploratory research, linked to case study analysis is necessary, to determine and prove the use of unifying modelling concepts and methods which can systemise and quantity benefits, constraints and costs of any given group of techniques.

Hence following literature review and analysis in the next two chapters, this thesis reported a set of state of the art modelling techniques was selected with a view to quantitatively predicting the benefits and costs of alternative manufacturing system configurations. Importantly deploying that choice allowed qualitative and quantitative prediction with reference to the business context in which any subject ME and its manufacturing systems must operate. Following which a set of unifying concepts and methods was conceived to enable the modelling techniques to be deployed in a coherent way. This was followed by conducting case study testing based on practical manufacturing scenarios drawn from an actual industrial ME. The overall research approach is considered to provide a reference model for the development of improved modelling techniques. The method adopted will be discussed in detail in Chapter 3.

CHAPTER 2

Literature Review

The description of the broad research scope indicated academic disciplinary areas in which further literature should be reviewed. Keeping this in mind this chapter reviews those key literature on flexibility, enterprise engineering, manufacturing systems, business process re-engineering, workflow management and in these areas considers modelling requirements, dynamics, exception handling and modularity.

2.1 MANUFACTURING ENTERPRISE FLEXIBILITY

2.1.1 Understanding of Flexibility

Upton [1995] defines flexibility as increasing the range of products available, improving a firm's ability to respond quickly, and achieving good performance over this wide range of products. At least 50 different terms for various types of flexibility can be found in the manufacturing literature [Sethi and Sethi, 1990], and can be understood with respect to the following three aspects:

- As a characteristic of the interface between a system and its external environment [Correa, 1994]. From this view point, flexibility acts as a filter, buffering the system from external fluctuation. Flexibility thus functions as an absorber for uncertainty.
- As a degree of homeostatic control and dynamic efficiency of a system [Mariotti, 1995]. Reference is made to a cybernetic system, namely one which incorporates mechanisms of measurement, control and regulation aimed at homeostasis; that is to say at the preservation of an existing state in the presence of exogenous changes. Flexibility is thus mainly understood as a degree of cybernetic adaptation.
- As an adaptation or change capability; was considered and extended to firms and concerns the range of states reachable and time for moving as a consequence of the variety and the uncertainty of demand [De Toni and Tonchia, 1998].

2.1.2 Manufacturing flexibility

Flexibility has been considered to be one of four dimensions of manufacturing strategy [Olhager 1993]. Hayes and Wheelwright [1984] consider manufacturing flexibility to be a strategic element of business, along with price (cost), quality, and dependability. Priorities assigned to each of these factors determine how an organization positions itself relative to it competitors. [Sethi and Sethi,1990] consider manufacturing flexibility as a set of elements that are integrally designed and carefully linked to facilitate the adaptation of processes and equipment to a variety of production tasks A classification of manufacturing flexibility often cited in the literature is that by [Browne et al.,1984] which, taking into account the Flexible Manufacturing Systems (FMS), considers eight different types or dimensions of flexibility:

- Machine flexibility: the ease of change to process a given set of part types'; sub-set of parts.
- Product flexibility: the ability to change to process new part types.
- Process flexibility: the ability to produce a given set of part types.
- Operation flexibility: the ability to interchange ordering of operations on a part.
- Routing flexibility: the ability to process a given set of parts on alternative machines.
- Volume flexibility: the ability to operate profitably at varying overall levels.
- Expansion flexibility: the ability to easily add capability and capacity.
- Production flexibility: the universe of part types that can be processed.

Hyun and Ahn [1992] introduced a cone model and suggested that flexible manufacturing competence involves sub-constructs. Their seven types of definition for these sub-dimensions of manufacturing flexibility are given in Table 2.1.

Table 2.1. The definitions of sub-constructs of manufacturing flexibility

Construct	Definition	Literature
Manufacturing flexibility	The ability of the organization to manage production resource and uncertainty to meet various customer requests	Chen et al. (1992), Leong et al. (1990)
Machine flexibility	The ability of a piece of equipment to perform different operations economically and effectively	Gupta (1993), Hyun and Ahn (1992), Chen et al.(1992), Sethi & Sethi(1990)
Labor flexibility	The ability of the workforce to perform a broad range of manufacturing tasks economically and effectively	Upton (1994), Hyun and Ahn (1992), Ramasesh and Jayakumar (1991)
Material handling flexibility	The ability to transport different work pieces between various processing centers over multiple paths economically and effectively	Hutchinson (1991), Sethi and Sethi (1990), Coyle et al. (1992)
Routing flexibility	The ability to process a given set of part types using multiple routes economically and effectively	Upton (1995), Gerwin (1993), Sethi and Sethi (1990)
Volume flexibility	The ability of the organization to operate at various batch sizes and/or at different production output levels economically and effectively	Carlsson (1989), Gerwin (1993), Sethi and Sethi (1990)
Mix flexibility	The ability of the organization to produce different combinations of products economically and effectively given certain capacity	Boyer and Leong (1996), Sethi and Sethi (1990), Gupta and Somers (1992)

(Source: Zhang Q et al, 2003)

2.2 SYSTEM THINKING AND ENGINEERING

2.2.1 Concept of System Thinking

"Systems" naturally exists throughout the whole world; wherever we have complex behaviour emerging from interactions among things that make networks [Kornwach and Jacoby,1996].

O'Connor [1997] defined Systems thinking as "a unique approach to problem solving", which views certain "problems" as parts of an overall system, rather than focusing on individual outcomes and contributing to further development of the undesired element or problem. Capra [1996] stated that system thinking is the only way to fully understand why a problem or element occurs and persists; and to understand the part in relation to the whole

"Systems Thinking" has become an organisational buzz word in the last decade since Peter Senge [Senge, 1990] first wrote *The Fifth Discipline*. Systems and the application of systems thinking has been grouped into three categories based on the techniques used:

- Hard systems — involving simulations, often using computers and the techniques of operations research. Useful for problems that can justifiably be quantified.
- Soft systems — For systems that cannot easily be quantified, especially those involving people holding multiple and conflicting frames of reference. Soft systems are a field that utilizes foundation methodological work developed by Checkland [1981] and Wilson [1990].
- Evolutionary systems — developed by Banathy [1996], a methodology that is applicable to the design of complex social systems. This technique integrates critical systems inquiry with soft systems methodologies.

"System Thinking" implies the thinking of systems as a whole rather than as simply an assembly of distributed and separate components [Von Bertalanffy 1976; Laszlo, 1996]. Which means not only collect components, but also put them into a rule-set environment. It extends beyond one sole system boundary to consider outside factors influencing the system [Axlerod, 1997]. More all-sided, it considers the operation of the system from its original inception, through its whole life cycle to its eventual disposal. Thus it could cover all systems of significant size including people, and people working with technology so as to form socio-technical systems.

2.2.2 Systems Engineering (SE)

Systems engineering (SE) is defined as the art of designing and optimising complex systems, starting with an expressed need and ending up with a complete set of specifications for all the system elements [Daenzer and Huber 1985]. Bahill and Dean [1999] consider Systems Engineering as an overall interdisciplinary process that ensures that the customer's needs are satisfied throughout a system's entire life cycle. They defined a process comprised of the following seven tasks.

1. *State the problem.* Stating the problem is the most important systems engineering task. It entails identifying customers, understanding customer needs, establishing the need for change, discovering requirements and defining system functions.
2. *Investigate alternatives.* Alternatives are investigated and evaluated based on performance, cost and risk.

3. *Model the system.* Running models clarifies requirements, reveals bottlenecks and fragmented activities, reduces cost and exposes duplication of effort.
4. *Integrate*. Integration means designing interfaces and bringing system elements together so they work as a whole. This requires extensive communication and coordination.
5. *Launch the system.* Launching the system means running the system and producing outputs -- making the system do what it was intended to do.
6. *Assess performance.* Performance is assessed using figures of merit, technical performance measures and metrics -- measurement is the key. If you cannot measure it, you cannot control it. If you cannot control it, you cannot improve it.
7. *Re-evaluation.* Re-evaluation should be a continual and iterative process with many parallel loops.

Bahill and Gissing [1998] summarized the above process as figure 2.1, with the acronym SIMILAR.

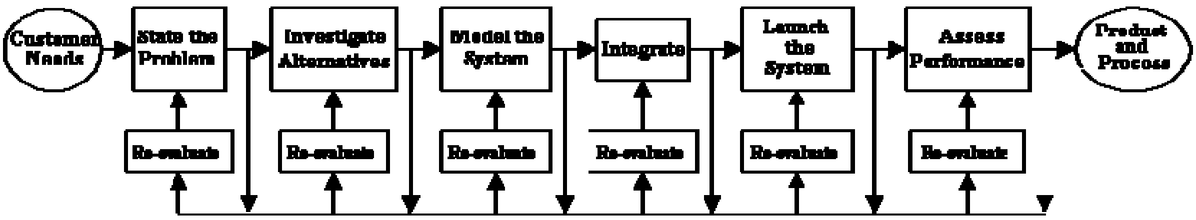


Figure 2.1. The system engineering process (Source: Bahill & Gissing, 1998)

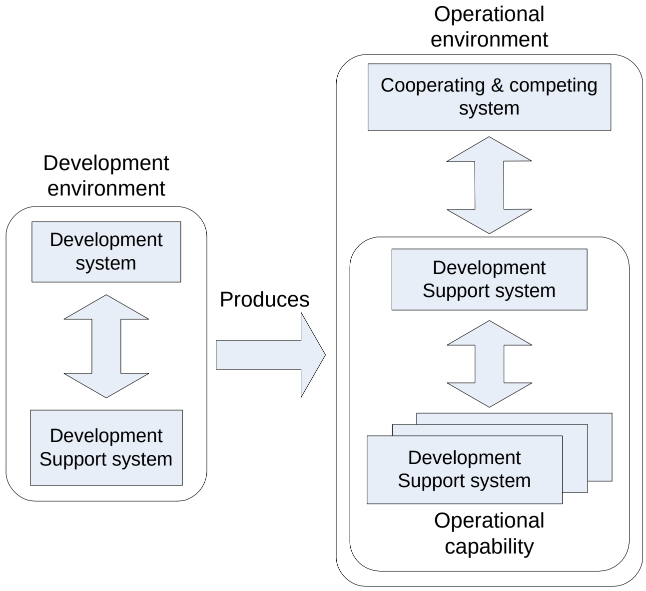


Figure 2.2. Development and Operational Systems [Source: Stevens et al, 1998]

As shown in Figure 2.2, the environment of one system may consist of a number of “external systems” such as cooperating or competing systems with which a product interacts and has to survive. Making an end product needs development support systems and perhaps a system to install or mass-produce the product [Steven et al, 1998]. Therefore, System Engineering is the expanding of research into multi-systems, "an interdisciplinary, comprehensive approach to solving complex system problems and satisfying stakeholder requirements" [Martin, 1997]. Where interdisciplinary means that systems engineering work traverses across more than one single system; complex systems normally require individuals from a variety of engineering and non-engineering specialties and functional areas contributing skills and knowledge in an integrated manner to realise an effective and efficient system.

Stevens [1998] stated that the development of SE is about creating effective solutions to problems and managing the technical complexity of resulting developments. From the outset, it is a creative activity centred on defining system requirements, and then concepts and details embedded into the product to be built. Then the emphasis switches again, to integration and verification, before delivering the system to the customer. According to [Martin, 1997], defining SE basically consists of three elements:

- SE Management – plans, organises, controls and directs the technical development of a system or its products.
- Requirements & Architecture Definition **–** defines the technical requirements based on the stakeholder requirements, defines a structure (or an architecture) for the system components, and allocates these requirements to the components of this architecture.
- System Integration and Verification **–** integrates components of systems at each level of the architecture and verifies that the requirements of those components are met.

2.3 ENTERPRISE ENGINEERING, MODELLING AND INTEGRATION

2.3.1 Enterprise Engineering

Enterprise engineering conceives and engineers enterprises as systems. It includes industrial engineering approaches & methods, and adds new techniques such as workflow management, information system design and analysis, dynamic resource allocation and management, or design of organisational structures. An enterprise has been described as a large complex socio-technico-economic system[Vernadat, 1995]. Such a system is interdisciplinary, with large-scale effort carried out by co-operating teams of users, designers, analysts and managers [Vernadat, 1996].

Mark [1994] stated that an Enterprise Engineering System is composed of four main components, namely: common-sense enterprise model, advisors, visualization, and information agents, as shown in Figure 2.3.

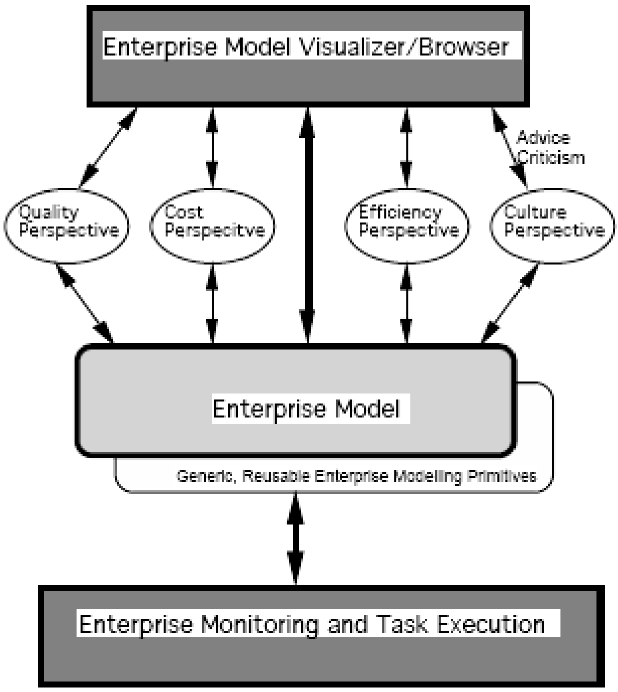


Figure 2.3. Enterprise engineering main components (source: Mark, 1994)

The foundation for the system is the common-sense enterprise model. It provides a set of generic re-useable representations of enterprise knowledge. This includes representations for processes, activities, time, causality, resources, quality, and cost. The enterprise model is used by all other components of the system by providing a shared terminology and set of constraints. Various perspectives exist in an enterprise, such as efficiency, quality, and cost. Any system for enterprise engineering must be capable of representing and managing these different perspectives in a well-defined way. These ideas are formalised in the notion of advisors that are able to analyze, guide, and make decisions about the current enterprise and possible alternatives.

In addition to representing the knowledge in an enterprise, enterprise engineering can be useful when it is able to visualise the different perspectives that we have in the enterprise. This requires the existence of an environment which can graphically represent the advisors in the system and interactions among these advisors; including workflow monitoring and execution.

Lastly, there is an execution environment where the portions of the enterprise design may be, i.e., those portions that define databases and machine executable activities, down-loaded for execution by the run-time system.

2.3.2 Enterprise Modelling

An enterprise could be considered as a set of interdependent business processes [Drucker, 1988; Hammer and Champy, 1993; Hammer, 1996], emphasize process as opposed to hierarchies with special emphasis on outcomes, customer satisfaction, rather than a set of functions [McCormack, 1999; McCormack and Johnson, 2000]. To develop and change a company to conform to this new philosophy requires a new way of thinking and some tools. Often they are based on graphical models which are introduced to illustrate essential concepts and interrelations and to communicate them to others. The term “enterprise modelling” has been introduced [Zachman, 1987], [Kramer and Tyler, 1995] in order to emphasize both the need for high levels of abstraction and the importance of a multi view approach. Vernadat [1996] further gave a definition for enterprise modelling as “the process of building models of whole or part of an enterprise (e.g. process models, data models, resource models, new ontology, etc.) from knowledge about the enterprise, previous models, and/or reference models as well as domain ontologies and model representation languages”. Enterprise modelling covers some set of activities, methods, and tools related to developing enterprise models for various aspects of an enterprise. The basic idea is to model different views on an enterprise and to allow for a seamless integration of the partial models. The methods of enterprise modelling represent a foundation for implementing such a change, and enterprise modelling techniques therefore become a crucial tool.

Fox and Gruninger [1998] viewed an enterprise model in two perspectives namely: design perspective and operation perspective:

Design perspective: Considers issues from the model building stage; the enterprise model should have the function to provide a language used to explicitly define an enterprise. When considering model construction, it should be changeable in terms of organisational structure, behaviour, and should be able to work under different possible sets of constraints that impact on an enterprise, which have existed or may occur during model operation.

Operation perspective: When the model is implemented in practice, it must be able to represent what is planned, what might happen, and what has happened. It must supply the information and knowledge necessary to support the practical operations of the enterprise, whether they can be performed manually or automatically by machines and related systems.

2.3.3 Enterprise Integration

Enterprise Integration (EI) is an interdisciplinary field of study, or discipline, designed to collect and organise knowledge necessary to better implement change processes in the enterprise. EI enables enterprises to achieve a very high level of maturity (called an integrated state). The integrated enterprise may be considered as an entity that has a set of current objectives and carries out its activities so as to successfully fulfil those objectives. As a consequence of this high level characterisation, an integrated enterprise is also an aware enterprise, meaning that changes in the internal or external environment will as soon as possible be reflected in the objectives and in its actions; making sure that activities of all the components contribute to the overall objective in a co-ordinated way. As a result the integrated enterprise is agile, and has a highly dynamic information and material flow [Bernus and Nemes,1997].

Enterprise integration can be approached in various manners. Vernadat[1996] and Weston[1998] defined three levels of enterprise integration through CEN TC310-Work Group 1:

- *Physical System Integration* – essentially concerns systems communication, i.e. interconnection and data exchange by means of computer networks and communications protocols.
- *Application Integration* – concerns interoperability between applications run on heterogeneous platforms as well as access to common shared data by the various applications. Distributed processing environments, common services for the execution environment, application program interfaces (APIs) and standard data exchange formats are necessary at this level to build co-operative systems.
- *Business Integration* – is concerned with integration at the enterprise level, such as business process co-ordination and knowledge sharing at the enterprise level. This requires good understandings about enterprise operations, rules, and structure in terms of functions, information systems, resources, applications, and organisational units. Use of some form of enterprise model and an integrating infrastructure are probably both mandatory pre-requisites of successful business integration.

Michel [1997] considers that integration can be obtained in terms of (1) data (data modelling), (2) organization (modelling of systems and processes) and (3) communication (modelling of computer networks, for example via the 7-layer OSI model).

2.3.4 Standards related to enterprise engineering, modelling and integration

The development of standards in this area has been another major aspect of effort in the last 3 decades. A significant body of development started at the end of the 1970s with the adoption of the ISO 7498 standard for Open System Interconnection (known as the OSI model). At this physical integration level, a well-known standard developed in the 1980s was ISO 9506; namely the Manufacturing Message Specification (MMS). Since the beginning of the 1990s, besides efforts to develop standards at the physical integration level, a number of other standards have been developed that deal with business integration and its application; in terms of concepts, principles, architectures and methodologies. At the international level, ISO TC184 (Industrial Automation Systems and Integration) has been a prime actor in elaborating standards in the area of enterprise modelling and Integration (EMI). Its two subcommittees specifically focus on: standardization of the representation of information (SC4); and standards related to enterprise modelling (SC5), by elaborating ISO 14258

– Concepts and rules for enterprise models, and ISO 15704 – Requirements for enterprise reference architecture and methodologies. Related work performed by SC4 have given rise to: ISO 10303 – Standard for the exchange of product model data (STEP); ISO 15531 – Manufacturing management data exchange (MANDATE); ISO 13584 – Parts library; ISO 14959 – Parametrics; and ISO 18629 Process Specification Language.

The European Union's standardization activities on enterprise integration and engineering are mainly carried out within the frame of CEN TC310 WG1 (System architecture). This frame is primarily focused on discrete manufacturing. Major outputs are: ENV 40003 – Enterprise Integration – Framework for enterprise modelling; ENV 12204 – Constructs for enterprise modelling; and ENV 13550 – EMEIS (Enterprise Model Execution and Integration Services). Other standardization work has been carried out by ISO in collaboration with other organizations, as Joint Technical Committees (JTCs).

2.3.5 Enterprise modelling and integration tools

Based on the above theories and standards, many modelling tools have been constructed and many remain under construction. The following paragraphs briefly overviews existing enterprise models and tools. Widely referenced enterprise modelling frameworks and tools include:

- Structured Analysis and Design Technique (SADT);
- The IDEF Suit of Methods;
- Integrated Enterprise Modelling (IEM) approach;
- Open Systems Architecture for Computer Integrated Manufacturing Systems (CIMOSA);
- GIM-GRAI Integrated Methodology;
- Architecture of Integrated Information Systems (ARIS);
- Purdue Enterprise Reference Architecture (PERA).

2.3.5.1 Structured Analysis and Design Technique(SADT)

SADT was developed for systems analysis and is has become a widely used standard. Colquhoun [Colquhoun et al, 1993] has reviewed a number of applications of SADT. Other important work in CIM systems planning based on SADT has been performed by Schaefer [Williams,1992] and [Krzepinski,1993]. They present a methodology for the design of CAD/CAM process chains. Schaefer focused on 'middle term planning issues' and proposed criteria based on which the need for integration and automation can be recognised. Krzepinski focused on structured modelling and the design process for data processing chains supporting the design process with a thoroughly defined methodology. Both approaches have been applied for the design of industrial CAD/CAM process chains.

2.3.5.2 The IDEF Suit of Methods

The IDEF suite of modelling languages arose in the 1970s out of the U.S. Air Force Integrated Computer Aided Manufacturing (ICAM) program. ICAM undertook the development of a suite of "ICAM DEFinition,", or IDEF methods. These include a so called "function," modelling method (IDEF0), a conceptual modelling method (IDEF1), and a simulation model specification method (IDEF2) [Menzel and Mayer, 1993]. Originally these IDEF methods provided three non-integrated modelling techniques and related applications and tools were developed during 1980s mainly by Douglas Ross [1977], and Timothy Ramey and Robert Brown [1987]. IDEF methods have been extended more recently with the most noticeable being: IDEF3 for enterprise behaviour modeling; and IDEF4 for ontology definition. The early 1990s saw the emergence of IDEF4 and IDEF5. IDEF4 is an object-oriented software design method that integrates requirements specified via other methods through a process of iterative refinement. It also supports the capture and management of design rationale. IDEF5 is a knowledge acquisition and engineering method designed to support the construction of enterprise ontologies [Mayer et al 1994 and 1995]

2.3.5.3 The IEM Approach

IEM borrows the activity box concept from SADT/IDEF0 [Vernadat, 1996]. However in IEM inputs and outputs of this box are states of three kinds of object, namely: product; order; and resource. IEM defines an activity chain (or process) as a sequence of activities combined using concatenation operators that describe the control flow of processes. It can be applied to a system requirements definition or a design specification; but does not provide an implementation description model. It can provide an executable model at the design specification level for simulation purposes [Mertins & Jochem, 1998]. The approach taken by IEM is an object-oriented focus on enterprise modelling but it separates the enterprise models according to only two main views: function view and information view.

2.3.5.4 Open Systems Architecture for CIM Systems (CIMOSA)

CIMOSA [ACIME,1993] was developed within the AMICE project and was the subject of a number of validation projects (VOICE, CODE and CIMPRES). Together with other non-ESPRIT funded projects, a number of partial and particular models of various manufacturing organisations have been built. CIMOSA aims to help companies manage change and integrate their facilities and operations to compete on price, quality and delivery time. It has been reviewed by Kotsiopoulos [1996] and Kosanke [1997], and is considered by many authors to be the most comprehensive of current public domain EM approaches [Vernadat, 1996], [Monfared, 2000]. CIMOSA introduced a process-oriented approach to integrated enterprise modeling; ignoring organisational boundaries, as opposed to various function or activity-based approaches. But more importantly CIMOSA has introduced the idea of open system architectures for CIM. Here an enterprise is considered to be composed of vendor independent standardised CIM modules, described in term of their function, information, resource and organisational aspects, and designed according to a structured engineering approach that can then be plugged into a consistent, modular and evolutionary architecture for operational use [Vernadat, 1996]. CIMOSA comprises: an enterprise-modelling framework; an integrating infrastructure; and a CIM system lifecycle. It presents a model-based approach to enterprise design, enterprise operation and enterprise management.

2.3.5.5 GIM-GRAI Integrated Methodology

Work on the GIM-GRAI methodology began in the 1970's. It was designed to help define a model of an integrated manufacturing system; in order to specify CIM Systems for subsequent purchase or development [Doumeingts, 1984]. Being developed in conjunction with manufacturing industry partners, GIM-GRAI has a strong emphasis on discrete CIM concepts (e.g. parts manufacturing) [Doumeingts, 1987 & 1992]. Another major concept in GIM-GRAI concerns definitions of re-useable modelling elements. GIM is composed of the following elements:

- GRAI conceptual model: a representation of the basic concepts of a manufacturing system, decomposed into three sub-systems: a physical system; decision system; and information system.
- The GIM modelling framework (RA) has three dimensions: views, life cycle, and abstraction level.
- The GIM structured approach: provides guidelines as to how to perform analysis and design of manufacturing systems in three main phases: analysis, user-oriented design, and technical-oriented design.
- GIM modelling formalism languages include: GRAI grid and GRAI nets, for decision system modeling; IDEF0 and stock/resource concepts for physical systems modeling; ER for information system modeling; IDEF0 for functional system modelling.

2.3.5.6 Architecture of Integrated Information Systems (ARIS)

ARIS stands for *ARchitecture for integrated Information Systems*. It deals with business-oriented issues of enterprises (such as order processing, production planning and control, inventory control, etc.). The focus of ARIS is essentially on software engineering and organisational aspects of integrated enterprise system design [Vernadat, 1996]. ARIS has been applied in a number of industrial re-engineering projects and can be considered as one of the market leaders in enterprise modelling [Didic, 1993]. Besides supporting analysis tasks, the ARIS tool set provides specialised support for the selection of software packages (e.g. PP&C or CAD systems) for enterprises. In support of its use, the ARIS tool allows reference models to be created and used in two different ways: first, a software vendor provides a reference model for his own software packages and the user selects the most suitable one, and adapts it to his/her own requirements. To facilitate this process, the user can be supported by tools which configure models according to allowable configurations of the software package. In order to skip this step, the ARIS Tool Set provides a so-called ‘Analyser Typology Diagram’; which allows the user to characterise the manufacturing process according to a few criteria. A second way to deal with reference models in the ARIS Tool Set is to take advantage of so called ‘branch-specific’ reference models.

2.3.5.7 Purdue Enterprise Reference Architecture (PERA)

The Purdue Enterprise Reference Architecture was developed at the Purdue Laboratory for Applied Industrial Control [Williams,1992]. It concentrates less on the formal representation of manufacturing organizations but is designed to provide a method which describes how to design manufacturing organisations. For the proposed planning stages some methods like ‘generic lists of requirements’ or ‘critical path methods’ are suggested but it remains open to users of PERA to decide how these methods can be integrated in one homogeneous model which can be maintained, reused, and updated.

The PERA methodology covers various lifecycle phases of an enterprise; starting with identification of the business unit itself, and its strategic role and objectives, and ending with enterprise operation [Kosanke, 1996]. PERA does not provide its own modelling language however; other modelling tools and techniques can be used to support its concepts. PERA identifies three classes of entities in an enterprise namely: information, human, and organisation. Particular importance has been given to humans and their organisation.

In addition to the above description three tables are attached in Appendix I. There tables introduce some other modelling approaches and compare some aspects of their framework, life cycle, model structure and language.

2.4 HUMAN SYSTEM, MODELLING AND ROLE CONCEPTS

2.4.1 Human system and modelling

Although interest in understanding the role of humans in systems and accommodating that role in design has a history of more than 60 years, there has been a continuing concern that, in each phase of development, the human element is not sufficiently considered along with hardware and software elements [BCSSE, 2007]. Evidently it is difficult for humans to model human (i.e. other people or themselves) for reasons that include the following:

- From an object point of view: People view from an object of modelling context, are complex entities that generate various (individual and collective) behaviours which are often context dependent.[Ajaefobi 2006]

- From the subject point of view: People acting as modellers, naturally have constrained understandings, knowledge and data about themselves, about the modelling context and about related contextual impacts.

The term ‘human systems’ is used to infer either: an individual working systematically; loosely affiliated ‘workgroups’; or closely coupled ‘teams’. The term also infers their incorporated appropriate organizational structures. The research colleagues of the present author have developed concepts and tools to effectively model ‘human systems’ [Ajaefobi 2004, 2006; Weston 2006]. While the human system modelling reviewed in this thesis was concerned with understanding and characterising problems and constraints associated with modelling people at work, the definitive foci of reporting is on creating and using models of ‘human systems’ in relation to common roles they perform in manufacturing enterprises. In MEs various types of organising structure are commonly deployed and have been classified under the following headings:

- *Human organising structures*, such as hierarchy, roles, responsibilities and authority [Steers & Black 1994; Ashfort 2000; Hendrick 1997];
- *Work organising structures*, such as processing routes, batching and prioritising rules and ‘job’ and ‘task’ assignments [Scott & Mitchell 1976; Ashkenas et al 1995; Medsker & Campion 1997]);
- *Product structures*, including product families, hierarchies and configurations [Bennis 1996; Vernadat 1996]);
- And *behaviour structures*, including skills, knowledge, motivation, etc.

With increased business fluidity comes a need for more definitive and ‘change capable’ role and role dependency definitions; so that organisations can: (a) facilitate needed changes to work patterns and work loads (placed on human and technical resources) [Ashfort 2000; Weston et al 2007] and (b) continue to provide a work environment which encourages people to realise their potential [Ashkenas et al 1995; Polignac et al 1995].

2.4.2 Role Concepts and its Modelling

2.4.2.1 Role concept early origin into literature

In sociology the concept of roles and role theory goes back to Merton [Merton 1957] in the 1950s. After that, the development of roles and associated responsibilities and authorities were mainly conceived to assign work to individuals and organisational groups of humans [Scott & Mitchell 1976; Medsker & Campion 1997; Hunt 1992]. Kazt[1966] has considered organisations as systems of interacting roles, where a role is considered both as a set of activities or as an expected behaviour. Sarbin[1968] has also identified that roles can be linked to workstations, or to organisational positions. Roles were also defined in terms of activity and task types that role incumbents should realise. Typical examples might be some engineers working on product development with a view to satisfy predicted customer needs; then workshop staff may manufacture those products to match the needs. The nature of the product types required, and the mixes of products that must be realised in a given timeframe to satisfy customers. Therefore roles can be viewed as a complementary perspective to functions that need to be performed by role incumbents [Pandya et al 1997; Weston 2004]. Another aspect of role consideration described by Giddens [Giddens, 1988] was in formalising the occurrence of roles in organisations, Giddens investigated aspects of roles acting in social structures. Ortmann [1990] considered formal relations in organisations, and discuss the concept of acquaintance between actors, the concept of role concern and the position of actors with organised connections. Ortmann also considered positional characteristics asked in relation to generic sets of expectations and related behaviours and competencies. Hence in such a scheme, roles are defined by position, personality and interaction situation. Roles are not independent of the sociological structure or environment where they evolve; rather they are considered to be restricted by organisations. Nowadays some sociologists, as well as computer scientists, use the term role as a bridge between common interdisciplinary work [Odell, 2000], [Parunak, 2001].

2.4.2.2 Role of human in relation to their competency

People can and will bring functionality and behaviour to roles and the management of role dependencies [Mintzberg 1989; Siemieniuch et al 1999]. Traditional approaches to competency understanding, and related modeling, encompass psychological behaviour and task aspects [Cattell 1957; Ajaefobi 2004; Byer 2003]. Conventionally the capture and reuse of competency knowledge has centred on time-consuming people interviewing and results analysis [Medsker & Campion 1997; McClelland 1973]. More distinction was made between the competencies of a person (termed gained competencies) and the competencies required by an activity (required competencies) [Franchini, 1999 and Harmosillo, 1999]. Recently observed needs to capture and reuse knowledge about people competencies have led to a number of initiatives worldwide that are using people models to support aspects of organisation design and change [Harzallah & Vernadat 2002; Hermosillo Worley et al 2005;Van Assen 2000; Athey & Orth 1999]. Thus far competency modelling has focused on individual learning and performance and exploring performances differences[Spencer, 1993; Shippmann et al. 2000; Raven and Stephenson 2001]. Future competency methods should encompass team and process performance, support qualitative and quantitative analysis at various levels of abstraction and enable the transfer and reuse of competency knowledge within and across organisations [Quinn 1992; Beevis & Essens 1996; Grote et al 1995; Dekker & Wright 1997; Weston et al 2003]. Also human systems exercise different role types when they are specifying, developing, realising and changing enterprise processes. These types have been catalogued and classified as: *interpersonal, informational, decisional* and *operational* roles [Parker 1990; Stahl & Luczak 1997; Ajaefobi et al 2005].

2.4.2.3 Modelling roles and competencies

Roles tend to be seen in observational terms, as tools for the specification and evaluation of systems [Kendall 1998]. They are used as a tool for implementation of models to distributed actions and activities. If interaction situations become too complex, roles may provide generic sets of expectations for behaviour and competence. Geller [1994] introduced necessity to model actors in roles from both position and personality view points. Position defines how actors fit in an organised social system, including necessary qualifications and access rights, and dependencies with other actors. With reference to position, roles become a kind of interface to the environment. This ideas is presented by Figure 2.4.

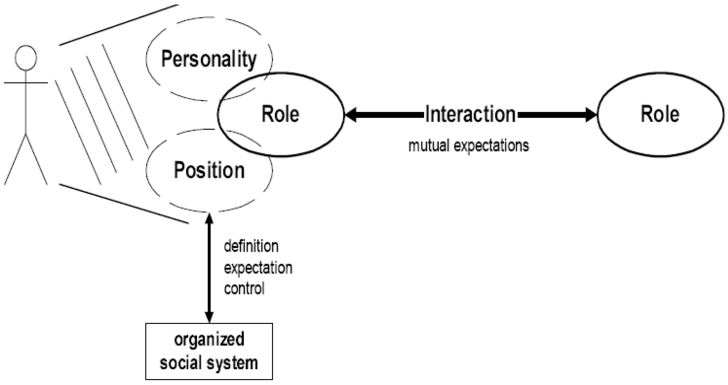


Figure 2.4. Structural relation among Personality, Position and Role (Source: Geller, 1994)

Katie [2006] developed a paper based method for resourcing processes with identified human roles. This presents a method which enables process owners, project managers and other practitioners to analyse, evaluate and select the most appropriate combination of human roles; with typical classification in terms of their class, profile, boundaries, interactions, authority and responsibilities, then different types of role can be analysed with reference to their applicability to the activities of a given process(as shown in figure 2.5). This generates visualisation by means of a rule-based, bottom-up approach; and the method involves three main stages: (1) from modelling process, (2) identifying roles required to process; (3) and the representation of these roles within role matrix.

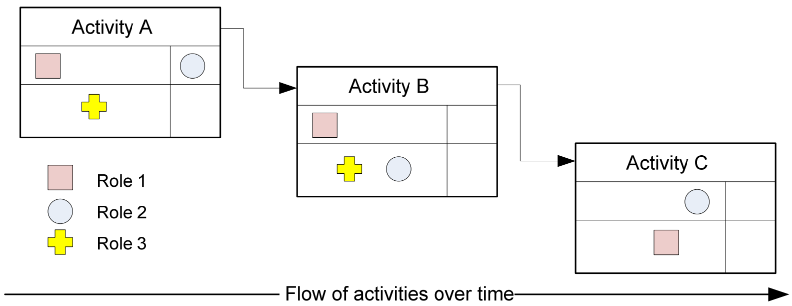


Figure 2.5. Role analysis building up for series of activities (Source: Katie, 2006)

Halpin [1996] developed an Object Role Modelling method framework more from database application perspective, to capture role organisational aspects of the complex business. Its main purpose is in designing and querying database models at a conceptual level [Halpin, 1998], used role concepts and traditional Entity relationship diagramming, to improve communications between entities within models.

Various competence models emerged in the 1980s to promote flexibility. Rather than assess a worker by comparing predefined activities with the ability of a worker to perform these activities, competence models provide means of directly qualifying abilities that persons possess that they can bring to the workplace [Zarifian, 2002]. Some companies need to determine new competencies required by the enterprise [Strebler, 1996] while others consider the concept of competence provides a common language to facilitate cultural exchange [Strebler, 1997]. Strategic aspects of competencies have been emphasized in the 1990s via the term core competencies; suggesting a new way to consider the competitiveness of a company [Prahalad 1992]. Competencies can be analysed at the level of an individual, gathering all the techniques that facilitate the emergence, maintenance and development of personal competencies; but also at a collective level even up to an enterprise level. A good summary on the different views with which competencies can be considered can be found in the competence cube suggested by MSI [Weston, Byer and Ajaefob 2003], shown in Figure 2.6.

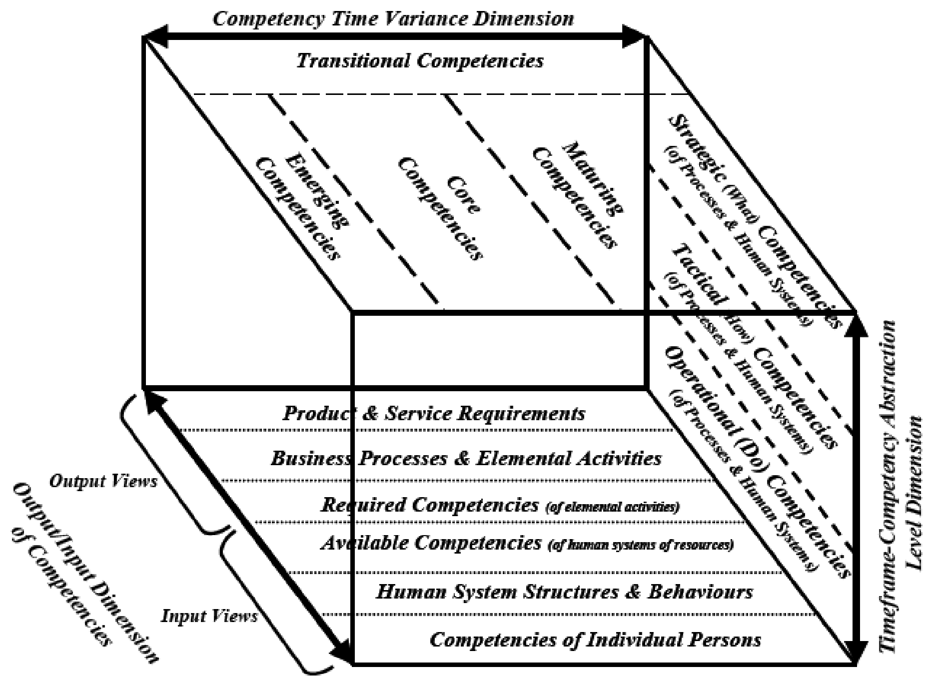


Figure 2.6. Competency cube (Source: Weston, Byer and Ajaefob 2003)

MSI investigation has concentrated on developing semantically rich models of processes and systems that explicitly define:

(I) *required attributes of roles, jobs, tasks and operations;*

(II) *available competencies* that are possessed by candidate human systems;

(III) *human system structures* that organize available competencies and behaviours;

(IV) *candidate human systems,* modelled at needed levels of abstraction.

2.5 DYNAMIC AND SIMULATION MODELLING

Since the early 1960's, simulation has been one of many methods used to aid strategic decision making within industry. A simulation is the imitation of the operation of a system or process over time. The behavior of a system as it evolves over time can be studied by a simulation model. [Sadoun, 2000]. Simulation modeling is applied to real world problems in order to get a clearer view of problems [Molina and Medina 2003] and to analyse the behaviour of the system as time progresses [Sadoun, 2000]. Dynamic modelling answers the question to 'how we can believe that it is possible to build static models of dynamic reality and expect them to aid our understanding to anything more than a very limited extent' [*www.system-thinking.org*]. With computer technology developments, system dynamics and simulation has been developing as a method of solving real world problems by computer simulation, including the modeling of natural systems or human systems in order to gain insight into their functioning [Smith 1998, 1999]. Simulation models can also predict performance indicators such as throughput times, work-in-progress and waiting times accurately as they take essential dynamic interactions found in real systems into account. [Debn´ar R.and Kuric I, 1998]

2.5.1 Dynamic simulation construction

In a generic view, system dynamics and simulation uses systems thinking as a conceptual tool for gaining insights into the structures that create the dynamic behaviour often found in complex systems [Bar-Yam, 1996; Boccara, 2004, Sterman J. 2000]. In essence, as shown in Figure 2.7, a system's pattern of behaviour primarily results from the interaction of three core factors:

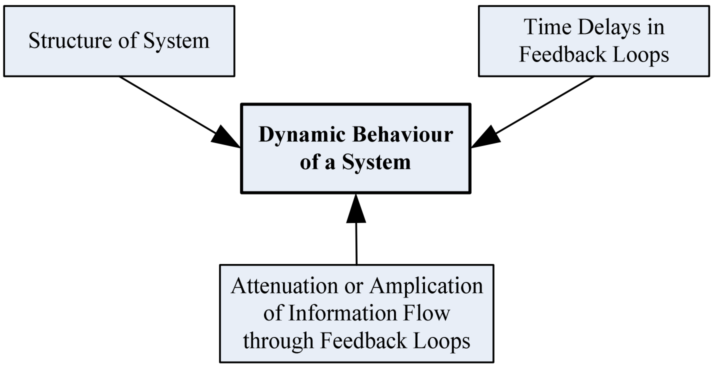


Figure 2.7. Dynamic interaction within a system

(1) the structure of the system, which is often expressed in the form of a process network; (2) the frequency and duration of time delays in feedback loops; and (3) the extent to which information flows and work are amplified through the system's feedback structure. The behaviour of a system can often be described through interrelationships resulting from this set of three core factors.

2.5.2 Discrete Event Simulation

Discrete Event Simulation (DES) was first used in the 1950s, with the objectives of improving efficiency, reducing costs and increasing profitability with respect to business problems. They mainly involved analysing the queuing of objects that had a small number of operations carried out on them and followed a limited number of routes from start to finish (e.g. mass production). The models created in the 1960s and 1970s were usually computer programmes written specifically for the scenario in question and the output was given as lists of numbers. By the 1980s, the models were enhanced by the addition of 2D animations that mimicked the system and provided a visual representation of the problem. Animations proved particularly useful for assessing and confirming the validity of the model. In the 1990s, simulation software was further enhanced to give 3D visualisation. Increases in computational processing power have enabled the software to include texture mapping and third person viewing; bringing them to the point of virtual reality.

There are a large number of potential areas for DES. One of the main areas currently being explored is in the application of new manufacturing philosophies [Detty and Yingling, 2000; von Beck and Nowak, 2000]. For example, if a company wishes to build a new production line, then first the operation of the line can be simulated to predict aspects of the feasibility and efficiency. Figure 2.8 shows key stages in using DES, the back loops between multiple stage are not indispensable but convinced to be rational to DES model building. It can be noted that this bears a strong resemblance to other simulation techniques and other analysis program development methodologies (prototype method) [Sommerville, 1992].

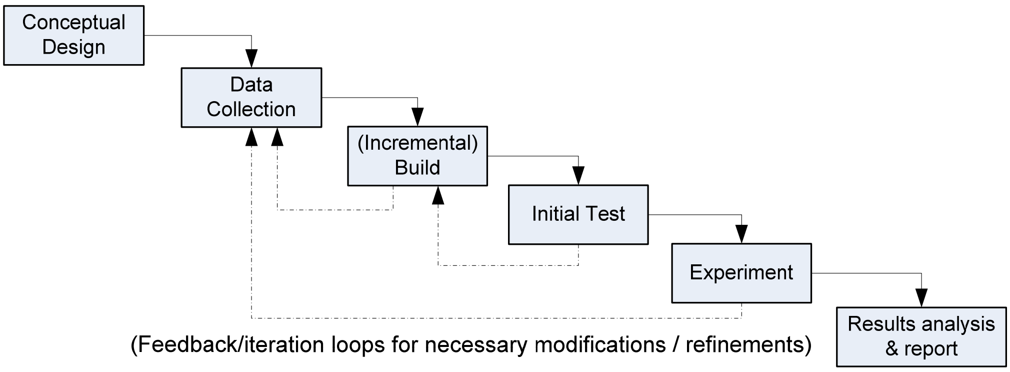


Figure 2.8. Key stages used in Discrete Event Simulation(DES)

Law(1991) described DES as modelling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time. Pidd(1992) used three key elements to describe discrete event simulation as shown in Table 2.2, as the principle frame structure within simulation models. Then Pidd used a simple machine operation process example to graphically interpreted these ideas in Figure 2.9. When a discrete event simulation model has been built following the above stages, for its execution, Ball(1996) simply divided related issues in two ways, as listed in Table 2.3.

Table 2.2. Three elements to Discrete Event Simulation

Event	Describes an instantaneous change, usually from a stop event to a start event. This is the most common one used, easy to understand and efficient and is acceptable to implement.
Activities	Represents a duration. Essentially groups a number of events in order to describe an activity carried out by an entity e.g. a machine loading. This approach is easy to understand and to implement but is not efficient.
Process	This approach groups activities to describe the life cycle of an entity e.g. a machine. This is less common and more difficult to plan and implement, but is generally thought to be the most efficient.

(Source: Pidd, 1992)

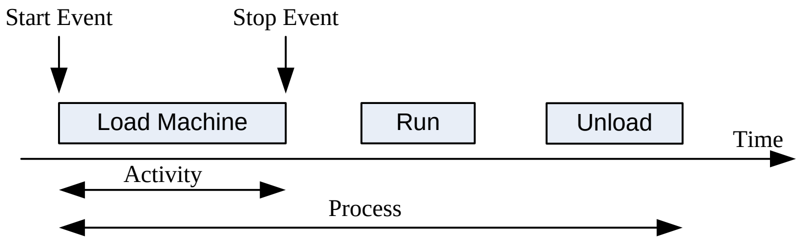


Figure 2.9. Interpretation to three different elements to Discrete Event Simulation

Table 2.3. Discrete event simulation execution manner

1	**Time slicing**	Advances the model by a fixed amount each time, regardless of the absence of any events to carry out.
2	**Next Event**	Advances the model to the next event to be executed, regardless of the time interval. This method is more efficient than Time Slicing, especially where events are infrequent, but can be confusing when being represented graphically (processes that take different times will appear to happen in the same time frame if the stop event is the next event after the start event).

Conceivably discrete event simulation can be carried out by hand, but also it can be computationally intensive. Thus early simulation models were often a specialised event/data driven application; such as 'BaseSim'(Monte Carlo Method) [Ulam S et al. 1947; Metropolis and Ulam, 1949]. From those simulation models there are five key features found:

Entities – Representations of real-life elements e.g. in manufacturing these could be parts or machines.

Relationships – Link entities together e.g. a part may be processed by a machine.

Simulation Executive – Responsible for controlling the time advance and executing discrete events.

Random Number Generator – Helps simulate different data coming into the simulation model. It maybe important that random data can be reproduced in different simulation runs.

Results & Statistics – Important in validating the model and for providing performance measures.

2.5.3 Basic differences between discrete event & continuous simulation models

Discrete Event Simulation concerns the modelling of a system as it evolves over time by representing changes as separate events. In DES, the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system

[Robinson, 2004].This is not the case in Continuous Simulation, where the system evolves as a continuous function. The continuous simulation model, described by differential and algebraic equations, requires numerical solution of these equations. A widely used class of solution algorithm discretises the continuous time line into discrete time instants; the interval between two consecutive time instants is called the integration step and according to the used solution algorithm this step can be fixed or variable. Bouchhima [et al 2005] introduce in Table 2.4 the main concepts characterizing these models: the notion of time, the communication means and the process activation rules of discrete and continuous simulation models.

Table 2.4. Basic concepts difference for discrete and continuous simulation model

Concept / Model type	Time	Communication means	Process activation rules
Discrete	Global notion for all modules of system. It advances discretely when passing by time stamps of events	Set of events(value and time stamp) located discretely on the time line	Process are sensitive to events
Continuous	Global variable involved in data computation. advances by integration steps.	Piecewise-continuous signals	Processes are executed at each integration step

2.5.4 Simulation software tools

Mechanisms have been proposed for carrying out discrete-event simulation, among them are the event-based, activity-based, process-based and three-phase approaches (Pidd, 1998). The three-phase approach is used by a number of commercial simulation software packages, but from the user's point of view, the specifics of the underlying simulation method are generally hidden.

IThink™ [www.hps-inc.com**]**

IThink is a simulation tool for modelling and analysis of systems and processes. It was developed by High Performance Systems, Inc.(HPS). The iThink tool supports systems a thinking approach, which primarily focuses on how the things under consideration interact with each other and with other constituents of a system. Systems thinking uses a language called causal-loop diagrams to develop mental models of systems. Thus iThink uses causal-loop concepts and allows the development of mental models of systems. These models can be extended when more factors that influence systems are taken into consideration. The tool supports system decomposition principles to decompose systems into sub-systems, and process modelling to analyse dynamic behaviour of these systems. It has a three-layer structure with specific model building blocks at each layer. It uses differential equations to produce dynamic behaviour.

Simul8™ [http://www.visual8.com**]**

Simul8 has been developed to take the risk out of Business Process Management allowing users to predict costs and service levels by simulating process capacities and timings. Simul8 has a strong focus on process; allowing users to rapidly develop 2D animated models of their process, using the animation to help validate and communicate the issues and use the strong reporting tools within simul8 to analyze the results. The Process being modelled may be a manufacturing process, or a clinical testing procedure or an A&E facility.Simul8 professional software incorporates the OptQuest optimization tool to facilitate rapid experimentation; it also interfaces directly with a large number of systems reducing the need to recreate important process maps. Indeed using Simul8 XML integration it is possible to work with two different packages on one file allowing the user to use the right tool for the job. Simul8 provides a powerful 'what if' animation and analysis tool, giving users the ability to see their business with a new perspective, all within a familiar Visio environment.

Tecnomatix™ Plant Simulation® [http://www.plm.automation.siemens.com/**]**

Tecnomatix™ Plant Simulation software is object-oriented simulation tool with a graphical UI. It enables modelling and simulating analysis of a production system, through graphically added material, information and resource flow features. In addition, with an integrated simulation language (SimTalk), it gives the tool a programmable capability to deal with more complex production system problems. The tool hence allows the creation of computer models and enables users to run experiments and 'what-ifs', so that it can support production system designers and planners with its built-in extensive analysis tools, statistics and charts. The evaluation of different manufacturing scenarios and model result comparisons can be used to explore current and possible future production systems' characteristics with a view to optimisation of solutions to improve performance.

Witness [http://www.lanner.com/en/witness.cfm]

WITNESS®, is a business simulation system to model working environment, simulate the implications of different business decisions and understand complex process. WITNESS simulation package is capable of modelling a variety of discrete (e.g. part based) and continuous (e.g., fluids and high-volume fast-moving goods) elements. Since its original launch in 1986, Witness has been developed into a product family (SDX, VR, Optimizer, Miner etc, as Optional modules), to cover discrete manufacture, process industries, BPR, e-commerce, call centres, health, finance and government, provides modular and hierarchical structure, with interactive graphical interface. Witness can generate comprehensive statistical input and reports via links to multiple database formats such as ORACLE, SQL Server, Access, etc.

Arena [http://www.arenasimulation.com/]

Arena® is a simulation and automation software developed by C. Dennis Pegden of Systems Modelling and become part of Rockwell Automation in 2000. In Arena, the user builds an experimental model by placing module (boxes of different shapes) that represent processes or logic, then modules can be joined together. Statistical data, such as cycle time and WIP (work in process) levels, can be recorded and output as reports. Arena integrates to Microsoft Visual Basic for Applications, models can be automated if specific algorithms are needed. It also supports the import of Microsoft Visio flowcharts, as well as reading from or outputting to Excel spreadsheets and Access databases, for enhanced data collection functions.

In addition to the above, there are also a number of other commercial software and tools with different features and strengths as follows:

- *CACI's SIMPROCESS* is used for process simulation.
- *ExtendSim* is a graphical general purpose environment for discrete event, continuous, discrete rate, and agent based simulation.
- *Facsimile* is a free, open-source discrete-event simulation/emulation library.
- *Jemula* is an open-source event-driven simulation environment in JAVA.
- *Simula* was the first object-oriented programming language, and was designed specifically for simulation
- *SimPy* is an Open Source process-oriented discrete event simulation package implemented in *Python*. It is based on *Simula* concepts, but goes significantly beyond *Simula* in its synchronization constructs.
- *SimEvents* is a discrete-time simulation tool offered by the MathWorks as an add-on package for *Simulink* and MATLAB.

2.6 WORKFLOW MODELLING AND MANAGEMENT

Work Flow Management is a fast evolving technology which is increasingly being exploited by businesses in a variety of industries. Its primary characteristic is the automation of processes involving combinations of human and machine-based activities, particularly those involving interaction with IT applications and tools. From a dynamic modelling point of view, workflow can also be considered as a dynamic modelling approaches; but more than simply a modelling tool.

2.6.1 Fundamental concepts and structure

The concept of workflow evolved in the industrial and the business worlds to refer to the processes taking place during manufacturing and in the office. Such processes have existed since the beginning of industrialization and since people began to look for ways to increase efficiency regarding routine work activities [Leymann and Roller, 2000]. Workflow is concerned with the automation of procedures where documents, information or tasks are passed between participants according to a defined set of rules to achieve, or contribute to, an overall business goal. Workflow is a general term that is used to refer to a number of concepts associated with either the engineering of business processes or automating information process flows. Whilst workflow may be manually organised, in practice most workflow is normally organised within the context of an IT system to provide computerised support for the procedural automation. *The Workflow Management Coalition(WfMC),* defines workflow as *'The computerised facilitation or automation of a business process, in whole or part'* [Hollingsworth,1995, Lawrence, 1997]. While some other definitions were also given by some other theorists such as "The automation of a business process, in whole or part, during which documents, information or tasks are passed from one participant to another for action, according to a set of procedural rules" [Lawrance, 1997]. "Manage, measure and revise work-processes that span the efforts of multiple workers and applications (and possibly companies)" [Butlergroup, 1996]. An analysis of these definitions reveals that workflow involves two perspectives; business processes and their automation. The distinction between these perspectives is not always made and the term workflow may refer to either or both perspectives [Weston, 1999].

2.6.2 Workflow and BPM

When reviewing the relationship between workflow and Business Process Management, it has been a subject of some debate whether there is any practical difference between workflow management and BPM. From definitions listed earlier many of the concepts are similar and, where there are differences, these tend to be in points of detail, or different emphasis. The following Figure 2.10 appeared in the 2001 edition of the Workflow Handbook to illustrate the evolution of what is now typically called BPM (in the original article it was described as e-Process Automation). Three main technologies have been converging—workflow, Enterprise Application Integration(EAI) and the Web, each however, coming from a rather different perspective.

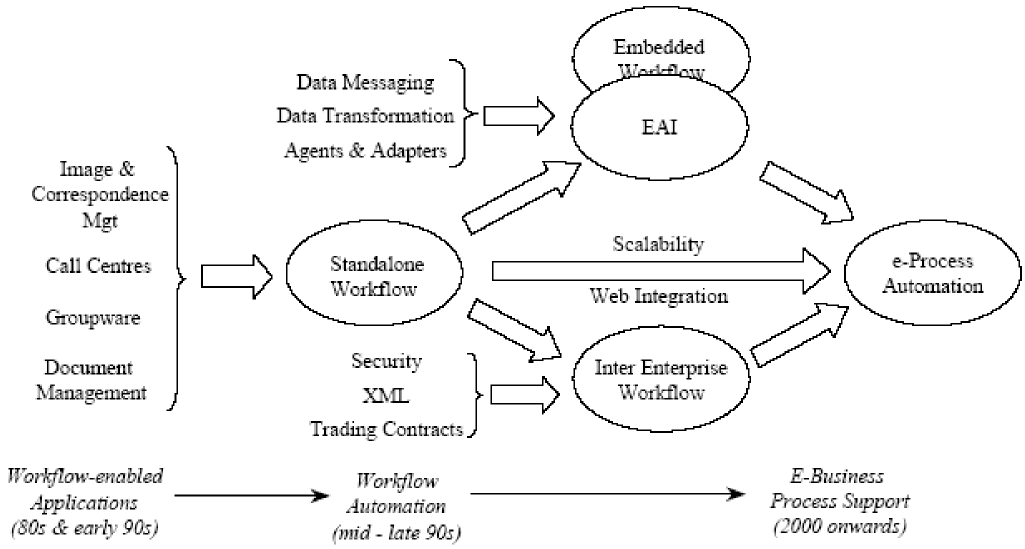


Figure 2.10. Evolution of Workflow & BPM (Source: Lawrance, 1997)

Traditionally workflow has placed more emphasis on organisation structure and associated roles and responsibilities[Peter 1997]. Business process models typically start from an organisational perspective with views of accountability and responsibility attributes and the roles and responsibilities associated with processing work activities. Work resources thus tend to embrace both human and machine. The typical EAI approach has placed more emphasis on engineering and automation aspects—sophisticated agents and transactional qualities. Process models typically start from a work perspective—data flows or transactional definitions—and focus on fully automated tasks without human involvement. The Web has brought a new infrastructural base, built around web services protocols, XML structured information content and massive potential scalability.

2.6.3 Modelling tools and techniques

Like dynamic simulation tools, quite a number of modelling tools and techniques were reviewed that were relevant to the enterprise engineering discipline and that had potential to be used in this research work. They are briefly described below.

I-Flow® [www.i-flow.com**]**

I-Flow is a web-based workflow management system developed by Fujitsu Corporation. I-Flow is a workflow engine that automates human and event driven business processes across an enterprise. It is a distributed client-server tool that was designed to manage co-ordination aspects of business processes, as well as the run-time integration of distributed processes and systems. It provides a set of modelling constructs designed to represent and enact representations of business process and activities, relationships linking activities, attributes of personnel assigned to activities, or in which process steps should take place and data needed for each step.

CIM-Tool [www.rgcp.com]

This tool was developed by RGCP (Rene' Gaches Consultant in Production), an independent consulting company operating for large-scale European companies, in the field of Computer Integrated Manufacturing. The CIM-Tool uses CimOsa/rg methodology, which was derived from CIMOSA by RGCP. The tool provides graphical representational formalism for processes, uses the CIMOSA decomposition principles, and provides a capability to develop information and functional activity models.

OmniFlow [www.astrait.co.uk**]**

OmniFlow is a scalable, multi-user rule based workflow system. It provides both document as well as form based automations and also facilitates integration with other business applications. It enables the definition and deployment of multiple business processes, sharing of resources across processes and thus helps streamline business processes.

The tool includes two principle characteristic modules:

*Graphical Tool for Process Definition - OmniFlow Process Modeler***,** provides a graphical tool that provides designing of business processes in a flow chart fashion

Desktop for monitoring Processes - OmniFlow Process Manager provides a desktop for administration and monitoring of all business processes. It offers various tools to administrators for controlling and refining business processes.

BizFlow 9 [www.handysoft.com**]**

BizFlow 9, HandySoft's Business Process Management platform, provides end-to-end process management, event detection and response, complete interoperability with J2EE and web service environments extending collaboration across the value chain, simplified modelling with dynamic routing capabilities. BizFlow 9 helps move companies from a static world where change occurs "after the fact" to a dynamic, responsive world driven by real-world business metrics**,** this tool enable you to simulate proposed changes to business processes before implementation, so that we can maximize their improvement, and aggressively tackle the challenges we face in the default mortgage marketplace."

iMarkup [www.imarkup.com**]**

iMakeup ltd is a provider of collaboration and workflow solutions for digital content and document management. The tools enable end-users to communicate, annotate, organize and collaborate over the Web, as well as providing business users with the tools needed to automate and manage their existing business processes. The iMarkup product line includes iMarkup Server v4, iMarkup Java Annotation SDK and the iMarkup Client.

2.7 COMPONENT AND COMPONENT BASED MODELLING

2.7.1 Definition of “component”

The term “component”, like the term “object”, is a highly overused term without a widely accepted standard definition. Although “components” and “objects” share similarities. Many authors and organisations had their own definition:

- Douglass [2000] offered a rather informal definition, reflecting the sometimes perceivable variety of the subject: “*What is a component? Well, [. . .] it’s whatever you want it to be.*”
- D’Souza [1997] defined “A component is a coherent package of software that can be independently developed and delivered as a unit, and that offers interfaces by which it can be connected, unchanged, with other components to compose a larger system.”

- Szyperski [1999] gave more precise definitions which reflect what has become a general understanding of components: "a unit of composition with contractually specified interfaces and explicit context dependencies only. A software component can be deployed independently and is subject to composition by third parties."
- OMG [2005] had a similar but more elaborate definition: "A component can always be considered an autonomous unit within a system or subsystem. It has one or more provided and/or required interfaces (potentially exposed via ports), and its internals are hidden and inaccessible other than as provided by its interfaces. Although it may be dependent on other elements in terms of interfaces that are required, a component is encapsulated and its dependencies are designed such that it can be treated as independently as possible.

2.7.2 Understanding of "component architecture"

Definitions of component are quite generic and thus it is not surprising that the term is used to describe rather different concepts. However there are common key features, which Völter [2003] summarized as follows,

- "Composition": The purpose of components is to be composed with other components. A component-based application is thus assembled from a set of collaborating components.
- "Interfaces": provide one or more interfaces to each component enables components to be composed into applications. These interfaces form a contract between the component and its environment. The interface clearly defines which services the component provides. It thus defines its responsibility.
- "Context dependencies": Namely a specific context, such as available database connections or other system resources being available. One particularly interesting context is the set of other components that must be available for a specific component to collaborate with. To support the composability of components, such dependencies can be explicitly specified.
- "Independently deployable": A component is self-contained. Changes to the implementation of a component do not require changes to other components. This also implies that interfaces remain compatible.
- "Third parties": The people who assemble applications from components are not necessarily the same as those who created a component. Components are intended to be reused – the goal is a kind of component marketplace where people buy components and use them to compose their own applications.

2.7.3 Component modelling technology and their commercial implementation

There are a variety of similar but not identical component technologies. Cox and Song [2001] referred there are two key questions to be answered for a component and its model: "how is a component developed?" and "how is the component applied in software development?" Cox and Song stated that a component model should address both questions. It was stated that even more formal components modeling concept has been developed [Boer et al, 2003], the development of the method itself is still not formal. [Grobe-Rhode and Mann, 2004]. Component-based techniques have known significant development, especially due to the use of object technologies supported by languages such as C++, Java, and standards such as UML and CORBA. [Gössler and Sifakis J., 2005]. But Gössler and Sifakis also pointed out the lack semantic frameworks for component-based engineering encompassing meaningful integration of synchronous and asynchronous components, as well as the use of various interaction mechanisms. The developed framework used an abstract layered model of components, considered components as the superposition of two models: a behavior model and an interaction model: 1) Behavior models describe the dynamic behavior of components; 2) Interaction models describe architectural constraints on behavior.

In the case of server-side components technology, there are three mainstream examples: JavaBeans, Microsoft's COM+ and CORBA Components, they are used in enterprise business applications. provide meta information, mainly for use at build time or deployment time. [Völter, 2003]. In this research the present author does not put emphasis on software developments side of components modelling technology. Cox and Song [2001] gave a summary list of the three main tools with some of their similarities and differences, as shown in Table 2.5. Ignoring differences in technical details, these technologies have essentially similar architectures and functionality. Each defines a component as a self-contained "black box" sending messages to and receiving messages from other components via a well defined interface, and performing its computation in response to the receipt of a triggering message (event).

Table 2.5. Comparison of current main commercial component model tool

	JavaBeans	COM	CORBA
Component	Module containing multiple classes	Module containing multiple classes or other implementation	Module containing any implementation
Interface	Java language	OLE IDL, defines interfaces as collection of functions	OMG IDL
Connection	Via event and listener.	Via interface pointers	Via Interface Definition Language
Variability mechanism	Inheritance and aggregation	Genericity, containment and aggregation	Inheritance and aggregation
Platform	Multiple platforms	Windows	Multiple platforms
Implementation Language	Java	Any languages, but primarily use C++ and Visual Basic	Any languages
Distribution Mechanism	EJB, Internet, RMI (remote method invocation)	DCOM, Internet	An ORB
Self-description	Support via introspection	No	No

(Source: Cox and Song 2001)

CHAPTER 3

Literature Analysis

The foregoing literature review indicates the overall state of art in the area of study related to this thesis. This chapter will analyse the literature to locate gaps and lack of provision of knowledge to identify new research objectives and the scope of this study.

3.1 LITERATURE REVIEW SUMMARY

The Literature review can be summarized from following aspects:

1. *ME flexibility requirements.* Enabling manufacturing flexibility has been widely recognised as an essential strategy in current manufacturing industries and enterprises. It can facilitate various forms of change to processes and resources within MEs. [Hayes and Wheelwright 1984, Fine and Hax 1985, Sethi 1990, Chen 1992, Olhager 1993, Hill 1995].
2. *Enterprise modelling aspect.* EM models can coherently represent MEs from different viewpoints and at alternative levels of abstraction. This can enable the development of well decoupled models of process segments and sub-systems and can facilitate model reuse in support of many types of change decision making [Vernadat, 1996]. EM approaches can potentially facilitate the development of better processes and systems, and can improve the timelines and cost effectiveness of change projects in MEs [ICAM 1981, Doumeingts and Chen 1992, AMICE 1993, Williams 1996, Spur et al 1996, GERAM 1999].
3. *Human system and role related modelling aspects.* Previous human systems theory has involved a study of organisational, work and product structures. The understanding developed can enable the identification of suitable rules, responsibilities and authorities related to the assignment of 'jobs' and 'tasks'. Those understandings have been widely developed over several decades [Scott & Mitchell 1976; Steers & Black 1994; Ashkenas et al 1995; Bennis 1996; Hendrick 1997; Medsker & Campion 1997; Ashfort 2000]. Related role modelling methods linked to models of ME processes have been developed by research colleagues of the present author to explicitly identify 'change capable' requirements [Ajaefobi 2004, 2006; Ajaefobi and Weston 2005,2006].
4. *Dynamic simulation modelling aspect.* System dynamics and simulation have been developed as a method of solving real world problems [Neelamkavil 1987; Smith 1998, 1999]. Reviewing the published literature shows that discrete event simulation (DES) and continuous simulation models that have been used to model various types of manufacturing system [Law 1991; Pidd 1992; Bank et al. 1996]. DES has been applied to study the application of different manufacturing philosophies [Detty and Yingling, 2000; von Beck and Nowak, 2000] and to support these and other application areas various commercial software tools have been developed.

5. *Component type architecture and related modelling aspect.* Notions about 'components' and 'component architectures' have supported the application of flexible concepts [D'Souza 1997; Szyperski 1999; Douglass 2000; and Völter 2003]. Commercial component modelling tools have also been developed to support different application domains [Cox and Song 2001].

3.2 GAP ANALYSIS OF THE LITERATURE

Not withstanding significant advances that have been made in support of the engineering of flexible manufacturing systems there remain significant gaps in knowledge, technology and method provision as discussed in this section.

3.2.1 Regarding human and technical system modelling in support of process improvement

Previous research has identified methods of using EM concepts to link models of engineering and production processes to corresponding models of human systems [Chatha et al. 2003]. This approach aims to satisfy a common requirement of realising organised associations between people (competences) and jobs (i.e. related sets of activities) [Vernadat 1996]. However, in practice the full potential of enterprise modelling has yet to be realised, particularly with respect to systematically designing and changing human systems [Chatha and Weston, 2005]. Both theoretical and practical limitations have been observed in respect of the current solution provisions, particularly with respect to characterising human systems and their potential roles in an enterprise [Kosanke 2003, Weston et al. 2003]. Therefore there arises a need to improve the EM concept and method provision in a way which more effectively supports human resource modelling. But this should not be limited to human systems modelling within MEs [Ajaefobi and Weston, 2005], but should also support the resourcing of semi-automated processes with combinations of human and technical resources that match the types of activity involved and the kinds of workflows through these activities. [Chatha et al. 2003].

3.2.2 Regarding dynamic and simulation modelling in support of resource systems

Ajaefobi et al. [2006] stated that current EM provision is not designed to encode process and system dynamics. It follows that it is not suited to modelling the loading of process networks with time-dependent instances of project, product and service flows; nor therefore to mixes of those flows. With increased business fluidity comes a need for more definitive and 'change capable' role and role dependency definitions. This is necessary so that organisations can: (a) facilitate needed changes to work patterns and work loads (placed on human and technical resources) [Ashfort 2000; Weston et al 2007] and (b) continue to provide a work environment which encourages people to realise their potential [Ashkenas et al 1995; Polignac et al 1995]. Hence the development of Simulation Modelling provision is needed to 'exercise organisational dynamics'; particularly with a view to replicating and predicting workload requirements associated with a designated role (requirements). Such developments should enable encoding of both static and dynamic properties of process flows, process instances and resource system assignment [Ajaefobi, Weston and Chatha 2006].

3.2.3 Regarding the integrated use of models of processes, roles and resource systems

A number of new modelling theories and methodologies are under development worldwide which seek to unify either EM with human systems modelling, EM with SM, or human systems modelling via SM. Some prominent developments have been made by research colleagues of the present author [Ajaefobi and Weston, 2005; Weston and Chatha 2006; Rahimifard 2007], while other related developments worldwide are reported by Vernadat & Grabot [2005], Rahimifard & Weston [2006]. Some benefits claimed by previous authors relate to the development and reuse of both qualitative and quantitative understandings about (a) alternative ways of organizing multi-product process flows through a constrained set of human and technical resources; (b) potential performance enhancements that can be achieved in process segments by deploying alternative systems of human and technical resources; (c) integrated static EM, role modelling and dynamic resource system simulation into a new modelling framework approach which can be widely deployed and (d) applying new modelling frameworks as a component architecture.

3.3 RESEARCH AIMS AND OBJECTIVES

Based on the understanding gained from the literature analysis, the overall aim of this research study was defined as follows: to "*conceive, prototype and test an advancement in current best practice when engineering and changing complex systems of processes and resources; thereby facilitating much improved organisational dynamics*".

To accomplish this aim the following research objectives were defined:

1. Specify modelling concepts (and a connecting framework) with capability to represent the requirement characters of combined people and technical resource systems associated with ME processes.
2. Specify the development of new systemic methods of capturing, reusing and updating characters of people and technical resource systems and their associated workflows; in order to facilitate organisation dynamics in scenarios where frequent work pattern changes occur.
3. Construct the modelling concepts and framework, including existing and new systemic methods conceived, via a unified use of state-of-the-art Enterprise Modelling (EM), Role based modelling, Causal Loop Modelling (CLM) and Simulation Modelling (SM) techniques.
4. Apply and test primary uses of the modelling concepts, and instrumented methods and characteristic models, in complementary scenarios of work pattern change faced by four collaborating manufacturers.

5. Document and disseminate the new understandings generated and consider potential exploitation paths.

3.4 SCOPE OF RESEARCH

To further investigate the identified gaps in knowledge and solution provision and achieve the overall research objectives, the following research scope was defined to guide specific research work:

1. Understand different types of models needed and maintain their coherence.
2. Seek synergy from the different modelling approaches and facilitate benefit through stepwise modelling.
3. Develop the use of a combined methodology including Enterprise Modelling, Role based modelling Dynamic modelling and Simulation Modelling into an integrated multi-modelling approach.
4. The essence of the new modelling approach should be based on use of decomposition principles aimed at creating understandable, and reusable social and technical building 'blocks'. Those 'blocks' should be readily reconfigured as 'components' of wider scope, complex MEs. Figure 3.1 illustrates the research scope to be covered.

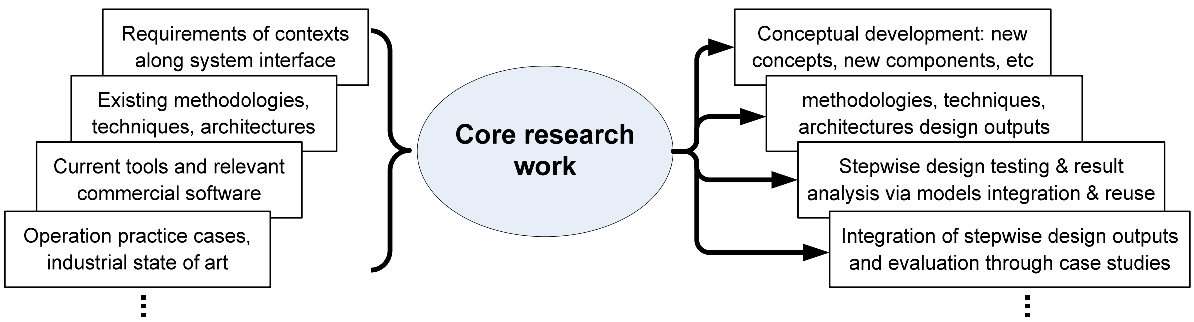


Figure 3.1 Research scope illustration

3.5 RESEARCH METHODOLOGY USED

To accomplish the objectives, a number of research methodologies were selected to be used during the research period. They included: Grounded theory; Descriptive and Exploratory methods, and Case-study research:

Grounded Theory – The intent is to generate or discover theory [Creswell, 1998]. This form of research was employed to develop concepts and make propositions based on current literature and the potential integration of ideas from the literature. Understandings were developed from previous studies. Also by using public domain software tools (available to this researcher and designed for process modelling) the present author observed opportunities and constraints related to process improvement. When generating these concepts the stance taken was that existing (grounded) theories, concepts or models can be further developed by ‘qualitative case study analysis’ [Sjoberg et al., 1991; Denzin & Lincoln, 1994]. By testing the applicability of these concepts in different cases it was shown that the developed concepts are general enough to be applied in different domains. The concepts developed were also evaluated with reference to state-of-the art modelling frameworks and methodologies.

Descriptive Method – Aims to find out more about a phenomenon and to capture it with detailed information” [Wisker, 2001]. 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.

Exploratory Method – Further to answer ‘what’ questions by descriptive methods, if further details need be captured regarding reasons of happenings, exploratory methods can be used. Exploratory research asks both ‘what’ and ‘why’ questions [Wisker, 2001]. While asking ‘why’ questions the exploratory research method also deals with complex issues of a phenomenon. 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, 2003].

Case-Study Research – This research strategy considers an object (whether a situation, individual, event, group, organisation or whatever) and develops a detailed understanding of it [Wisker, 2001]. In this kind of research, the selection of the case is often dependent upon data accessibility. Also in this study it depended upon the present author’s and research colleagues’ previous experience and knowledge of complex engineering processes and their life cycle engineering. The data obtained from cases was analysed using a strategy of ‘developing case descriptions’ [Yin, 2003] in an embedded way [Creswell, 1998].

Evaluation – Maxwell [1996] described eight strategies for evaluating qualitative research, namely: the modus operandi approach, searching for discrepant evidence and negative cases, triangulation, feedback, member checks, “rich” data, quasi-statistics and comparison. Maxwell also gives an account of generalisation in qualitative research and treats it as a separate means of evaluating the quality of qualitative research.

CHAPTER 4

Research Design

Bearing in mind the general aims and objectives and the lack of provision identified by analysis of the current literature, this chapter designs a research framework and proposes a new modelling approach with key principles. This is supported by a detailed literature review of current candidate modelling approaches. Then a stepwise research development plan is presented with respect to chosen modelling tools and new modelling methods and tools that will require development.

4.1 NEW MODELLING METHODOLOGY DEVELOPMENT PRINCIPLES

The new approach is required to model complex process-resource systems via the methodological use of both currently existing and newly developed modelling tools. Collectively these tools are required to enable the capture and reuse of explicit understandings about alternative ME 'configurations', 'characters' and 'behaviours'. The approach is also designed to enable quantitative predictions to be made about candidate ME production system organisation designs, when they are subjected to change (predictable and uncertain) in patterns of work. Thereby an improved scientific basis for advancing best organisation design and change practice is under study in this thesis. In particular potential advance arises from the qualification and quantification of people and characteristics of technical resource system behaviours, and their fitness to realise changing roles and patterns of work assigned to them. Importantly human and technical resource systems (with various technological tasks they will need to deploy) are modelled as an integral element that can be computer exercised under specific operating and interoperating conditions. Execution of these models and related results analysis will be used in support of decision making via the innovative and coherent application of process modelling, work pattern modelling and complex system modelling techniques. It follows that this research is investigating 'model integration principles' and 'modelling techniques' that support decomposition and integration.

When specifying and developing the new modelling methodology the following set of principles was considered to be critical, and should be embedded in the new modelling development:

1. The (functional) 'eligibility' and (behavioural) 'suitability' of alternative people & technical resource systems needs to be judged in the light of (relatively enduring) properties of the workplace, in which they must work, and the dynamic variations in work patterns they will need to cope with in a timely and effective manner.
2. Systemic (including both qualitative and quantitative) matching between characteristic models of candidate people systems and characteristic models of specific workplaces with changing work

patterns. This will be facilitated greatly, and could be widely applied in manufacturing organisations, by adopting the use of two intermediary sets of modelling concepts, namely (1) role related concepts that maintain (short and long term) structural dependencies linking and (2) dynamic producer unit concepts.

3. The use of new and existing modelling concepts will provide a ‘coherent, conceptual hook’ into the world of business process modelling. Here systematic decomposition of process networks will lead to characterizations of separable (essentially modular) process segments expressed at appropriate levels of granularity as activities, tasks, functions and so forth that can (a) be considered to be roles (with structural dependencies between roles defined by inherent structural properties of the process network concerned) and (b) be assigned to people and technical systems, that are characterised in terms of parameterised attributes of productive units.
4. Characteristics of people and technical systems should be systematically matched to candidate ‘role ~ resource component couplings’. Matching mechanisms that are being encoded and investigated here are based upon ‘eligibility’ (largely functional as in principle 1) and ‘suitability’ (largely psychological behavioural) criteria [Ajaefobi et al 2005; Weston et al 2007]. Competencies of candidate resource system are being characterised from various points of view including functional, capacity and interpersonal(as role dependency) and change capability characteristics. However this research does not seek to model individual traits and characters of people nor does it expect to prove possible to model and usefully quantify all relevant ‘softer aspects’ of people system behaviours.
5. Work pattern dynamics need to be characterised and causally linked to scenarios of ME requirements change, such as customer order change resulting in mixed and dynamic multiple products flows through process segments and roles, that impact on assigned resource systems with designated responsibility for roles and role dependencies. The present author and research colleagues are instructing their modelling concepts and consolidation principles with the overall aim of prototyping of a new modelling tool that possesses an ability to: simulate the operation of workflows through virtual models of roles, role dependencies, and resource systems being assigned roles, thereby enabling strategic and tactical decisions to be made about how to: best organise the work and apply manufacturing paradigms; reorganise processes and derivative roles; alternatively resource roles and role structures, etc.

4.2 DETAILED ANALYSIS OF CANDIDATE MODELLING TOOLS

This section will provide more specific and detailed analysis about current candidate modelling tools and currently available application software which if potentially selected or further developed could be included into the overall new modelling approach.

4.2.1 CIMOSA modelling as tool of decomposition to handle complexity

Enterprise Modelling techniques were observed to usefully provide means of handling organisational complexity. They offer modelling concepts to decompose (general and specific) process networks from a top level of abstraction, down to more detailed components and process segments. [Kateel et al, 1996]. Also existing EM techniques provide means of documenting and visualising associated flows of activity, material, information, control and so forth. Thereby knowledge about any specific manufacturing organisation which normally is distributed amongst many personnel concerned with 'operational', 'tactical', 'strategic' and 'infrastructural' processes of any organisation can be modelled in a visual, reusable fashion; this can provide a formalism needed by the organisation over given timeframes and can capture knowledge that can support various decisions and actions carried out that can causally impact on other process segments of the organisation.

Relating to a number of process modelling approaches and frameworks, CIMOSA was well developed in respect to process modelling. [ACIME 1993; Kotsiopoulos 1996; Vernadat 1996; Kosanke 1997; Monfared 2000]. This was particularly the case when the present author's research was initiated. The present author and his research colleagues at MSI have used and developed the CIMOSA approach over a decade with respect to numerous industrial projects. Therefore CIMOSA was selected as a prime decomposition tool by the author. However some of its pro's and con's are analysed as follows.

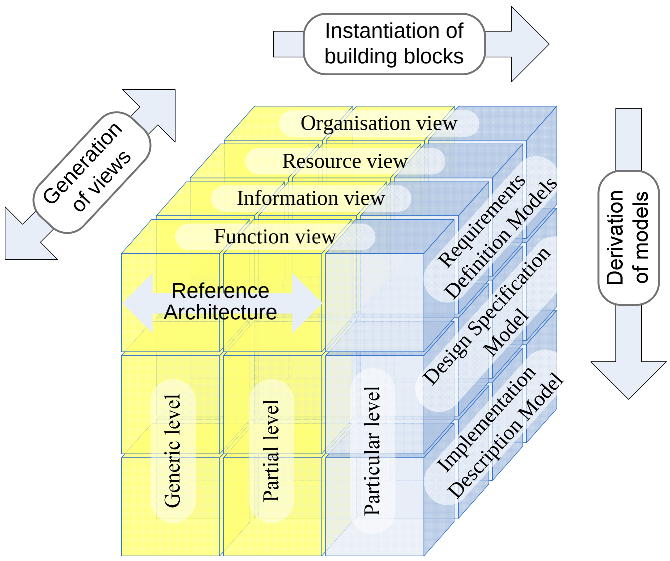


Figure 4.1 CIMOSA model framework (source: Vernadat 1996)

The modelling framework of CIMOSA, shown in Figure 4.1 provides a reference architecture which partitions 'generic' and 'partial' modelling; where at each level of support different views about a particular enterprise model are captured. The concept of views allows users to work with a subset of the model (i.e. one or some cubes located in the whole cube) rather than with the complete model. This provides especially the business user with a reduced complexity model for his particular area of interest. CIMOSA has defined four different modelling views, namely: Function, Information, Resource and Organisation. However this set of views can be extended as needed. The CIMOSA Reference Architecture supports three modelling levels of the complete life cycle of enterprise operations, namely: Requirements Definition, Design Specification and Implementation Description. This cycle corresponds to what CIMOSA calls the derivational direction. Modelling may start at any of these life cycle phases and may be iterative as well, depending on the intention of model engineering, only some of the life cycle phases may be covered.

Monfared's RPM approach (2002) include a four-type-diagramming templates based on use of CIMOSA principles, namely: 'Context Diagrams', 'Interaction Diagrams', 'Structure Diagrams' and 'Activity Diagrams'. Figure 4.2 gives a brief snapshot of this graphical modelling technique.

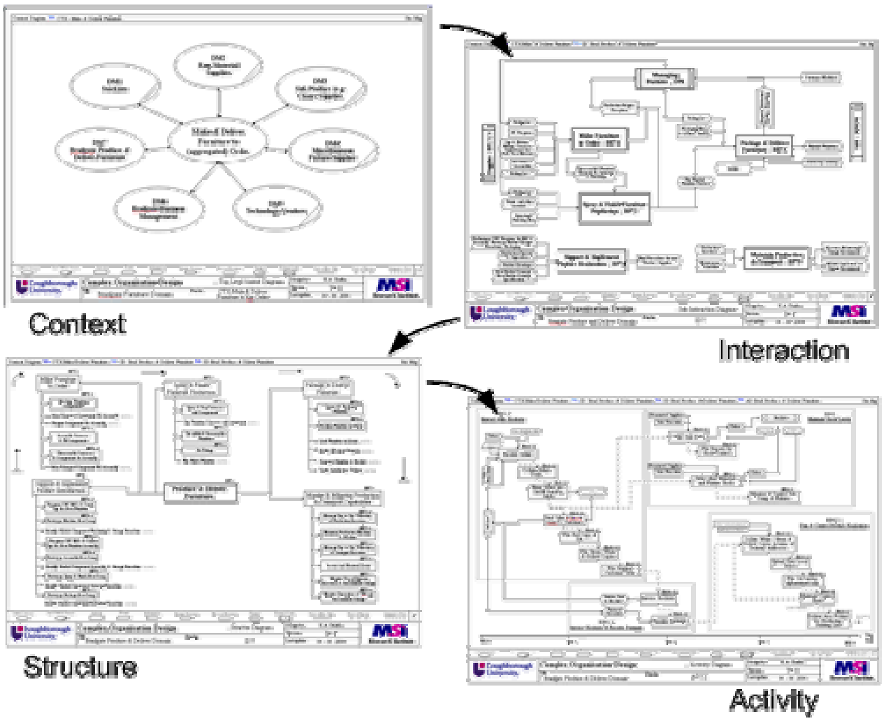


Figure 4.2 Hierarchical CIMOSA model demonstration

It was observed that with standard RPM's CIMOSA model diagrams, Activity Diagrams are the primary tool to present process flow. However this tool was considered to be deficient to indicate and support operation routing sequencing and logic control to various flows. Particularly, the diagrams do not cover aspects related to: process behaviours, i.e. its reachable states and state transitions; how a process will behave differently in response to different stimuli; and how activity outputs will be affected by input variation. Sequencing rules for complex processes are also not covered. When facing varied scenario, what kind of conditional control would be transferred from one process or activity to others is also not elaborated. Also a weakness was observed in respect of clarity when differentiating the types of process and enterprise activities in terms of their contribution to value generation in value streams. So these drawbacks to CIMOSA needed to be overcome for the purpose of evaluating current enterprise business performance. RPM's model as an enhancement of the CIMOSA approach is highly constrained in its support for dynamic process modelling. It cannot provide much useful data to export for dynamic processes mapping and related status and state monitoring of each entity in the processes.

4.2.2 Modelling 'Roles' and 'Competencies' of resource Systems

'Roles' and 'competency' are concepts used widely. However, different perspectives are considered separately in business, IT or human science literatures. Thus far competency modelling has focused on individual learning and exploring performances differences [Harzallah, 2002, Lindemann, 2002, Aburub, 2007]. Hence significant further advance is needed to develop sufficiently semantically rich competency modelling concepts that can be operated effectively with reference to specific people and process contexts subject to uncertain work pattern variation, such that they can be explicitly attributed to suitably configured sets of responsibilities of human and technical resources. New competency methods should encompass team and process performance, support quantitative analysis at various levels of granularity and enable the transfer and reuse of competency knowledge within and across organisations [Quinn 1992; Grote et al 1995; Beevis & Essens 1996; Dekker & Wright 1997; Weston et al 2003].

Recent research in MSI Research Institute at Loughborough University has investigated the use of a well defined set of process-oriented roles to decide how best to resource work to roles [Ding and Weston 2007; Khalil and Weston 2008]. In this research it is assumed that either (1) people or (2) some form of machine and IT system or (3) some combination of (1) and (2) will prove most effective; and that generally these kinds of 'active resource'; will be constrained in terms of their availability. Also assumed is that (a) the nature of roles and (b) the work loads placed on the roles will resolve the most effective match of 'role holders' to 'the defined set of process oriented roles'. Furthermore it is assumed that the work loads in ME's are typically determined by customers and that these workloads will frequently change. These points provide a baseline rationale for this study in that an improved systematic method and supporting modelling tools are needed to compare the match of different choices of candidate human and technical resources to process oriented roles and their work loads; and also that such a method and tools should support short term planning of resource deployment as well as longer term strategic decisions when engineering good quality resource systems. The underlying idea is to create multi-perspective models that can be computer executed in the form of simulation models such that they can provide a computer tool to inform 'ongoing planning' and 'longer term investment' decision making; leading to effective use of human and technical resources. Here modelling can be with respect to (i) known competencies (of people) and capabilities (of machines), (ii) behavioural capacities and performance levels (of both human and technical resource types). This multi-perspective modelling approach is designed to enable: (I) independent change to the two perspectives (i) and (ii); (II) reuse of models of ME's in the form of process and enterprise models; and (III) ongoing systematic reuse of models belonging to those three viewpoints, as required in support of short, medium and longer term ME decision making.

4.2.3 Dynamic and Simulation modelling tool selection

MSI has several years of experience utilising simulation modelling and discrete event simulation software in various projects across different industries. Among the simulation software tools mentioned in the literature review, MSI has used several software applications and has a range of knowledge and experience. Several discrete simulation software packages have been utilised in the past by authors and colleagues of MSI Research Institute.

The present author's previous knowledge of both discrete event simulation software packages and detailed information on the case studies developed enabled a comparison and selection of modelling software tools. A comparison of two software packages currently preferred by MSI researchers were Simul8 and Plant Simulation. Table 4.1 presents a capability mapping which draws a comparison between these two software tools. Observed comparative advantages of Plant Simulation and pilot usage experience made the present author select it as the primary simulation modelling software package during research reported in this thesis.

Table 4.1 Comparison between SIMUL8 and Plant Simulation

Capabilities	SIMUL8	Plant Simulation
Work centre	Single operation	Single/Multiple operations can be modelled
Processing time	Statistical	Statistical
Entry points	Single production unit can be processed	Multiple production units can be processed
Exit points	Accept multiple production units types	Accept multiple production units types
Resources	Applicable to work centre	Configurable resource pool
Human modelling	Number of workers and shifts	Number of workers, services provided, efficiency, shifts
Model statistics	Inside each object within model	Inside each object, can be presented in an external graph
Graphical display	Within objects	External graphical display can be processed
Hierarchy	Only graphical	Reusable objects
Programming	Modifies unit behaviour	Modifies units, production flow, object behaviour

(Source: Guerrero A et al 2008)

4.3 KEY FEATURES OF NEW METHODOLOGY DEVELOPMENT

4.3.1 Requirements and solutions decoupling

It was presumed that any effective deployment of existing modelling tools and new modelling approaches should be designed to maintain systems engineering separations between ‘what needs to be done’, ‘how frequently it needs to be done’ and ‘by what means it will be done’. This constitutes a good mental discipline when thinking about possible ways of changing elements and element relationships within multi product dynamic systems. Of course in reality causal and temporal dependencies occur across boundaries between ‘what needs doing’, ‘how frequently’ and ‘by what means’; but this can naturally be investigated by developing and using causal loop models. Potentially when designing and implementing a multi product dynamic system the designer and builder should decide which of those variables should change to achieve the system purpose and those that should remain constant. When so doing causal loops can help understand and predict how changes to one variable will propagate into other variable’s changes giving rise to resultant system dynamics. Consequently it was decided that clear separations (at least conceptual ones) should be made when creating models of the ‘process segment’, ‘candidate resource’ and ‘work flow’ to maintain ‘what’, ‘how’ and ‘by what’ decoupling features.

4.3.2 Top-down and Bottom-up mechanism usage

Top-down design was promoted in the 1970s by IBM researchers Harlan Mills [Mills 1975, 1976, 1983]and Niklaus Wirth.[Wirth 1971]. A top-down approach is essentially breaking down a system to gain insights into its compositional sub-systems. Using a top-down approach, an overview of the system is first formulated, specifying but not detailing any first-level subsystems, each subsystem is then refined in yet greater detail. Top-down can be re-applied at all research levels to deal with complexity and to modularise designs at different modelling stages. Therefore these principles need to be reinforced through modelling approach development. Detailed explanation of how this was done will be given in the following chapters. This was expected to bring the following advantages, but this needed to be tested via case study application:

- Separating the low level work from the higher level objects can lead to a modular design.
- Modular design means sub-solution development can be self contained.
- Less operation errors and easy to maintain(more manageable within each modelling stage, if an error occurs in the output, it is easy to identify the errors generated from which stage or step of modelling development).
- Solution specification can be with the assistance of "black boxes" to make it easier to manipulate. However, black boxes may fail to elucidate elementary mechanisms or not be detailed enough to realistically validate the model.

On the contrary, when using a bottom-up approach, the individual elements of any system are first specified in great detail. These elements are then linked together to form larger subsystems, which then in turn are linked, quite often there at multiple levels, until a complete top-level system is formed. It was expected that essentially bottom-up specification and development would be used during simulation model compilation and execution, so as to create a set of basic 'data structures' which can be used for representing the model, at all planning stages of the design process in a computer processable format. This point needed to be achieved based on two aspects of work, the emphasis of which are described in previous sections. (1) Clear model requirements and objectives, and model configuration are needed to tackle mapping work of all planning stages. (2) Successful local or partial simulation model design completion, to help to deal with representing tasks. Then the main job for this element is to define the graphic and descriptive structure of a model by a stepwise combining of partial models in conformance with overall model planning. While working towards an integrated modelling environment requires aggregated model outputs and analysis of results, bottom-up would also need to set up rules to guide the design of combinations of model components, taking the following issues into account:

- Unambiguous object identification;
- Referential consistency;
- Partial model completeness;
- Model simplification;
- Semantic consistency.

4.3.3 Visualisation for the new model approach

Visibility is one key feature of modelling tool development and deployment, making the building procedure visible to the modeller and models as outputs to users. This should help to establish credibility and confidence [Robinson, 1994]. CIMOSA modelling is a graphical modelling approach, which explicitly can describe a whole modelling procedure and presentation in a visual way. The intended development can be control logic and model templates that maintain visibility in a consistent way. Role based modelling begins with CIMOSA model activity diagrams and activity groups distributed into models, this is an inherent graphical feature for visualisation. Main body of role based modelling uses tabulating method to identify, aggregate and configure role entities, to provide indexed and comparable model outputs, thus keeping the modelling development visual and formalised. Causal Loop diagrams are also a graphical modelling tool, that can generate qualitative understandings by utilising the support of many popular drawing software tools. The model outputs inform a picture of inter-causal impact relationships and dynamic change. They actually indicate dynamics features in static way, while maintaining a qualitative dynamic analysis functionality. Graphic simulation model building procedures allow computer execution via interactive simulation with on-screen animations. This enables the status of a model to be viewed as it progresses through reachable states, e.g. a machine that breaks down may change its colour to red. This enables visibility to be passed back to the audience of the simulation models (either the modeller himself or model users), so action can be taken where necessary. Additionally, such visualisation is useful in convincing management of the model's credibility.

4.4 RESEARCH APPROACH DEPLOYMENT

4.4.1 Research methods adopted during the research

Appropriate research methods need to be adopted during the research. The main research methods chosen in this study are presented in Table 4.2. The table shows the main groupings of activities carried out during the research and the thesis chapters in which they are reported. Corresponding to each activity, the four main research method(s) referred in the last chapter are presented along with the data type involved during method deployment.

Table 4.2 The Methodology adopted during this Research

Chapter	Main Activities in the Research	Research Methods	Data Type Involved
1	General introduction to current ME production systems, new requirements and features regarding flexibility, modularity, process centred organisation, systems engineering, etc.	Grounded theory Exploratory	Qualitative
2	General literature review covering broad domains	Descriptive	Qualitative
3	Summary of literature review, current literature gap analysis, so as to tackle overall research aims and objectives	Descriptive Exploratory	Qualitative
4	Research design and research principles and new methodology feature setting through detailed and specific modelling tools analysis	Descriptive Exploratory	Qualitative
5 - 7	Specific current modelling tool application and new modelling approach development through stepwise demonstrative case study		
5	Select and use EM modelling tool to generate process and activity network, construct and locate where human and technical resource systems will be applied.	Descriptive Case-study	Qualitative
6	Develop role based modelling approach for chosen process networks through definition and configuration	Descriptive, Exploratory, Case-study	Qualitative
7	Use of dynamic and simulation modelling tools and software to verify and test chosen process elements and candidate resources with respect to their behavioural attributes.	Exploratory Case-study	Qualitative Quantitative
8	Reflection of new modelling approach development work Partial testing of the integrated modelling concepts and methods through second case study	Descriptive Exploratory Case-study Evaluation	Qualitative
9	Summarise, review and conclude methodology development.	Descriptive Evaluation	Qualitative

4.4.2 Comprehensive research achievement plan

A primary modelling approach (Role based modelling) has been developed to methodologically integrate the use of three existing modelling approaches (i.e. (i) Extended CIMOSA Modelling, (ii) Causal Loop Modelling and (iii) Dynamic & simulation modelling) to investigate case study manufacturing systems design issues in this thesis.

Each modelling approach aspect relates to specific emphasis and different use of techniques. The extended set of research activities carried out during this research study is listed in Figure 4.3. Each main research phase and stage is associated with a thesis chapter and principle modelling approach allocation.

1) The first research phase centred on initial background research which allowed the author to understand general research problems in the study area. This also covered general then more specific literature review and analysis. The prime output of phase 1 was: a defined research aim and objective identification; and the research plan design. This phase include Chapter 1 to 4.
2) The second phase concerned stepwise development of the proposed Role based modelling methodology, along with case study application as methodology testing. In this phase studies of the three complementary aspect modelling approaches were applied. Key outputs during each phase were: (i) from a methodology view, the new modelling concepts created and technique developed; (ii) from the case study and application view, and models generated, the results analysed and research findings discussed. This phase covers Chapter 5 to 7.
3) The third phase concentrated on reflection to use (existing) and develop (new) modelling approaches during phase 2 and interpret them from an integrated view point. This phase also concerns broader reusability of the methodology. Such conceiving was tested in the scoping exercise, which was carried out in same industry company as the first case study, but from a different level of abstraction and modelling areas. Some further methodology and technique conceiving and implementation was also followed in this phase. This phase is in Chapter 8.
4) The fourth phase concluded the research, reviewed and evaluated overall research outcomes in chapter 9. Research achievements, contributions to knowledge, and conclusions and suggestions about possible research extensions are considered.

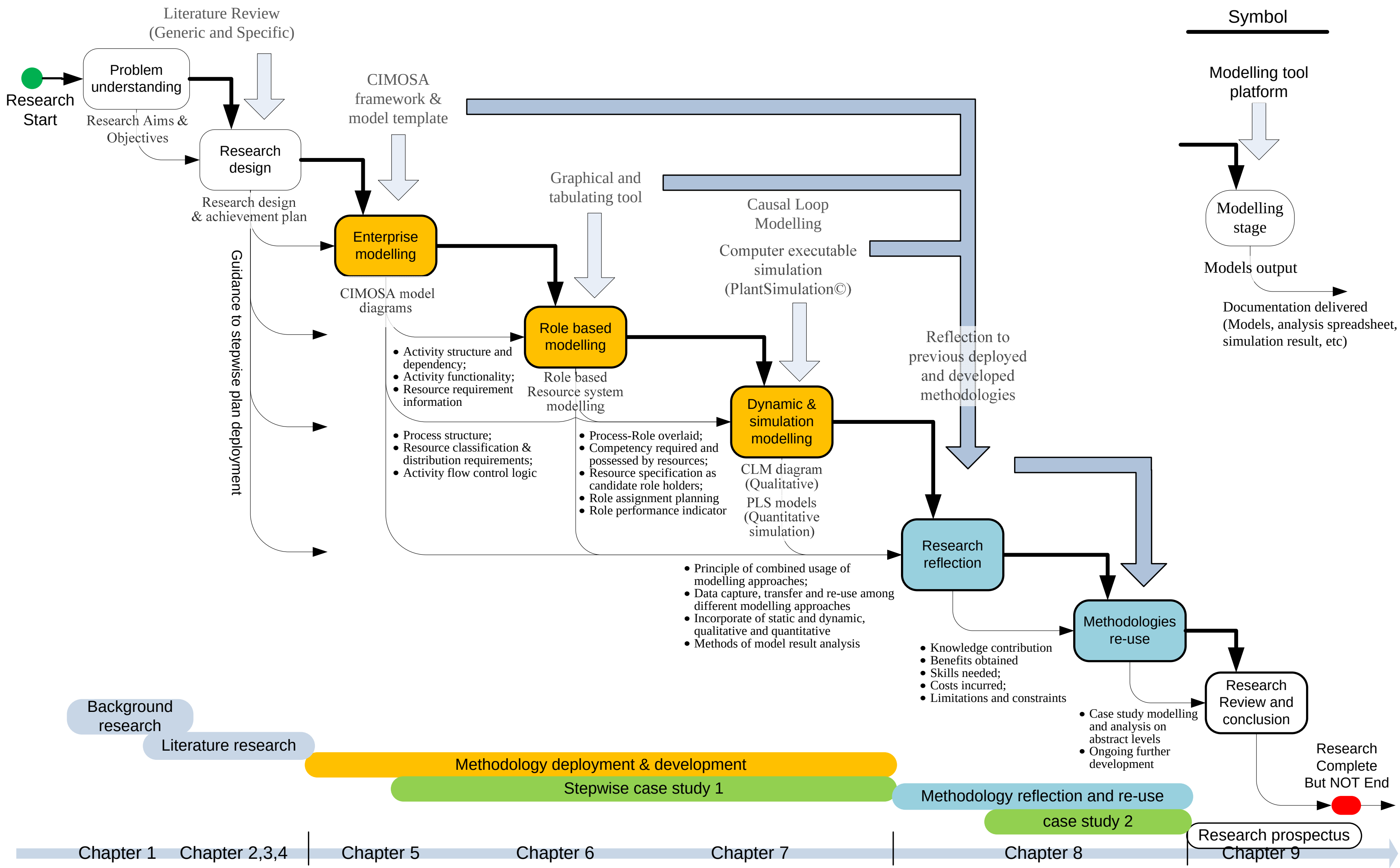


Figure 4.3 Gradual research achievement plan map

53

4.5 RESEARCH NOVELTY EXPECTED TO BE DELIVERED

By the end of this research, the new knowledge generated was expected to be in the following areas:

- New concepts related to the design of resource system organisational structures in manufacturing enterprises that help realise and enforce decomposition principles needed to deal with complexity and change;
- Multi perspective modelling methods that extend the status quo when using models to design organisations so that optimal use of resources can in theory be achieved;
- A new modelling framework that covers static modelling, dynamic modelling and simulation modelling, integrated via a role based resource modelling formalism, along with a proof-of-concept method of implementing that framework;
- Capability and feasibility assessment of the integrated modelling approach by creating useful models that can predict enterprise behaviours in support of ME decision making;
- Modularity and flexibility concepts that can be readily embedded into process designs, naturally leading to reconfigurable and flexible organisation.

CHAPTER 5

Enterprise Modelling Approach

It was observed in the last chapter that the state of the art of Enterprise Modelling (EM) can provide an effective tool to graphically represent structural aspects of complex ME process networks. Starting with the EM approach developed by R.P.Monfared (which is hence termed as the RPM modelling approach), this chapter reports the use of CIMOSA and its new developments through an illustrative case study. The new developments upon existing RPM modelling diagrams lead to improved data sharing and an enhanced logic control ability. The resultant EM models and its technique enhancement will be used in subsequent chapters of this thesis to structure the new development and use of the role based modelling approach to process oriented MEs.

5.1 INTRODUCTION TO THE CASE STUDY COMPANY

5.1.1 Choice of the case study company

Selection criteria were needed to ensure that the chosen study company could: (1)facilitate relevant EM developments and (2) enable testing of the applicability of those developments. The case study company was selected for of the following reasons:

- A local manufacturing company; located in the vicinity of Loughborough University, of medium size and making a range of products. The location was considered important as was its commitment to work with the University to enable knowledge acquisition and data collection.
- The company's manufacturing processes could be modelled to understand the primary operations carried out to realise the range of products on an ongoing basis.
- The company deployed a combination of technical and human resources to realise its primary processes and business objectives.
- Having captured knowledge and data and coded this into a company, the company should be willing to verify the correctness of that knowledge and data and where possible to reuse it.

A number of local companies possessed the above characteristics, one such company, which will be known as Fixed Furniture Ltd. (FFL), was selected as the prime subject of case study.

The FFL company makes pine wood furniture products, employ approximately 50 personnel. Basic components are made to stock but final products are assembled to order. FFL sell products solely through stockists. Over the last 3 years FFL sales had increased by 25% annually, but lead time had doubled from 4 weeks to 8 weeks. Although longer lead times were acceptable to some customers, the company had also received many complaints. Hence the company strategy was to grow while seeking to re-engineer its existing processes and resources to create more timely production systems.

5.1.2 Products and essential operations

FFL's furniture manufacture (especially assembly)is driven by an aggregation of sales orders from customers. Figure 5.1 indicates the main processes required to achieve order fulfilment. The main control 'signals' are numbered as relating to the physical processes:

1. Sales orders are received mainly via fax but also by post and telephone from customers.
2. The order information is input into a Sales Order Processing (Sage) software. A unique Order Acknowledge Number and documents are generated and allocated.
3. Then a production "Picking List" is produced by Sage which will be used to drive the factory, and is sent to the factory to initiate manufacturing processes.
4. After products have been manufactured, the delivery process starts; furniture is checked (to ensure consistency with orders), packed and loaded onto lorry, then despatched.
5. Once delivered, invoices are issued via Sage system to make sure payment is received.

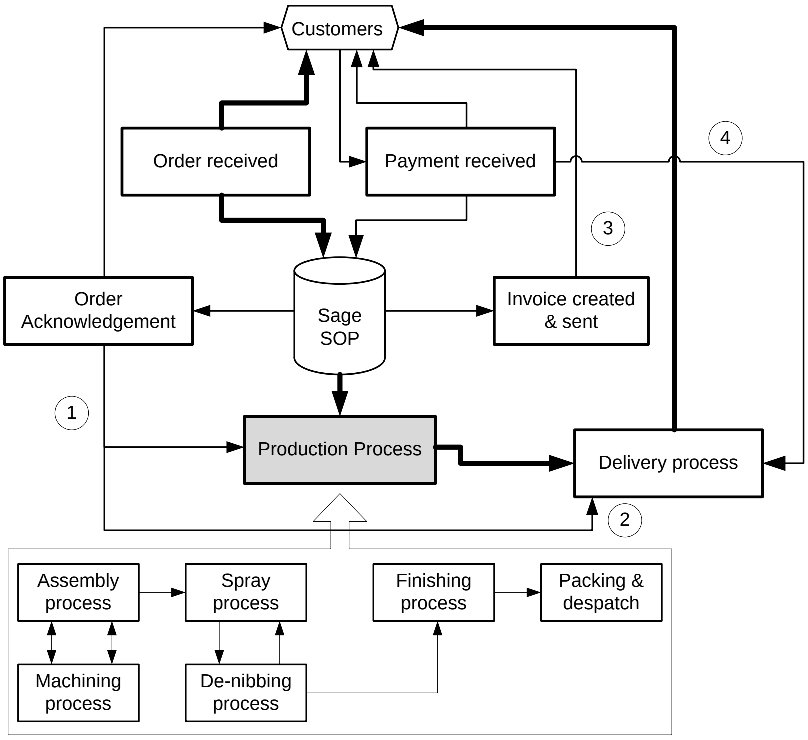


Figure 5.1 Overall order fulfilment process

5.1.3 Targeted modelling domain in FFL

The modelling context must be defined before deploying the CIMOSA modelling approach in FFL, so as to identify the domains of concern with the study scope. It was observed from Figure 5.1 that 'production process' as direct value generation was considered to be of interest in the study. Figure 5.2 interpreted the 'production process'. There are both parallel and sequential flows through production processes, as indicated by the timeline at the bottom.

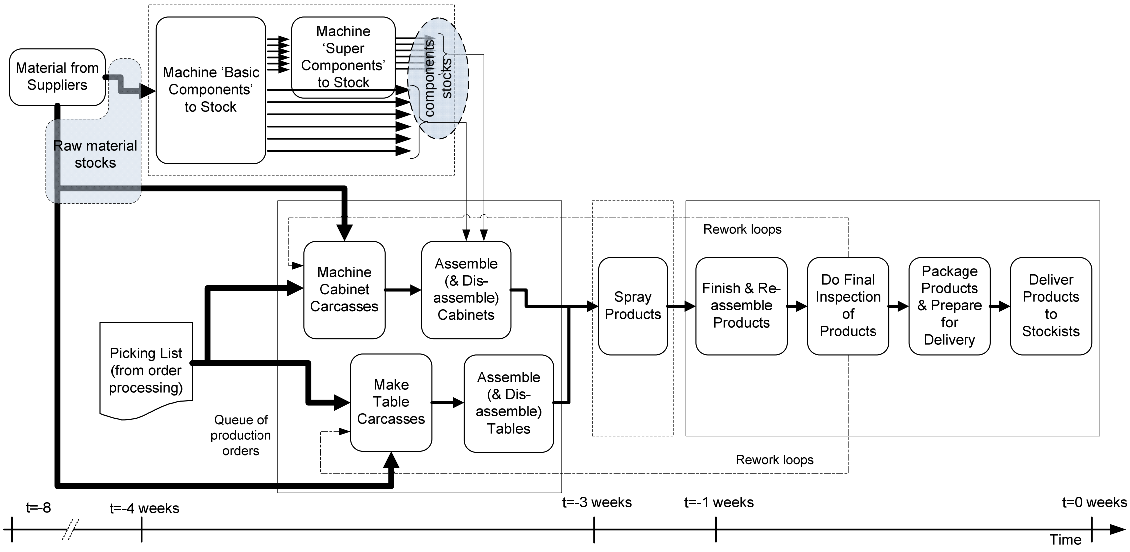


Figure 5.2 Multi-flow network within production process scope

5.2 CIMOSA BASED ENTERPRISE DECOMPOSITION AND MODELLING

The present author used CIMOSA modelling, instrumented by RPM's approach to create EM diagrams to explicitly document relatively enduring structural aspects of FFL's order fulfilment.

5.2.1 Top level context diagram

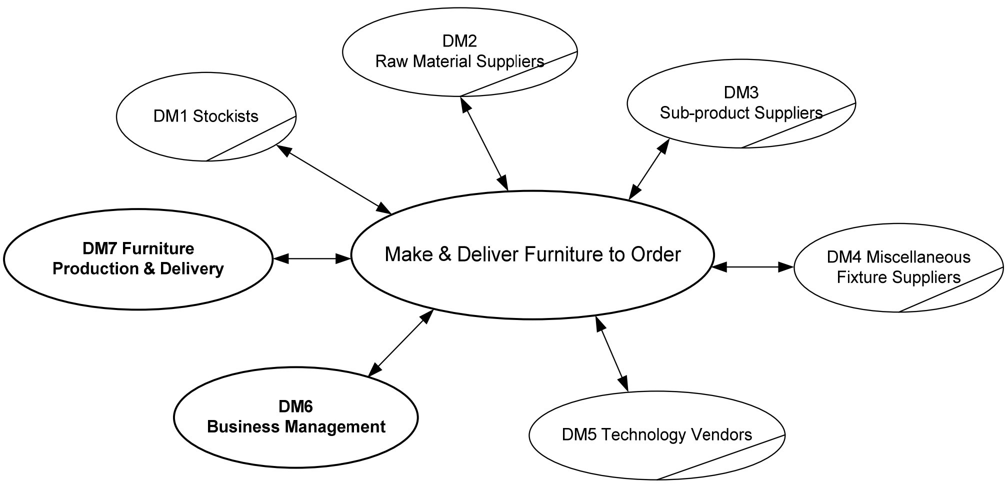


Figure 5.3 Top level context diagram in FFL

RPM's graphic modelling approach is based on the use of four types of diagrams. Figure 5.3 shows a top level ConTeXt diagram (CTX) created for FFL, explicitly defines the scope of the current modelling exercise in terms of the domains that contribute to the processes being modelled. For instance in this diagram, the text "Make & Deliver Furniture to (aggregated) Order" explicitly indicates that furniture is made and delivered according to aggregated orders received from the customer (so called stockists). This also points out the strategic importance in the operation policy adopted by FFL in its current state. In the FFL context diagram, 'Make & deliver Furniture to Order' is realised by surrounding domains (DM6 and DM7 in this case). The extent of modelling domains in detail may be restricted by available modelling time and resources, data and information availability or research focus priority. In this study for the focus a concern was on 'DM6 – Business Management' and 'DM7 – Furniture Production & Delivery' which needed to be decomposed into their elemental business processes (BPs) then Enterprise Activities (EAs). While domains that will not be modelled at this point are given a crossed oval.

5.2.2 Top level interaction diagram

An INTeraction diagram (INT) is used to detail associations between domains (which may be or may not be modelled in CIMOSA in detail), so that impact between the domains can be determined. Figure 5.4 shows the top level INT diagram created for FFL which corresponds to the context described in Figure 5.3. When conducting CIMOSA modelling, domains identified in Context diagram are considered to comprise one or more domain processes that realise the purpose of that DM. In the case of Figure 5.4, DP6 and DP7 are derived from DM6 and DM7 in Figure 5.3. The interactions occurred among domains are connected by texted symbols with arrows.

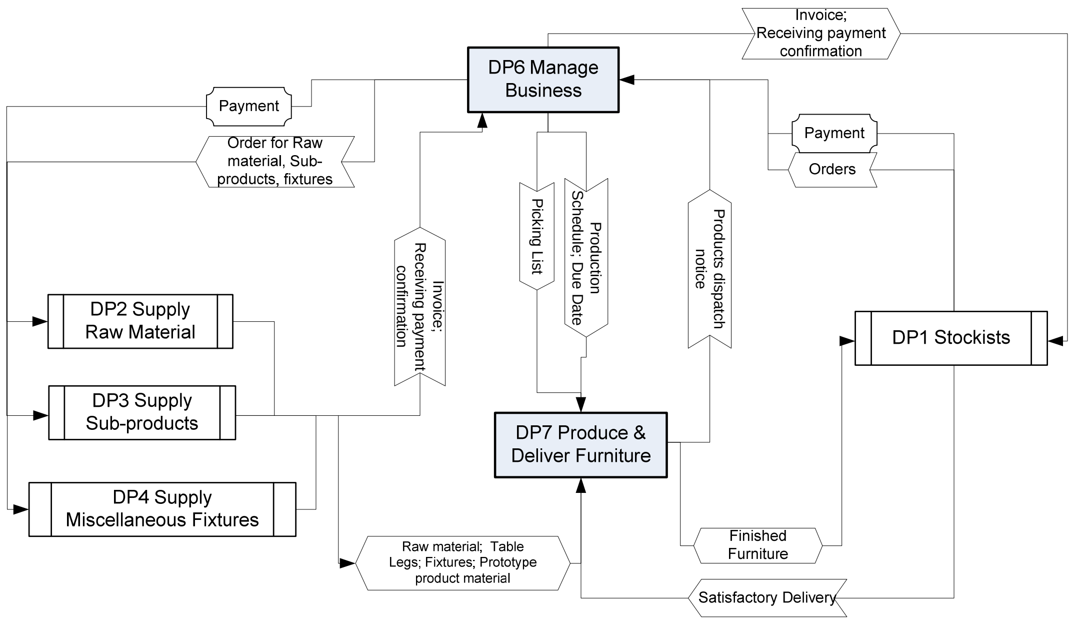


Figure 5.4 Top Level Interaction Diagram in case scenario

RPM's diagrams use five types to construct the in-flows and out-flows between domain elements, namely: Event, Information, Human Resource, Physical Resource and Finance, presented by different symbols. In Figure 5.4, it can be observed that DP6 provides "Production schedule, Due date, Picking list" information to the DP7. On completion of production, "Products dispatched" is given as information feedback. This provides a visual graphic way of documenting relatively enduring dependencies between processes and it makes possible to trace and locate the source of effects that cross organisational boundaries. However the emerging sequence of those impacts are not displayed in this diagram type.

5.2.3 Structure Diagram of a selected Domain Process

A STRucture diagram (STR) explicitly documents the dependency structure between domain processes, business processes and enterprise activities in a visual organisational hierarchy. Figure 5.5 graphically describes the structure within DP7, which is one of the main processes of concern identified in this study of FFL. It can be observed that DP7 comprising four BPs which were numbered BP71 to BP74. Each of these BPs comprise sub-business processes (sub-BPs) and elemental enterprise activities (EAs). This hierarchical decomposition defines ownership type relationships. For example BP72 'Make furniture to Order' is a Business Process of DP7 but itself consists of three Sub-BPs (BP721, BP723 and BP724) and two EAs (EA722, and EA725). Sub-BPs may themselves break down to EAs but EAs correspond to the lowest level at which the modeller will details process elements; i.e. they are at an atomic level unit in RPM's approach diagram. In addition, logical sequences of the modelled processes are represented in structure diagrams by means of arrow-headed lines around whole diagram, indicating the general process flow. This is not necessarily a flow which is strictly followed, rather it is a logical procedure used to achieve some higher level i.e., in this case, successfully produce furniture in conformance with orders and to deliver them to stockists on time. Producing one or more structure diagrams offers a simple but useful way of structuring all processes that contribute to the purpose of an enterprise.

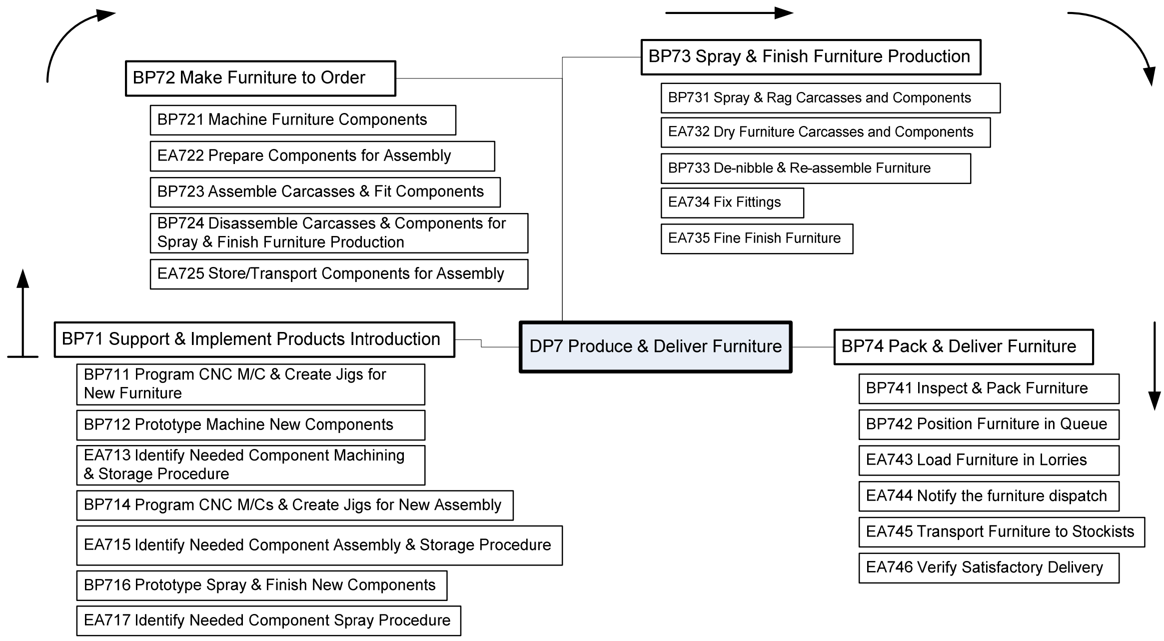


Figure 5.5 Structure diagram of selected domain process(DP7)

5.2.4 Sub-Level interaction diagrams

A CIMOSA DP typically represents a complete end-to-end process that can exist independently. A DP may include sub-DPs that work together and interact with one another to fulfil the superior purpose of the DP. Also commonly complex interactions occur between DPs (often owned by different domains) and their constituent BPs normally cannot be represented effectively in a single level Interaction Diagram. Sub-Interaction Diagrams hence need to be created to specify and represent interactions among Sub-DPs and BPs. Figure 5.6 demonstrates one Sub-interaction diagram developed to represent more interactions for DP7. This diagram shows interactions between the 4 BPs of DP7. Similarly, where necessary, sub structure diagrams can also be developed to present more detailed process oriented structural decompositions.

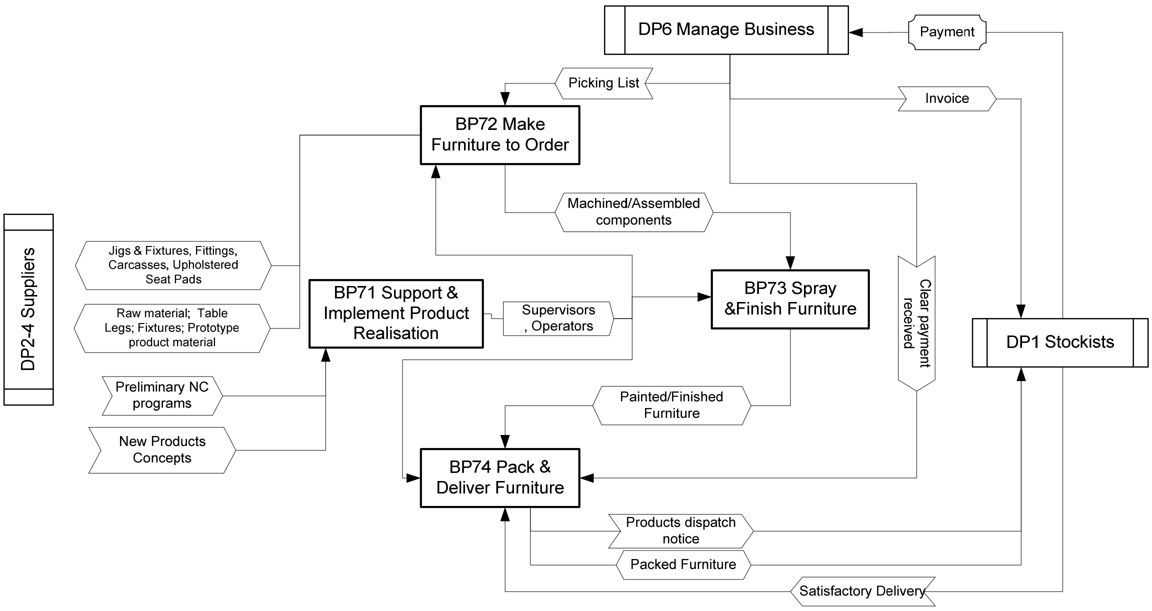


Figure 5.6 Sub-Interaction Diagram to 'Produce & Deliver Furniture' Domain Process

5.2.5 Activity Diagram modelling for selected Business Processes

The fourth type of RPM diagram used for requirements capture is ACTivity diagram (ACT). ACTs are used to encode the sequential nature and routing of DPs, BPs and EAs. For FFL Activity Diagrams were created to show how furniture manufacture sequences are realised. For example the Drop Leaf (DL) table assembly process is shown in Figure 5.7. This diagram explicitly describes a segment of the 'Make Furniture to Order', which is clearly indicated by the numbering (BP723 and belonging EA7231). The main steps of this process are collect parts and components; shape and sand separate parts; then assemble into a complete table. For better clarity, groups of EAs can be included into the same BP or Sub-BP and are enclosed by a frame-box. The timescale arrow at the bottom of diagram roughly indicates the duration of the end to end business process. ACTs also detail the required key resources to achieve individual activities. The three sub-activities of EA7234, sanding different pedestal parts can be triggered together by the arrival of components; also at a similar time, other EAs (such as EA7232-1 and EA7233) can be triggered by this condition. In the reality resource availabilities vary and this constrains execution of these activities.

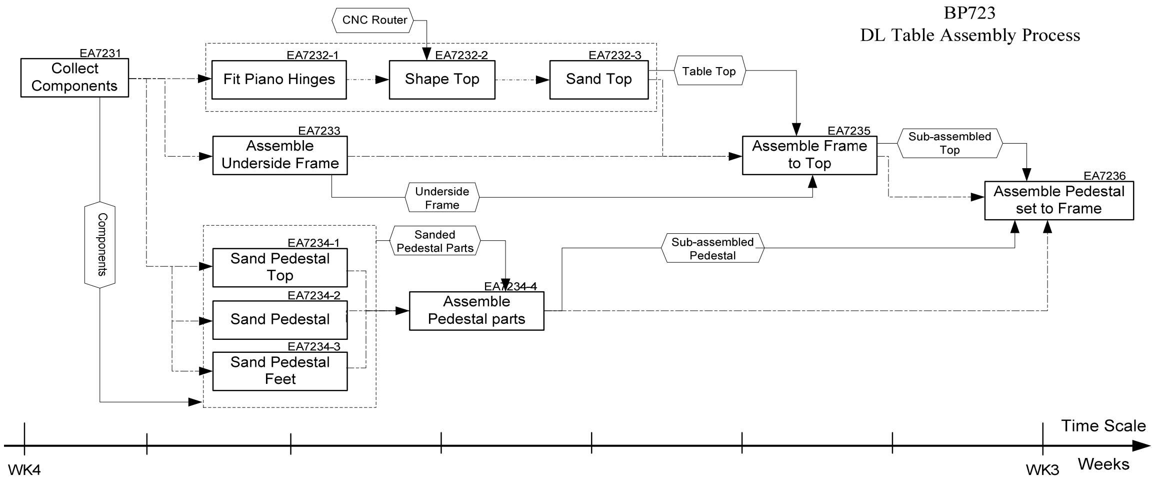


Figure 5.7 Assembly Process Activity Diagram within Production Domain Process(DP7/BP72)

5.3 DEPLOYMENT OF CONTROL LOGIC IN CIMOSA MODEL DIAGRAMS

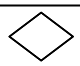
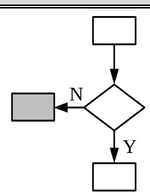
While using CIMOSA RPM approach to build business process networks in ME's, the present author considered how information and data presented in models could be used effectively by simulation tools. RPM's CIMOSA diagrammatic modelling approach was observed to be lacking in its encoding of logical sequences of activities. Logical sequential routing is one of the significant constraints in activity diagrams, and the connected activities have no ability to show optional flows (such as to handle exception flows). This is because some processes and their elemental activities can only be triggered when pre-set conditions are satisfied; also some parallel activity must be aggregated at certain points before going to the next step. Neither of these situational conditions can be explicitly encoded by RPM's approach.

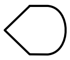
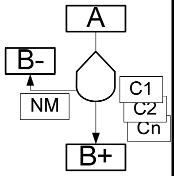
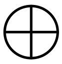
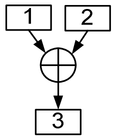
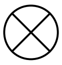
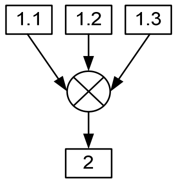
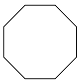
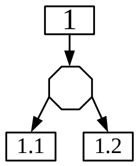
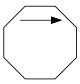
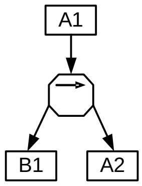
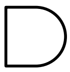
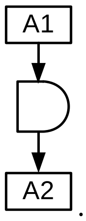
Numerous theories, methodologies and tools have been developed and used in different academic and industrial fields related to workflow control [Russell N et al. 1996; Jablonski and Bussler 1996; Schal 1996; WFMC 1999; Kiepuszewski et al. 2003]. After studying and reviewing previous work, Flow Control Logic (FCL) nodes were developed by the present author to specifically overcome the aforementioned weakness in RPM's activity diagrams, and to better differentiate process modelling behaviour during activity flows. Those nodes are deployed among BP and EA entities and attributed to activity flows previously encoded using RPMs activity diagrams, so as to generate 'more controllable process and activity flow network'. Seven types of FCL node were developed namely: *Conditional; Case; OR; AND; Sub-Process; Chained-Process* and *Delay*. The seven types can be grouped into four sub-categories in terms of their different criterions:

1. ***Exit instruction control:*** This type includes Conditional and Case nodes that define flow routing via pre-defined criterion(s) within the node. Conditional node responses to whether condition is satisfied, is a Boolean type 'If… then, else…'. While Case node is essentially an advanced Conditional node. For Case nodes, a set of satisfaction criterion are defined, each of them will control flows to corresponding output route depended upon entry conditions. Only when none of the defined conditions are met, will the flow go to the 'No Match(NM)' output route. This node can be described as 'In case of … then…; otherwise…'.
2. ***Input collection:*** OR and AND nodes both function as a multi-entry aggregation point. Both nodes receive multi-incoming activity flows, either synchronously or asynchronously. The main difference between OR and AND nodes is their exit release control signal. Any single entry arriving with a satisfied status will trigger the exit release of an OR node, while the AND will not to be released until all entry conditions are satisfied. Prior to that, the node will keep the process flow in a Suspended (Waiting) status.
3. ***In process control:*** Sub-Process and Chained-Process trigger a process separation, that are driven by a previous activity. The nodes define next procedure of the separated process, particularly inter-constraints between parallel processes. Sub-Process and Chained-Process are differentiated in terms of their end condition; such as whether collective re-gathering is needed or if they can independently proceed further. Sub-process requires all separated processes to flow back together at some subsequent point; while following a Chained Process node need not rendezvous.
4. ***Time Constrained:*** This type of node introduces a time delay, which most frequently will be related to an out-of-the-process event. The node triggers a period of 'Waiting' state to the process flow.

Table 5.1 gives detailed descriptions to above FCL nodes. Abbreviation and graphic symbols are listed in left column. The graphic symbols are also presented along with a reference number when they are deployed in model diagrams. In the description column for each node a brief explanation is given of their operating principle. In addition, in the right hand column illustrations of usage of each node are listed.

Table 5.1 Flow Control Logic (FCL) node list

Node (Abbreviation) / **Symbol**	**Description**	**Usage Illustration**
Conditional Node (CO) 	When a process reaches this node, next flow direction is decided by evaluating the inflow status and compare with pre-defined CONDITION in the node. If satisfied, the flow will take the Yes direction; otherwise diverts to No. This type of node is used to handle "either or" two way decision making.	

Cases Node (CA) 	When a process reaches this node from A, the flow direction is decided by comparing the inflow status with pre-defined 'Condition cases list' in the node. If a match to any case in the list is found, then release to B+(positive) exit.. Otherwise, if none of them matches, flow is diverted to NM route B-. CASE node is considered to be a functional extension of Conditional Node, to deal with more complex coming conditions.	
OR Node (OR) 	Multiple inflows (Block 1 and 2) come to this aggregation point. Their arrivals may refer to time basis or criterion satisfaction basis. The outflow release is of response to inflows satisfaction. Either one of entries arrival (time basis), or satisfied(criterion basis). If there are multiple exit routes, all of them will be released simultaneously.	
AND Node (AN) 	Multiple inflows (Block 1.1 1.2 and 1.3) come to this aggregation point.. Their arrival may refer to time basis or criterion satisfaction basis. The difference to OR node is that the outflow won't be released until all entries are completed (all arrived from time basis, or satisfied from criterion basis). This node is used to gather and synchronize multiple inflows in a process. In this research, AND nodes is particularly designed to be coupled usage with Sub-process Node for sub flow control.	
Sub-process Node (SP) 	When a flow reaches this node, sub-processes are triggered (Block 1.1 and 1.2 for instance). Control of the process is passed to each sub-process, and the node enters a 'Waiting-for-Sub-process' state. When all sub-processes complete, control will pass back to the main flow and continue for further operations. Sub-processes are often coupled with an AND node at the end of sub-processes.	
Chained Process Node (CP) 	When the entry(A1) reaches this node multiple exits are activated simultaneously. Besides main flow proceeds into the next step (A2), another process(B1) is activated. From this point of view it's similar to a Sub-process. However, A flow does not enter suspended state, and subsequently the chained B process operates as an independent flow. B1 process is not always necessary rejoin main process later, may end itself.	
Delay Node (DE) 	This node is a checking point gate. There is no routing diversion at this node. When the workflow reaches this node(from A1), the process pauses and stays in a suspended status, until the pre-defined timer attached to the node is timed out. Then the node releases the flow and continues operations (A2 in this case). The reason for delay can vary, mainly from sources outside of the process, but the node is used here to simplify such reasons.	

5.4 VALUE STREAM CLASSIFICATION TO PROCESSES

Typically in a complex ME multiple value streams flow through the process networks. However not all processes and activities are adding value to final products. Thus often it may be useful to differentiate process and their entities (activities) in terms of their contribution to value adding. Thus classifying processes and activities during enterprise modelling can subsequently facilitate cost analysis during modelling stages of dynamic simulation.

Pandya's [1997] 'Generic Operate Process' Group and Salvendy's [1992] process classification method were reviewed and interpreted to classify processes and activities commonly found in MEs, with particular reference to the use of Activity Diagrams. Three types of operation were identified to label model entities such as BPs or EAs differently in terms of their contribution to the achievement for order fulfilment objectives; which was interpreted as a core value adding stream:

- *Direct Generation* (operations that directly add value to final products): The creation of products within any ME leads to the satisfaction of customer requirements; which is considered here to be a primary source of profit value generation. The operations directly involved in realising this objective are classified as Direct Generation type operations. Typical operation examples include operations that add value to raw materials such as parts machining; parts and sub-assembly assembling; and product functionality testing.
- *Direct Support:* Such operations themselves do not involve transforming material into products directly. However these operations provide direct support to maintain *Direct Generation* type flows. Typical examples in this category include material and parts transferring; final product packaging and delivery; new product design and current product development.
- *Indirect Support:* Compared with *Direct Support*, operations belonging to this category do not have direct correlation with any *Direct Generation*. Hence they cannot benefit value addition. However they may provide support to Direct Support operations, such as by co-ordinating and maintaining relationships between operations. Most business oriented operations belong to this operation type.

Figure 5.8 Illustrates how the proposed value oriented classification was used in the FFL study. This presents a mixed process and activity flow in FFL which is used to achieve overall order fulfilment objectives. The process and their component activity entities are differentiated by a variable block background filling style. In this way they are graphically labelled in terms of adding value along the flow. Such a static differentiation can be documented in this way and reviewed during later dynamic simulation stages; when analysing the performance of processes and process segments.

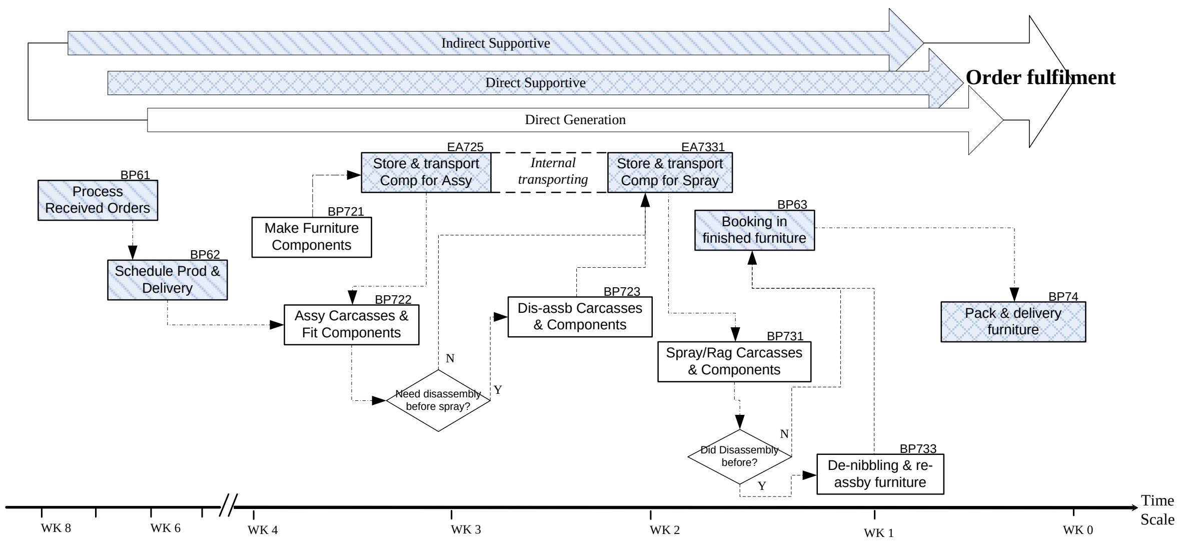


Figure 5.8 General Workflow diagram with process classified in FFL

5.5 NEW EM TEMPLATE TO COMBINE MODELLING DEVELOPMENT

This thesis section describes how the logic control nodes and process classification proposed by the present author can be used in an integrated fashion through the improvement to CIMOSA RPM template developed by Monfared (2000).

5.5.1 Catalogue of building blocks

Model building entities, including previous and newly defined, are categorised into five groups; listed in Figure 5.9 part A. These entities are presented as sets of graphical symbols in the modelling template, shown as Figure 5.9 part B.

General blocks
- CIMOSA Domain
- Non-CIMOSA Domain
- Process/Activity
- External Link
- Event

Flow control logic
- Conditional
- Case
- OR
- AND
- Sub-Process
- Chained Process
- Delay

Resources
- Information
- Human Resource
- Physical
- Finance

Operation type
- Direct generation
- Direct Supportive
- Indirect Supportive

Flow type
- Flow of Resource (solid line)
- Flow of Process (dash-dotted line)
- Alternative Flow (dashed line)

Part A

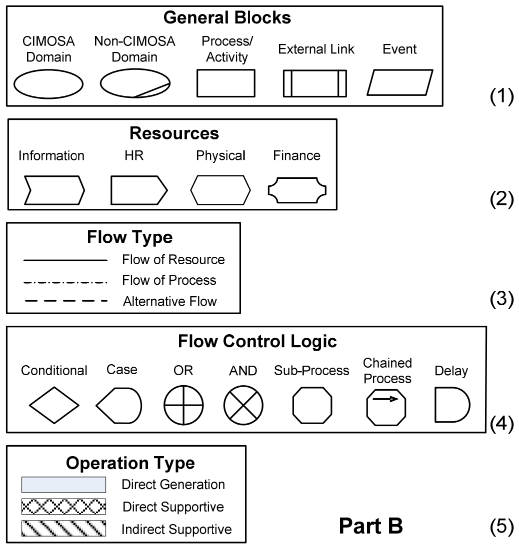


Figure 5.9 Improved building blocks in CIMOSA model diagram template

5.5.2 Illustration of new template implementation

With the introduction of logic control nodes integrated into a new template, activity diagrams can contain enhanced semantics, i.e. they can more clearly describe the complexity of the process network, by attributing workflow interactions, constraints and time scales among entities. An example model built with new template is illustrated here, using the same FFL case earlier in this chapter, with a view to comparison. Due to the case speciality, not all nodes were used.

The activity diagram for the model of the DL table assembly process (see Figure 5.7), was re-created as Figure 5.10 by using the new modelling template. The primary sequential nature and routing of the activities within the process were categorised and presented. Also two Sub-process node(SP01, SP02) and three AND node(AN01, AN02, AN03) were added into the diagram to identify required operational sequence logic. For this specific process model, two types of value addition are included: EA7231 Collect components, an internal parts transport operation of the direct support activity type;

while a number of other activities directly physically transform parts towards realising the final product (finished DL tables). They belong to the direct value addition type. More diagrams created by using the new template are attached in Appendix II.

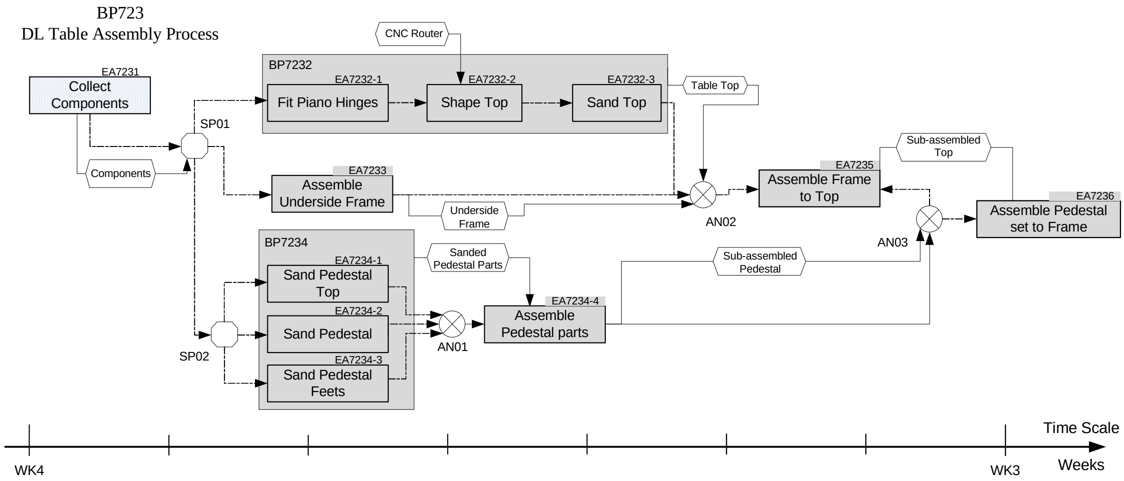


Figure 5.10 Operation type categorised activity diagram with logic control nodes

Tables 5.2 and 5.3 were used in conjunction with Figure 5.10, to enable definition of conditions associated with the involved nodes. The two Sub-Process nodes are specified by Table 5.2 in which there are four columns plus a comments section. The four columns provide a simple way of listing additional information related to the nodes, while the comments provided a more flexible descriptive explanation. The three AND nodes are specified by Table 5.3. One special column 'Coupled Node' was added in Table 5.3. This column is used to identify whether earlier nodes defined are coupled to this node, and whether their status would trigger a node state change; as a type of control signal release. This kind of information can be important during later dynamic modelling and used during the development of computer executable models. The other node types did not apply in the case demonstration. A completed FCL specification table template for all seven type nodes is attached in Appendix III.

Table 5.2 Sub-Process Node(SP) specification table in BP723

Sub-Process No.	Previous Entity	Forward Entity	Delivered Products components
SP01	EA7231	EA7232	DL Table Top Parts
		EA7233	DL Table Top Frame Parts
		EA7234	DL Table Pedestal Parts
Comments: All parts received from EA7231, were diverted into parallel sub activity group for further operations.			
SP02	SP01	EA7234-1	Pedestal Top
		EA7234-2	Pedestal
		EA7234-3	Pedestal Feet

Comments: Pedestal parts received from SP01, need further separation, diverted into parallel sub activity, doing sanding work on different parts.

Table 5.3 AND Node(AN) specification table in BP723

AND No.	Entry list	Aggregated elements	Forward Entity	Coupled Node(if avail.)
AN01	EA7234-1	Sanded Pedestal Top	EA7234-4	SP02
	EA7234-2	Sanded Pedestal		
	EA7234-3	Sand Pedestal Feet		
Comments: Collect all pedestal parts sanded before send into pedestal assembly, the release of this node will return with SP01 waiting status complete.				
AN02	EA7232-3	Fitted and Sanded DL Top	EA7235	
	EA7233	Grouped Frame		
Comments: Collect sanded table tops parts(fitted) and grouped frame parts, send through for assembly				
AN03	EA7235	Assembled top with frame	EA7236	SP01
	EA7234-4	Assembled pedestal		
Comments: Collect assembled top/frame and assembled pedestal sub-assembly, prepare for whole assembly, the release of this node will return with SP02 waiting status complete.				

5.6 CHAPTER CONCLUSION

This chapter illustrates how the previously established CIMOSA modelling concepts and diagramming techniques are used to systematically decompose complex manufacturing system to focused scope and scale for further detail modelling. Based on that, some modelling technique improvements were proposed to enhance the modelling ability of (1) process flow control and (2) specifying process (and its segments) value addition differentiation. The state of the art enterprise modelling approach and its proposed improvement are both illustrated through the case study. The methodology and its application provided an initial stage for further methodology development and intensive case study modelling work, this will be explained in later chapters.

CHAPTER 6

Role Based Conceptual Modelling and System Configuration

Process modelling (CIMOSA in this research case) can be used to explicitly represent a context dependent network of process segments (i.e. sub-processes and their elemental activities); so as to define relationships between those segments in a potentially measurable and controllable way. Then Role based modelling was introduced and developed in this study as a flexible way of linking (1) process segments (and their activity elements, that are considered to be a cognate set of activities) to (2) candidate resources, that are potential holders of roles defined under (1).

Research reported in this chapter seeks to develop an improved way of modelling a human and technical resources system; so that they can be assigned process-oriented roles. With that purpose in mind, the development of a new role based modelling methodology(R-BMM) is described. This methodology builds upon the use of the previously established process oriented modelling framework (CIMOSA was selected in this research) and some new modelling concepts. Role related modelling issues raised in this chapter seek to address (1) decomposition and hierarchical aspects of roles (which are considered to be relatively enduring structural aspects of roles); (2) with respect to different life cycle aspects of role modelling; and (3) enable decouple/match 'role processing requirements' from 'competencies of candidate resource systems'(as potential role holders).

6.1 GENERAL PRINCIPLES TO ROLE CONCEPTS DEFINITION

Notions related to 'roles' have been widely used to model authority, responsibility, functions, and interactions. Roles are also commonly associated with organisational positions that are held by people. Review of the research literature showed that no previously published methodology existed for overlaying role definitions onto process maps, such that the boundaries of responsibility for resource systems can be explicitly defined in terms of required processing activities. Hence central to the research reported in this chapter is the research assumption that this can be usefully achieved with two main purposes in mind: (1) to overlay a 'role based organisational structure' onto process models, so as to graphically and explicitly represent how organisational structure can be defined relative to predefined flows of activities required to realise the various purposes of any subject ME and (2) to provide a modelling mechanism which can flexibly link processing requirements space coded by (1) to candidate groupings of resource systems, that possess the 'abilities' and 'capabilities' needed to act individually or collectively as the holders of required roles also defined by (1). The idea therefore was to consider the pros and cons of a new way of flexibly linking *process models* to *(human and technical) resource system models* with a view to systematically selecting between potential role holders and later quantifying their relative performances in fulfilment of the defined roles. It was understood however that specific ME expertise would be likely to be needed to 'determine role boundaries', 'judge relative performances of role holders' and 'determine potential role holders'. But the focus of research attention here was on systemising key aspects of the life-cycle engineering of MEs, by facilitating the development and re-use of models used during both 'requirements definition and analysis' and 'resource system (and conceptual solution) design'.

In the following sub-sections it was decided that previous notions about competency modelling could be used to instrument the 'static mapping' of role requirements (explicitly defined in terms of process and activity flows) onto abilities possessed by candidate resource systems. But it was understood that this mapping would be 'static' in the sense that during ME operations, role holders would likely occupy roles (specified during requirements modelling) for some period of time. However, as role holders, they would likely need to perform specific and changing jobs, tasks and activities during the defined time span. Hence it is also necessary to quantify the way in which different role holders would perform as the specific jobs, tasks and activities that they carry out to change. Here it was planned that simulation modelling technologies could be usefully deployed to model relative role holder behaviours.

A key need envisaged would be to flexibly map role requirements onto candidate role holders. Here it was presumed that often production system requirements are defined first; following which role requirements can be identified, after which suitable resource systems can be specially configured. Then as production and role requirements change, the aim is to flexibly map to this needed solution changes. In principle the ideas developed could also allow the solution aspect to trigger a review and subsequent role and production requirements change. In framing the research assumption that (process oriented) roles can be graphically and explicitly defined in support of the life-cycle engineering of MEs, it was implicitly presumed that roles can be usefully defined in process-oriented terms. It was understood that many manufacturing systems are process oriented, as are related manufacturing systems engineering processes. But it was understood that the approach might not suit more 'organic types of role', and related organic systems engineering. However part of the investigation envisaged would be to consider the extent to which the approach might be used in MEs.

6.2 ROLE BASED MODELLING CONCEPTS

Figure 6.1 indicates what the author considered to be prime concepts and related entities that need to be understood and modelled so as to characterise roles from requirements and solution perspectives. They are divided into three aspects: '***descriptions and requirements of Role***', '***Competency***' and

‘***Role Holder***’. Each aspects requires embedded modelling concepts that will be described in detail through this thesis. The three aspects primarily concern the following:

- Descriptions and Requirements of Role – Roles are overlaid onto process oriented models placing organisational boundaries that decompose process models from an organisational point of view; the process flows (and their elemental activity flows) are encoded within and between role boundaries to explicitly identify processing requirements and also related sequential, concurrency and precedence relationships. Further the activity requirements encoded can be analysed to define the ‘functionality requirements’ needed to perform roles, which in turn can be linked to ‘competency requirements’ to perform roles.
- Role Holders – These are viable (human and technical [such as machines and IT]) resource systems that can be assigned with those requirements as Role Holders capable of performing the roles.
- Competencies – which take two forms, namely ‘competencies required’ to perform roles which is derived from the requirements space; and ‘competencies that need to be possessed by resources’ which determine ‘Role Holders’ aspects within the solution space. Thus the definition and design of competency concepts was conceived to enable linkage between Role Definitions (requirement space) and Role Holders (solution space).

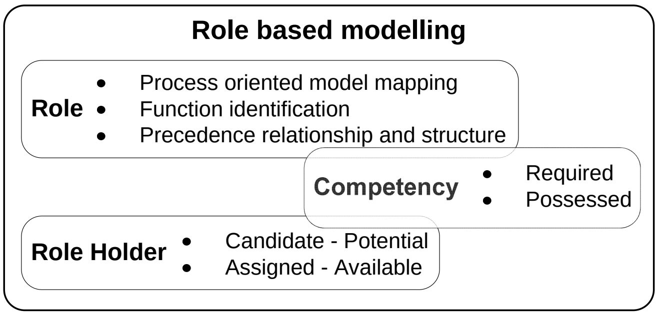


Figure 6.1 Key concepts and aspect of Role based modelling entities

6.2.1 Role and its Requirements

Role is defined as *being of a cognate unit of connected operations and activities, that is required to accomplish (one or more) tasks, where it is expected to be realised by an appropriately constrained set of resources* [Sarbin,1968; Ortmann,1990; Pandya et al 1997; Weston 2004]. There are several key words in the above definition. ‘Connected operations and activities’ implies that process oriented elements forming a role will have some underlying commonality and temporality. This means those activities are logically linked in some specific manner. Therefore it will be assumed that ‘Requirements of Role’ can be explicitly and usefully defined by models of related activities and connectivity between those activities. Process oriented models can usefully decompose complex production systems into a structured process network and their segments. Such groupings explicitly define the scope and activity-based content of unitary roles and sets of unitary roles that collectively can define the specific parent process network. The structures that link activities within a role coverage and between roles will typically be of a sequential or concurrent nature, and may have assigned precedence relationships. This kind of structure can be deduced explicitly from a process network coded, for instance, derive from CIMOSA Activity diagrams (ACTs). Also organisational structures, such as supervisory relationships can be deduced and coded from such ACTs.

6.2.2 Role Holder

Role Holder: *The resource who takes one (or more) specific role(s) in a certain scenario or sets of scenarios*. Here the definition points out that resources are the object of a role holder. In theory all possible composition resource systems that can actively produce (i.e. combination of people and technical resources) are eligible and could have the potential to be role holders. However the viability of resources as role holders in production systems, will need to be specifically determined through design and analysis. It follows that role holders can have two statuses during production systems engineering, namely:

- *Candidate:* The resources which have potential ability to be a role holder for a specified role. Role holders need to be gathered for the purpose of analysing, comparing and investigating their quantitative capability to achieve the specified requirement before any role is assigned. Candidates within similar capabilities may be grouped into a *Resource Pool* to reflect the fact that they share the same potential to realise a certain role.
- *Assigned:* During specified time frames, one or multiple candidate role holders can be assigned to a role with a specified workload requirement scenario. During that time, the resource (or structured resource group) acts as assigned role holder, expected to fulfil role tasks.

Having defined role requirements and selected role holders, there arises opportunities to systematically match the potential of candidate role holders to the role requirements explicitly defined. In the general case there is no strict limit of resource types or amount, so that multiple resources could fulfil any unitary role (with satisfaction of their requirements). However in most practical situations, resources will have limited availability and need to be selected and utilised in an organised and efficient way; possibly where a unitary resource is assigned multiple roles at different times. Further more, with only a limited resource availability, typically resources need to be used in various different ways when the task and job changes.

6.2.3 Competency

Competency relating to role is naturally related to the ability to carry out the processing of a task (or tasks), thereby achieving a goal or completing a mission [Harzallah and Vernadat, 2002]. Competency is defined as: *A tailored range of skill, knowledge, or ability to perform an identified* *role (or roles) under specialised manufacturing environment* [Cattell 1957; Byer 2003; Ajaefobi 2004;]. From these definitions we can deduce that notions about 'competency' can be used in two distinctive ways, viz: (1) to define 'competency needed to fulfil a role (or roles)'; and (2) to define 'competency possessed by a resource who may be applicable as a candidate role holder'. Thus in this research the competency notion was designed to bridge the process-oriented Role and Role Holder aspects. Competency descriptions need to be coherent from the requirements and solution aspects. Further it was deduced that in addition to characterising functional abilities, the competency concept can be used to describe 'structural capabilities', 'change capabilities' and 'behavioural properties'. In this study initial attention is paid to using competency concepts to describe functional abilities. In this respect the author decided to deploy the use of 'functional operation' (FO) and 'functional entity' (FE) modelling concepts previously defined by CIMOSA, as a starting point. These are recommended for use in low level CIMOSA requirements modelling. Competency notions were further classified in this study in terms of their different Type and Criticality:

- *Competency Type*: To classify similar competencies into a list or catalogue or stereo-type, in terms of different perspectives that may need to be considered to decide if a resource can achieve a role;
- *Competency Criticality*: to be specified in terms of their critical differences regarding the state or degree of importance, urgency and necessity to satisfy a role.

6.3 ROLE BASED MODELLING METHODOLOGY FRAMEWORK

Bearing in mind the definitions and principles described in the foregoing sections, the author conceived a new ***Role-Based Modelling Methodology*** (R-BMM) to support designing change capable production systems. The stages of the R-BMM are illustrated by Figure 6.2.

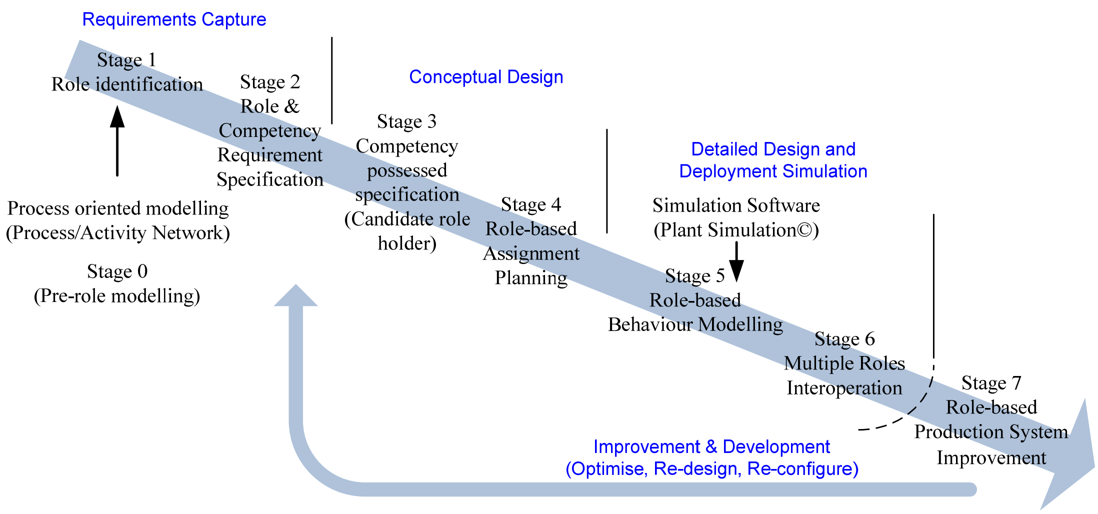


Figure 6.2 Main development stages of role modelling development

During stage 0, which is called the 'Pre-role modelling stage', CIMOSA Enterprise Modelling constructs are used to capture the process-oriented requirements of a subject ME. This captures the network of processes that the ME currently realises, or need to realise in the future. Also at this modelling stage details of how different products flow through the process network are added. Process structure could include both current (the As-Is status) version and possible future (To-Be status) version. However during stage 0, the Roles that must be resourced by human and technical resources will not yet be explicitly modelled. CIMOSA models produced will explicitly describe: ME process segments (and their formal decomposition into elemental activities); and process-oriented dependencies between those process segments. It follows that stage 0 modelling can define processing requirements of any subject ME at needed levels of abstraction; and this 'big picture' decomposition provides a basis for explicitly specifying current or possible future ME Roles and dependencies between Roles.

Following the pre-role modelling stage, Figure 6.2 proposal that the R-BMM should build upon use of a specific EM so as to complete 7 further stages of Role-base modelling; which are as follows:

1) Role Identification;
2) Role & Competency Requirement Specification;
3) Competency Possessed Specification, for Candidate Role Holders;
4) Planning the Assignment of Role Holders to Roles;
5) Role-based Behaviour Modelling;
6) Specification of Multiple Role-based Interoperation;
7) Role-based Production System development.

The author recognises that modelling stage 0 can also be realised to some extent using simpler 'process mapping' and 'value stream mapping' techniques than that of CIMOSA modelling. The point is made though because there are a number of process mapping techniques that essentially begin by creating activity flows (or diagrams) which currently are favoured by industry because of their simplicity. However in this study CIMOSA was chosen as being the process mapping techniques. Because unlike simple maps commonly used in industry, CIMOSA EM generation incorporates: formal decomposition mechanisms to cope with high levels of ME complexity; multiple modelling views and related modelling constructs; a framework for life-cycle engineering of MEs. This enables the development of a big picture process-oriented framework of ME's, into which organised groupings of roles can be explicitly placed into their current, or possible future, context of use.

All these stages can be viewed as traversing 4 life-cycle engineering phases of production systems, namely: 'Requirements Capture'; 'Conceptual Design'; 'Detailed Design and Deployment Simulation'; 'Optimise, Re-design, Re-configure'. The mapping of R-BMM stages onto these phases will be considered in the following sections along with discussion about the purpose of stages and the propose use of role-based modelling concepts during stages. It was considered to be essential that the R-BMM can be deployed at any level of modelling granularity; such as when modelling Roles and Role dependencies of whole companies, as opposed to modelling Role descriptions and Role dependencies of individual persons and their related sets of technical resource. Here it is presumed that multi-level R-BMM might be repeated at different levels of detail in a given enterprise context, such as by 'drilling down in detail' into ME segments, to enable detailed modelling of production systems in their specific and changing business and engineering contexts

6.4 ROLE BASED MODELLING METHODOLOGY DEVELOPMENT

The proposed Role-Based Modelling Methodology then needs to be stepwise developed in more detail according to the R-BMM stage framework. Figure 6.3 illustrates an application of the seven R-BMM framework, it will be described along with methodology development.

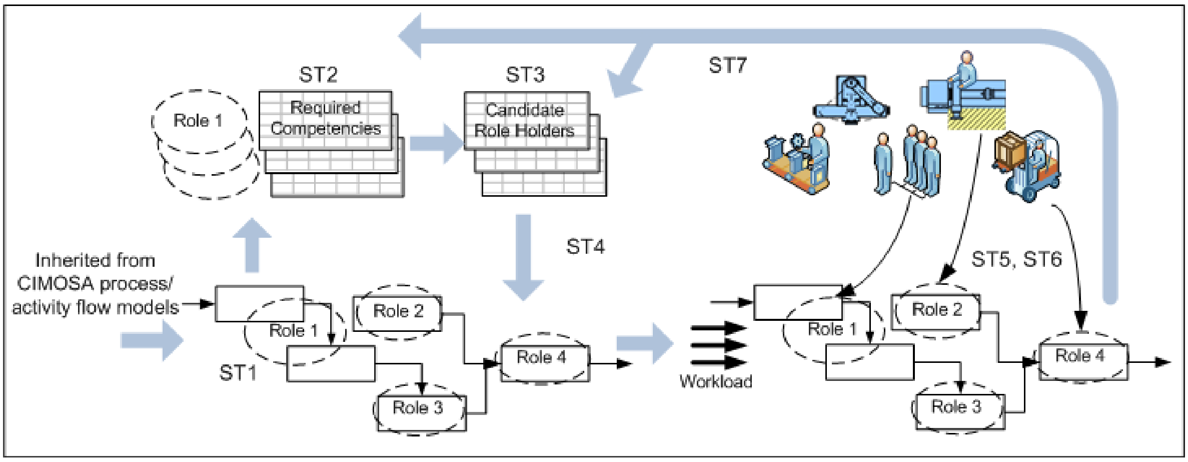


Figure 6.3 Role based modelling methodology development and application steps

6.4.1 Role Identification (ST1)

Having created CIMOSA models of a subject ME, Role-based modelling can begin. Firstly the modeller should understand how different products of the ME flow through the modelled process segments. Also the modeller should directly observe operations, resource usage, process states and timings. All of these factors can guide the identification of viable Roles and their Role dependencies; bearing mind 'what tasks need to be accomplished' and 'what typical human and technical resources might have competency to accomplish the tasks that need to be done'. The Roles defined are then mapped onto the activity groupings forming ME processes explicitly defined by the CIMOSA EM. As shown in Figure 6.3, when formulating the R-BMM it was proposed that the Roles identified should be indicated via ellipses that overlap relevant activities (see ST1 in Figure 6.3). Dependent upon specific Role mappings onto specific ME process segments then sequential, concurrent and precedence relationship within and between Roles will naturally be defined by the pre-defined EM.

6.4.2 Role & Competency Requirement Specification (ST2)

All Roles defined need to be resourced by a suitable set of human and technical resources. Where multiple resource units are needed it was presumed that also required would be an organising structure to link the activities performed by the various resource units into a whole resource system that can realise roles assigned to them. This research assumes that the suitability of those resources can be modelled explicitly by deploying competency concepts.

6.4.2.1 CIMOSA FO and FE link to role and competency

As the stage 0 modelling tool, CIMOSA EM analyse the operations in relation to the resources at the system design level (as its lowest level) in terms of FOs and FEs, coming out from further decomposition of CIMOSA EAs. Each FO specifies as basic unitary function block required for achieving a task; while each FE as basic unitary block of which are capable to receive, process and deliver (so as to achieve) tasks. FO and FEs generate a link via (1) FE are designed to having potential to execute one or multiple types of FOs; (2) FE where available actually execute one or multiple types of FOs under specific requirements. The collection of structured FOs clarify group of requirements embedded in process segment (group of activities); collection of different type FEs generate active resources (such as humans, machines and ITs)with optional capabilities. From the definition of competency, it covers both requirement (expected function) aspect and solution aspect (having skills and capability to deal with tasks). Hence in this research, R-BMM proposes that Role requirements are specified through the competencies that Roles require.

Hence it was decided that the functional requirements of activities, that lie within boundaries placed around roles, can be analysed to form specific Role Descriptions which can be analysed to define the (functional) Competencies needed to realise roles. A list of activities for each role can be used to draw up a corresponding list of elemental functional operations that the designed resource systems would need to perform and accomplish for each elementary activity in a role. Also the list of functional operations could be analysed to determine necessary elements of functionality (termed ‘functional entities’) needed to achieve those operations. In this way the functional entities required could be used to draw up a corresponding list of ‘competencies required’ to perform each activity component of any given role’. Clear identification of requirements was considered key to effective role model design and later matching suitable resources and resource systems to role requirements even as they change over time. At this stage, tabulation templates were designed as the main tools to explicitly specify role requirements in terms of ‘competency requirements’ and provide a basis for later information collection, analysis and matching of resources to roles.

6.4.2.2 Competency Classification

The author also investigated various ways of explicitly defining requirements other than functional competency requirements. For example ways to investigate how 'structural' and 'change' aspect competency requirements (of individual and collective roles) can be explicitly defined. By so doing the aim was to specify relatively enduring aspects of roles and those aspects that might change slowly as part of an ME re-design problem. At this stage the author considered ways of defining 'Competency Types' and the 'Criticality of some of these types', as illustrated by Table 6.1 and 6.2.

Table 6.1 Competency Type incremental classification

Type	Code	Description	Examples
Understanding	CT1	Can understand basic knowledge involved with specific competency.	Can read the specific symbol in assembly picture.
Identifying	CT2	Capable to locate and recognize the characteristics of items, can compare with pre-defined criterion where necessary.	Manually find & confirm right parts sensor's ability to automatic detect parts' arrival location.
Demonstrating	CT3-1	On own understanding basis, capable to present and indicate information validity by explanation or experiment, provide evidence.	Teach teams how to read diagrams; On screen highlight to error when detected.
Executing	CT3-2	Independently complete specific task with necessary tool support	Assembly parts into assembly; Paint exterior to required colour.
Calculating	CT3-3	Quantify required parameter in addition to recognition	Measure parts dimensional data; Auto detect area size by sensors.
Analysing	CT4	Capable to find out the reasons of consequences across multiple competencies with their inter-relations	Programming error compiling; Balancing line staffs workload; Analyse annual budget data.

As shown in Table 6.1, six different types of classified competencies are listed in first left column. This competency classification was developed from understanding and analysing typical example operations observed at collaborator sites during production. Figure 6.4 structures these six types within four levels, connected with an incremental hierarchy of knowledge. The four levels are interpreted as follows:

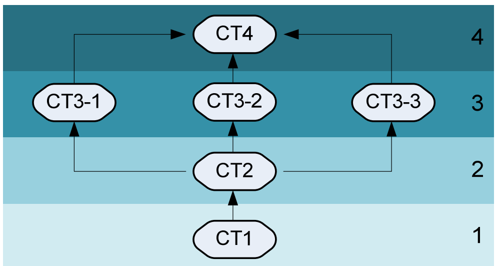


Figure 6.4 Competency type distribution at incremental levels

- Level one, Understanding as a basic competency.
- Next level, to identify some objects such as parts, diagrams, program codes etc.
- Third level competencies involves abilities to 1)demonstrate and transfer knowledge; 2) self-support to execute and complete tasks; or 3) carry out quantity calculations for further use. The three types are all need the possession of the first 2 levels of competency.

- The fourth level of competency was not only to be involved in direct physical production operations but also to be able to assume related managerial responsibilities.

Another angle to specify competency characteristics is class of criticality. They were initially developed by Ajaefobi (2004) to classify semi-generic competency classes in to model human competency, are coded as CCL1 to CCL4, shown in Table 6.2. The interpretation here was to group impact criticality levels in a given target enterprise environment. It was designed to signify the importance and necessity of a given competency in terms of achieving role objectives. These are only two of many way to specify Competency, trying to design an explicit approach to describe role and competency requirement specification.

Table 6.2 Competency Criticality Level classification

Criticality	Code	Description	Examples
Strategic	CCL4	the competency which usually concern the long term, overall investigation and thinking to organisations which would directly affect whole organisation trends etc.	Change marketing policy; Develop new organisational goals Analyse annual budget data
Tactical	CCL3	Mainly concerned with mid-term perspective, would significantly affect a scope within whole organisation to carry out its overall task objective.	Single project budgeting; One new product prototyping, Improve the functional capability of an existing product
Skilled Operational	CCL2	Direct affect one specific task's accomplishment, usually need specific skill training and period of time practice to catch the requirement.	Understand technical manual and instruction; Install & operate systems; Teach team members how to read diagrams.
General Operational	CCL1	Basic competency to achieve a task	Collect and move components, tidy working area.

When all competencies required by each roles are specified, they are collectively listed. Table 6.3 was designed to list and store specified competencies, which in this case includes their classified type, criticality level and description. The list also links required competencies to previously identified roles; and therefore to their constituent activities (operation) and the objects of related operations.

Table 6.3 Specified competency collection list template

ID	Objects	Operation	Required Competency	CT	CCL	Role linked

By the end of this R-BMM stage, The role requirements are explicitly identified, classified and specified. The tables designed later proved an effective tool in case study work to capture, map and document those requirements. This gave clear guidance when designing a resource system to fulfil requirements.

6.4.3 Competency Possessed Specification, for Candidate Role Holders (ST3)

Role requirements identified during ST2 enables the beginning of the conceptual design of the resource systems. The aim at stage ST3 is to begin to decide ‘how to accomplish the roles required’ and later to decide ‘can any chosen candidate resource systems realise the work-loads that may be placed of each role’. However definitive focus during ST3 is on a static matching of ‘competencies possessed by candidate resources’ to ‘explicitly defined role requirements, expressed in terms of required competencies’. The purpose of so doing was to draw up ‘a list of viable candidate resource systems’ so that later choice amongst candidates can be made, probably based mainly in respect to performance criteria when those resources are work loaded.

Viable resource systems for production systems were known to include different types of resource entities (including people, machines, computers and support networks and other accessorial tools) which have the ability to accomplish tasks. In this study structural organisation was to be systemised assuming that this could be process-oriented. As earlier discussed resource system design varies according to different specific requirements regarding needed competencies. It was assumed that resource entities that possess similar competencies can be grouped into a stereo-type and possibly gathered into a Resource Pool, holding them as Candidate Role Holders, for further analysis. This method was designed to enable: 1) clear listing of all candidate resource types with the required competencies; 2) aggregation of stereo-type resources according to their competency, rather than their organisational location; 3) attribution of candidate resources to all relevant roles, using a manageable format. Bearing in mind that resources will in general possess multiple competencies which may or may not be required by different roles, it was evident that one resource type (and indeed multiple instances of actual cases of this type) can appear in more than one Resource Pool. These factors need to be considered when assigning viable candidate role holders during resource system design. However, it is understandable that an individual resource entity could only act as role holder to one role at a time. Table 6.4 was designed to enable systematic configuration and assignment options of resources to roles. Also as explained later, indexed ‘Resource Pool’ and ‘Applicable to resources’ columns were developed for case study use to ‘collect resources’, while Referenced ‘Role ID’ and ‘Required Competency ID’ columns were designed to link with Table 6.3, to start to create a bridge from resource system (solution side) to the requirements (problem) side.

Table 6.4 Competency applicability among resource

Role ID	Required Competency ID	Resource Pool ID	Applicable to resources		

6.4.4 Planning the Role Assignment to Role Holders (ST4)

Prior to modelling stage ST4 focus has been on achieving a static match (essentially a kind of structural match) between roles and role holders. But to make an effective choice it was understood that different selections of viable candidate resources need to be analysed and compared in a quantitative way bearing in mind the kinds of work load that will occur in the real ME environment. Here it was understood that a great potential benefit could accrue in many MEs if simulation technology can be utilised to support ST4; hence reasoned choice can be made through predicting relative performances of different candidates before they are actually assigned to roles, to reduce risks of assigning resources inappropriately, such as without the capacity to cope with the work loads expected.

Before simulation modelling, it is necessary to design a well structured work pattern scenario planning method. Also some key evaluation criteria needed to be defined to compare and contrast the simulated behaviours and performances of different resource options, so as to inform and give quantitative support to the planning and assignment of resources to sets of roles in modelled production systems. Here the author chose two useful performance indicators: *Unit operation time* and *Generation rate.* These indicators were chosen as they can provide straight forward criteria which directly reflect value adding during product realisation. *Unit operation time* was defined as the time spent on one unit of product; while *Generation rate* was defined as the quantity of production work done within unitary time. Both criteria can be based either on a single product calculation or on multiple products with statistical analysis. Table 6.5 is designed to show how resources, acting as candidate role holders, can be compared to inform their selection and assignment to roles, provides a designed environment to integrate aspects of operations, products, roles, competency and resources, to complete a planned role assignment to a specific work pattern scenario:

1) In this specific scenario, work items are the objects identified;
2) Work on these items involves specific activities, defined by relevant roles, and their required competencies;
3) Alternative resources from the resource pool can be selected as candidate role holders, to evaluate their operation time in respect of specific work items;
4) Having found the resource that best suit the working conditions, informed assignment to roles as role holders can be made.

Table 6.5 Planning template of role assignment to candidate role holder resource

Work items						Scenario ID	
Activity	Work item unit	Covered Role	Relevant RC	Enquiry RP	Candidate role holders	Operation time	Assigned role holder

6.4.5 Role-based Behaviour Modelling (ST5) & Specification of Multiple Role-based Interoperation (ST6)

As the planning stage support is now in place, it is now necessary to specify how simulation modelling should be used as part of the R-BMM; and particularly to simulate different work load scenarios where there are variations in product volumes and product types that need to be realised by a given production system model in which process-oriented roles are matched to alternative choices of viable resources. The author considered ways of defining the use of mathematical and statistical criterion to analyse production system behaviours with specific work pattern and resources assignments. This included Role behaviour modelling (ST5) and Multiple roles interoperation (ST6). These two stages required software support, through building, running and analysing simulation models. The detailed work will be reported in next chapter, but three main aspects were considered to measure performance as follows.

6.4.5.1 Measurement 1: Achievement rate

One key performance aspect is the 'speed' of production operations. Examples of this aspect include 'time spent' by a role for a batch of work items. Multiple type parts and changeable mix may go through any modelled production system. Equations (1) and (2) were developed and used to measure 'speed' aspects in later case studies.

$$N(t) = \sum_{x=1}^{x=m} (N_x) \qquad \text{Eq (1)}$$

N(t): The total number of work items processed over period of time *t*. Where

N_x: The number of work item *x* processed, from item type 1 to *n*

$$V(t) = \sum_{x=1}^{x=n} (V_{unit,x} \times N_x) \qquad \text{Eq (2)}$$

V(t): Total value adding from all work items processed over period of time *t*. Where

$V_{unit,x}$: Unit value adding to work item *x* (item needs to be value measurable);

N_x: The number of work item *x* processed, from item type 1 to *n*.

6.4.5.2 Measurement 2: Relative ratio of effective time and waste time

Different resources will have variable operational efficiency. During their assignment as role holders, their working time is divided into an effective portion (in which value is added) and wasted portions (in which no value is added, and they are waiting, blocked, failed etc). The ratio between these two portion will affect their actual efficiency to complete tasks of roles. Ratio η_1 as defined by following equation (3):

$$\eta_1(m) = \frac{\sum_{x=1}^{x=n}(T(x)_{eft})}{\sum_{x=1}^{x=n}(T(x)_{wst})} \times 100\% \qquad \text{Eq (3)}$$

$\eta_1(m)$: The ratio of effective to wasted time during the evaluation period after the role has been assigned to the role holder *m,* Where

$T(x)_{eft}$: Total effective working time that role holder *m* spends on work item *x*, from item type *1* to *n*;

$T(x)_{wst}$: Total wasted (non value added) time, including when waiting, blocked, failed etc., during work on work item *x*, from item type *1* to *n*;

6.4.5.3 Measurement 3: Relative ratio of value adding and cost

Consider assigning specific roles to resources as role holders in the ME production system, the process designer or managers, who are usually decision makers, need to consider value addition and process costs. To maximise the value added by a given set of roles (and their embedded requirements) it may be important to minimise various 'wastes'. Higher performing resources, such as advanced machines and work stations, and highly skilled experts, will typically be capable of producing higher value products or producing them quicker with better quality. However usually their use will also lead to higher investment (purchasing, maintenance) or cost (training, labour cost). Therefore increase value adding will introduce higher performing resources and should be judged in relation to the cost increases incurred. Hence equation (4) was developed to account for such factors:

$$\eta_2(m,t) = \frac{\sum_{x=1}^{x=n}(V(t)_{RHm})}{\sum_{x=1}^{x=n}(C(t)_{RHm})} \times 100\% \qquad \text{Eq (4)}$$

$\eta_2(m,t)$: The ratio between value adding and cost over period of time *t*, when role is assigned to role holder *m*, Where

$V(t)_{RHm}$: The value added of all work items processed by role holder *m* over period of time *t*, *V(t)* refer to Eq (2);

$C(t)_{RHm}$: The cost caused by role holder m during the period of time t, $C(t)_{RHm} = C_{unit,m} \times t$

$C_{unit,m}$: Unit cost for role holder *m*

6.4.6 Role-based Production System Development (ST7)

The qualitative and quantitative modelling and analysis of multiple roles within their covered production process network has been done by the last stage. The models generated using R-BMM can highlight the performance of a current process-resource system under a specific work pattern scenarios, and the behaviour of a current structured processes and resource system. The role based model outputs need to benefit the target production sector and extended production system, to develop from current status to improved level. From a role based modelling requirement (required competency) – solution (possessed by resource) view, the development may carry out from the following two angles:

1. Find solution to satisfy the requirement – Concentrate on enhancing capability of competency processed by resource system. The specified needs are verified from model outputs as either i) no required competency possessed, or ii) all required role competencies possessed but with insufficient capacity. For the former need, improvement may focus on dedicated skill training (human resource basis) or upgrade (artificial intelligent knowledge system or NC machines basis). While for the latter solution targets an increase in the number of resource or unit capacity of current resources. In practice such production system improvement may be implemented by purchasing extra machines.
2. Based on the solution to re-design requirement – This focuses on keeping the current resource system, especially if the outputs of behaviour modelling indicates low resource utilisation. Then the improvement may concentrate on re-design of the role and their required competency. The re-design can be carried out from i) re-structure of role overlay to process segment and activity group and re-configure role dependency, so as to change the competency required by roles. Hence modelling will back to the ‘new’ competency requirement specification and competency possessed specification (ST2 and ST3). ii) the resource then has ‘changed’ potential to match ‘changed’ competency as candidate role holders, may achieve overall production system requirement by improved resource utilisation hence improved capability.

The two different development options are both acceptable but rely on intensive model analysis. Both options however need to remain the overall objective of the target production system in terms of value adding and cost control. Detailed method selection can only be achieved through the analysis of specific cases.

6.5 CASE STUDY APPLICATION AND TESTING OF THE R-BMM

The R-BMM needs to be applied and tested in a relevant case study ME. As explained in Chapter 5 a CIMOSA based pre-role modelling stage had already been conducted for the FFL company. Hence the process network of FFL and its ‘as is’ resource systems was used as a test -bed for the R-BMM.

6.5.1 Role Identification

In this case study, a previously developed activity diagram for the ‘table assembly’ process segment of FFL (from Figure 5.10) was used as the starting point for Role identification; i.e. for ST1 of the R-BMM. Figure 5.10 shows the FFL table assembly activity diagram defined by the EM of FFL.

After observing actual operations carried out in FFL and current functions that humans and machines perform, seven table assembly Roles were identified as shown in Figure 6.5. The seven Roles were given unique identifiers, namely: ‘R1-Preparation’, ‘R2-Top-maker’, ‘R3-Frame-maker’, ‘R4-Pedestal-maker’, ‘R5-Assembler’, ‘R6-Internal Transport’ and ‘R7-Assembly supervisor’ Roles. In Figure 6.5 the scope of these roles is shown via the use of grey blocks to which an oval symbol is assigned. Each of these Roles was observed to have a self-standing functions (such as make table tops; make frames). In addition they have a collective function, namely to complete make and assembly operations of a DL Table.

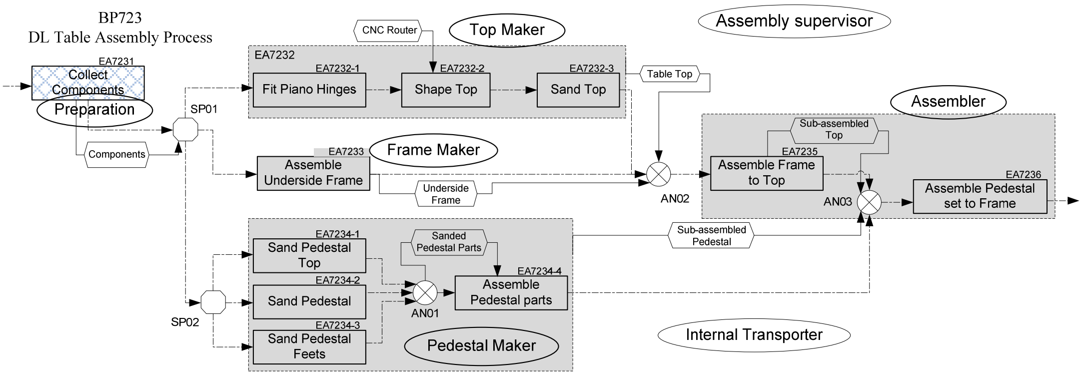


Figure 6.5 Role identification from the FFL assembly activity diagram (Source Fig 5.10)

The resultant Role structure inherits logical dependencies from the CIMOSA activity diagram. It was observed that for the four table-making Roles (R2,R3,R4,R5) and the three roles (R2,R3,R4) related to making table sub-assemblies, these roles were decoupled logically from the Preparation role; while all three of these Role groupings are logically aggregated into an Assembler Role. This is reasonable because: the table top; underside frame; and pedestal; can be made on their own in a self-standing fashion. Here each of these table elements constitutes a sub-assembled component prior to final assembly. In addition to this physical table making work, there is a need to consider the transportation of parts and table sub-assemblies among work stations and from and to neighbouring work sections. One extra role, namely R6, was indentified to realise this process.

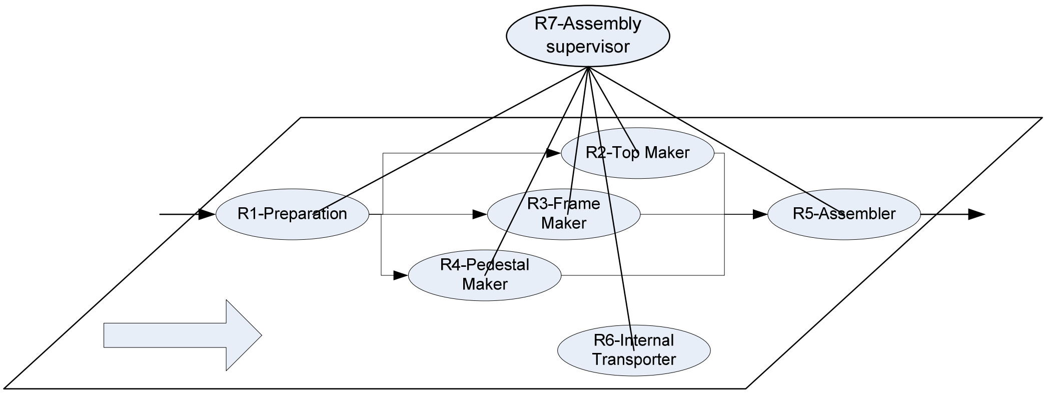


Figure 6.6 Role dependencies within targeted process area

In addition from a management and coordination point of view, a higher level Role ‘R7-Assembly Supervisor’ is required to control and monitor instances of production Roles. R7 oversees the use of production planning information, to harmonise, instruct and facilitate inter-operation between all lower level roles involved in the table assembly segment of FFL. Correct management of Role dependencies is needed to ensure that the company as a whole operates efficiently. Relationships between these roles was illustrated graphically as shown in Figure 6.6

6.5.2 Competency Requirement Specification

Stage 2 of the R-BMM is focussed on specifying competency requirements of Roles defined during stage 1. It was constructed during stage 2 in the case of FFL and presented as Table 6.6 (partial).[1] This table specifies key competencies required, individually and collectively, to fulfil FFL table assembly roles defined during stage 1. Identifiers used begin with RC ('Required Competency') followed by an index number. The listed objects relate to different table parts, components or assembled tables and the object definitions specify the target for Roles (and their related operations). Operations were derived from the CIMOSA activity diagram for the assembly shop. Required competency descriptions are explicitly described in Table 6.6. In this case, as the competencies specified are restricted to table assembly operations, their listed types and criticality levels are fairly similar. The final column lists which role these competencies is required by.

Table 6.6 Competency requirements specification (partial)

ID	Objects	Operation	Required Competency	CT	CCL	Role linked
RC01	Parts & components	EA7231	Identify parts & components	CT2	CCL2	R1-Preparation
RC02	Parts & components	EA7231	Deliver parts to right sections	CT3	CCL2	R1-Preparation
……						
RC06	Underside frame parts	EA7233	Identify frame parts & assembly	CT3	CCL2	R3-Frame Maker
……						
RC11	Sub-assembled components		Identify components and transport	CT2	CCL2	R6-Internal delivery
RC12	Assembled DL tables		Load tables and transport	CT2	CCL2	R6-Internal delivery

6.5.3 Competency Possession Specification by Investigating Resource System

During stage 3 of the R-BMM, the 'Required Competencies' defined during stage 2 need to be matched to 'Competencies Possessed' by candidate resources. The aim of so doing is to establish which candidate resources possess the functional abilities needed to carry out specified roles. However during stage 3 only 'can do' competencies are considered when drawing up a viable list of candidates, whereas in the later R-BMM modelling stages viable candidates are chosen based on their relative behavioural performances. In the actual 'as is' table assembly section of FFL, specific human and technical resources were already assigned, and as needed re-assigned, to assembly

[1] Completed version of all partial tables in following sections of the chapter are attached in Appendix IV.

operations; albeit that in the current FFL, roles, and related assignments of role holders, had not been explicitly specified. But for the purposes of the case study testing of the R-BMM the author chose to take a ‘clean sheet of paper approach to assignment of role holders to roles’ in the sense that R-BMM was followed and the modelling outcomes were only compared later with the current best resource assignment in FFL table assembly.

It was found from the earlier CIMOSA modelling studied at FFL that the table assembly section is highly manually work oriented; i.e. the main active resources are operating staff, supported by their accessory tool kits. Their related work flows comprise raw material, components, and sub-products; which are considered as work items. The author interviewed FFL staff and interpreted the survey results into a pre-specified ‘competency formulation’. This generated a list of competencies distributed among staff, partially presented in Table 6.7(partial). Defined Roles (Role ID) and Required Competencies (RC ID) came from Table 6.6. The right hand columns listed the staff involved along with the competencies they possess. The table used a tick ‘√’ to apply the competencies in the matrix. The applicable candidate resources were then grouped into indexed Resource Pool (RP ID).

Table 6.7 Competency possession distribution among resources (partial)

Role ID	RC ID	RP ID	Applicable to Resources											
			S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
R1	RC01	RP1	√				√						√	
	RC02		√			√							√	
……														
R3	RC06	RP3								√	√			
……														
R6	RC11	RP6						√					√	√
	RC12							√					√	

For such a highly manual working case, measuring capabilities as an achievable rate is difficult. Competency classification developed by Ajaefobi [2004] (shown in Table 6.8), was used to differentiate skill levels, and linked notions about work efficiency to judge the average performance of human resources when selecting such candidate role holders.

Table 6.8 Skill level related to applicable competency

Level No *.	Skill title	Typical behaviour characteristics
SL1	Trainee	Competent, active, low autonomy, low flexible
SL2	Practiser	Competent, resourceful, knowledgeable, ‘reflective’, confident
SL3	Skilled	Highly competent, flexible, knowledge transferable, flexible
SL4	Expert	Highly competent, versatile, proactive, innovative, outstanding experienced
* Each level could be relatively measured by different ratios to standard performance in terms of effective speed complete tasks, the standard speed relies on specific competency and associated to products		

(Source: Ajaefobi, 2004)

To evaluate the resources (mainly operation staff team in this case) whose qualitative possessed competency have been list as Table 6.7, the method in Table 6.8 was used, try to evaluate more detailed capability of resources. Some part of the results are listed in Table 6.9, 6.10 and 6.11 to give examples, but also to summarise resources as candidate role holders and to indicate some capability characteristics in common as follows:

1. It is very likely that multiple resource entities possess the same specific competency, all having potential to be candidate role holders. For example in Table 6.9, Resource Pool (RP1) gathered two staff (S1 and S11), who both possess Competencies (RC01 and RC02) required by Role R1; similarly S8 and S9 to Role 3 (Table 6.10); S6 and S11 to Role 6 (Table 6.11).
2. Resources may possess multiple competencies that make it possible to belong to multiple resource pools, as candidate role holders to multiple roles. In the case studied, S11 appears in both RP1(Table 6.9) and RP6(Table 6.11) as the staff possess competencies CR01&CR02 required by Role 1, and CR11&CR12 required by Role 6.
3. Capability level of candidate role holders may vary to specific work requirements. Such variation may refer to dealing with different products, or being assigned different roles. Still take staff S11 as an example, he indicates different capability level if he is assigned Role 1 and works on the four different product types (SL3, SL3, SL2 and SL2 in Table 6.9); while if he take Role 6 instead, the capability levels varies (SL2, SL2, SL4 and SL2 in Table 6.11).
4. Competencies requirements may be specific to product types. Table 6.10 indicated such an example. S8 and S9 possess the competency (CR03) required by Role 3, and have variable capabilities to table types. However in the case table PT3 doesn't have "making frame" operation, the competency CR03 is not applicable, hence the capability level indicated as "N/A".

Table 6.9 Resource evaluation as candidate role holders (R1)

RP ID	RP1	**Associate Competency / Role**			RC01/R1
Applicable Resources		S1	S5	S11	
Associate products	DL4	SL3	SL2	SL3	Skill level associated to products
	DL6	SL4	SL2	SL3	
	FT6	SL4	SL3	SL2	
	PT3	SL4	SL2	SL2	
RP ID	RP1	**Associate Competency / Role**			RC02/R1
Applicable Resources		S1	S4	S11	
Associate products	DL4	SL3	SL2	SL2	Skill level associated to products
	DL6	SL3	SL1	SL2	
	FT6	SL3	SL2	SL2	
	PT3	SL3	SL2	SL2	

Table 6.10 Resource evaluation as candidate role holders (R3)

RP ID	RP3	**Associate Competency / Role**		RC06/R3
Applicable Resources		S8	S9	
Associate products	DL4	SL2	SL2	Skill level associated to products
	DL6	SL3	SL1	
	FT6	SL4	SL2	
	PT3	N/A		

Table 6.11 Resource evaluation as candidate role holders (R6)

RP ID	RP6	**Associate Competency / Role**			RC11/R6
Applicable Resources		S6	S11	S12	
Associate products	DL4	SL3	SL2	SL2	Skill level associated to products
	DL6	SL3	SL2	SL1	
	FT6	SL4	SL4	SL2	
	PT3	SL6	SL3	SL2	
RP ID	RP6	**Associate Competency / Role**			RC12 / R6
Applicable Resources		S6	S11		
Associate products	DL4	SL4	SL3		Skill level associated to products
	DL6	SL4	SL2		
	FT6	SL4	SL3		
	PT3	SL4	SL3		

The above static analysis provides useful information about the capabilities of candidate role holders. However the reader should bear in mind that it is still difficult to obtain realistic measures of the 'performance' of humans, and that the skill level can only provide an indicative characteristics capability. Appendix IV provides more detailed resource evaluation of all seven roles.

6.5.4 Role Assignment for Assumed Static Scenario

Many modern MEs need to realise an uncertain mix of product orders from customers. In the FFL's case study reported so far, four types of products were considered. A study of FFL historical sales and production data, showed that Drop Leaf(DL) table products took up a primary position. For this reason DL tables were selected for illustration in this case study.

Table 6.12 is a partial illustration of role assignment instances. Resource assignment of other roles didn't appear here, they are listed in Appendix IV. Under the designed scenario S-01, parts of DL4 and DL6 tables are the work items. Take Role 1 assignment for example, the operation on DL4 and DL6 parts involve activity EA7231 (referred from CIMOSA activity diagram Figure 5.10), require competency RC01 and RC02. It has been identified that staff S1, S5 and S11 are the candidate role holders, they are listed here taking their skill level into account, relative to operation time specific to the DL4 and DL6. It was seen both S1 and S11 possess both RC and are capable to be candidate role holders, but S1 has a higher skill level, hence in this scenario, S1 should be assigned role 1 and acting as role holder. By going through the similar procedure, S8 is assigned to Role 5 when working on DL4; while S3 is selected as role holder when working on DL6.

Table 6.12 Role assignment and resource allocation (Single scenario) (partial)

Work items		10 DL4 + 4 DL6 Tables				Scenario ID	S-01
Activity	Working item unit	Role	Relevant RC	Request RP	Candidate role holder	Unit Op. Time	Assigned role holder
EA7231	DL4 parts	R1	RC01	RP1	S1/SL3, S5/SL2, S11/SL3	15min	S1
	DL4 Parts		RC02		S1/SL3, S4/SL2, S11/SL2	10min	
	DL6 parts	R1	RC01		S1, S5, S11	10min	
	DL6 Parts		RC02		S1, S4, S11	10min	
		⋮			⋮		
EA7233	DL4 frames	R3	RC06	RP3	S8/SL2, S9/SL2	10min	S8
	DL6 frames				S8/SL3, S9/SL1	15min	
		⋮			⋮		
	DL4 parts	R6	RC11	RP6	S6/SL3, S11/SL2,S12/SL2	12min	S6
	DL6 parts		RC11		S6/SL3, S11/Sl2, S12/SL1	10min	
	DL4 parts	R6	RC12		S6/SL4, S11/SL3	15min	
	DL6 parts		RC12		S6/SL4, S11/SL2	12min	

6.5.5 Discussion of role potential from case study

When specific product orders (derived from customer orders, specify products) are brought into the production system, this in turn defines the needed instances of roles and competencies. It was understood that in the real system's operation, suitable resources were selected with reference to competencies required for each role that were previously defined. In the case study, DL4 Tables have pedestal with 5 feet, while DL6 only have 4 feet, no pedestal. Hence role holders need to treat different DL table types differently. this highlights the importance of another competency requirement to the role, rather than the products specification itself, i.e. the need for assigned role holders to be flexible ('programmable' in this case) such that product differences can be recognised and alternative actions taken. It follows that candidate role holders need at least two distinctive kinds of competency potential, namely *functional* and *flexibility* competency classes. Role holders assigned to roles must possess both competency types in multi-product systems. For instance, the method of Resource Pool usage, with reference to specific roles the process designer can aggregate resources into different pools, thereby generating explicit feedback at an early stage of analysis that candidate resources have potential to match differentiated role competencies, from functional and flexibility viewpoints. The actual need for flexibility arises because manufacturers seek 'economies of scope' by using a common set of resources to make a product range such that variations in customer demands can be averaged out to some extent. Only when actual work loadings are placed upon the overall production system and its specific process segments (Table Top assembly segment in the assembly area for instance), can multi-products work flows through any given process segment be specified; so that the suitability of a role design and its assigned role holders can be meaningfully assessed.

Another set of potential considerations are from the role performance aspect. It may prove effective for process designers to systematically consider value analysis when designing sets of roles and assigning role holders. In FFL table assembly area the roles ‘Preparation’, ‘Internal transport’ and ‘Assembly supervisor’ include non-direct value adding activities, such as collect components from the parts area, set up machines and tools, and transport sub-assembly parts from station to station. These operation are necessary to complete the table assembly tasks, however, they do not directly add value to products. Whereas other role holders will directly impart value, e.g. by transforming components, in terms of their size, shape, structure, composition, function, etc. This kind of analysis was observed to provide useful reference points especially at later stage when role performance analysis with multiple product work patterns and enriched values and cost data during dynamic simulation, and can help to optimise the selected topology and occupancy of role / role holder set.

6.6 CONCLUSION OF THE CHAPTER

This chapter has introduced the new R-BMM (Role-Based Modelling Methodology) and has described the purpose of its modelling stages. Also it has illustrated the use of the first 4 stages of the R-BMM in a furniture assembly case study. Having produced a process map (in this case by previously creating a CIMOSA EM and its derivative activity diagrams) the main modelling tools used to support the first 4 ‘static modelling’ steps of the method were tables and graphical, diagrammatic models. Table creation was instrumented bearing in mind structural/configurational information, earlier defined during enterprise modelling, as described in the last chapter.

Tabulation proved useful to enable the gradual construction of role and role holder models. This was in effect carried out in “requirement capture” and “conceptual design” phases. The first phase focused on the explicit description of role requirements. Then second phase had emphasis on identifying, locating, aggregating and experientially choosing suitable candidate resources; so as to systemise the static matching of candidate resource competency potential to competency requirements of roles. The data stored in these tables can readily be recorded into a database, for further referring, reuse and enrichment of data. Also to enable use of this data during more realistic dynamic modelling and analysis. Dynamic analysis was considered necessary as the analysis of a single scenario in a static mode is unlikely to be convincing enough in most industrial cases, Figure 6.2 shows the three further stages of the R-BMM which are aimed at achieving dynamic analysis and a corresponding case study application of these further stages will be described in Chapter 7.

CHAPTER 7

Dynamic Simulation and Role Performance Modelling

Use of the previous stages of the R-BMM had systemised the static matching of '*competency potential*' possessed by candidate resources, to '*competency requirements*' specified with reference to process-oriented roles. This had established which resources were candidate role holders and could operate as part of a viable 'Role-Resource System' couple. This chapter studies how system's dynamic modelling can enhance the use of EM and the developed role based modelling approach. Therefore it reports on dynamic modelling in respect of stages (ST5 and ST6) of the R-BMM. The emphasis is on computer exercising configurations of 'Role-Resource System' couples (chosen from among viable candidate resources); so as to predict their time-based behaviours when fulfilling designated dynamic tasks (defined in terms of work loaded roles). It was understood to be necessary to evaluate relative behaviours of alternate resources within an experimental dynamic environment, based upon parametric change and statistical analysis. It was presumed here that much of the parametric data and some structural details of the simulation models (needed to achieve a dynamic match) could be derived from previous Enterprise Modelling (EM) and Causal Loop Modelling (CLM) activities, but with adjustment or transformation for use in the simulation modelling environment. Hence it was envisaged that information contained in previous EMs and building of CLMs in Section 7.2 of this chapter could be reused to support the creation and testing of dynamic models. This was important for two main purposes: (1) so that the behaviours of alternative resources as candidate role holders assigned to roles can be evaluated, within the context of the 'big picture' explicitly defined by the EM and (2) so that the cost and effort of modelling, and its related data capture, can be reduced.

7.1 NECESSITY TO MODEL DYNAMIC BEHAVIOURS

Having explicitly defined a process network and decomposed this network into roles that a subject ME segment must perform, it is necessary to (a) select suitable candidate resources that have necessary abilities to perform the roles and maintain needed role dependencies, then (b) to decide which of those resource (as potential role holders) can perform the roles best. The previous chapter considered (a) and explained how modelling techniques were developed to support role specification and viable resource selection. It also illustrated use of a developed systematic approach to (a) in respect of case study scenarios. However dynamic analysis and performance predictions are also required to achieve (b) and thereby to determine if a given role – role holder set can cope with different work patterns. Also this requires use of modelling technologies that capture and exercise both causal and temporal impacts arising in any given process segment of a subject ME. In order to systemise and support dynamic analysis of production systems within a context previously defined by CIMOSA and role modelling, the present author deployed a combination of dynamic systems analysis (centred on Causal Loop Modelling) and simulation modelling (centred on use of a selected simulation modelling tool).

7.2 CAUSAL LOOP DYNAMIC ANALYSIS

Following static modelling and analysis, where the candidate role holders had been identified (during modelling stages 1 to 4 of the R-BMM), a Casual Loop Model (CLM) was developed to achieve qualitative analysis of dependencies amongst 'roles', 'competencies', 'performances' and other key production system variables.

CLM diagram is to understand how causal impacts propagate through complex dynamic production systems. Here specific focus is on the impacts amongst aspects of roles. Those impacts propagate via multiple loops, some that reinforce themselves and grow the effect of impacts (shown with the symbol "+") others induce decay or a damping effect (shown with the symbol "_"). Also it can be observed that change in any one variable can impact on a number of other variables and that any given variable can itself be impacted on by many other variables. When understanding or explaining behavioural effects of CL diagrams it is important to choose a logical starting point and then follow chains of propagated impacts to understand the flow and significance of dependency relationships.

7.2.1 Segments of the CLM diagram and links to role modelling stages

The CLM diagram Figure 7.1 was divided into several segments to indicate the reuse of information across the EM-SM (CIMOSA Enterprise Modelling – Simulation Modelling) boundary. The segment on the left side bottom, is concerned with customer related behaviours that typically impact on products and order requirements in the case company. These behaviours are usually initiated by customer desires generated outside the company; normally they are largely out of the company's control and may be more random than predictable. In this diagram, customer satisfaction was believed to be an essential factor that would impact on future trends in customer purchasing behaviour. Thus this could be set as a logical starting point when trying to understand and think about causal impacts arising from the loops. The yellow and green background sections are within the company boundary. Also some causal loops are designated as a type called "Re-generation loop". All elements within Re-generation loops are expected to provide a positive growth effect. In this diagram, the elements with blue colour is in a type R loop indicate such forward growth. Most other loops in the diagram are balanced loops, they all together give more detailed causal relationship analysis. The rest of the entities in this diagram, grouped and numbered from ① to ③ with dash line rectangles, are the key segments directly concerned with role based thinking and their propagated causal impacts.

92

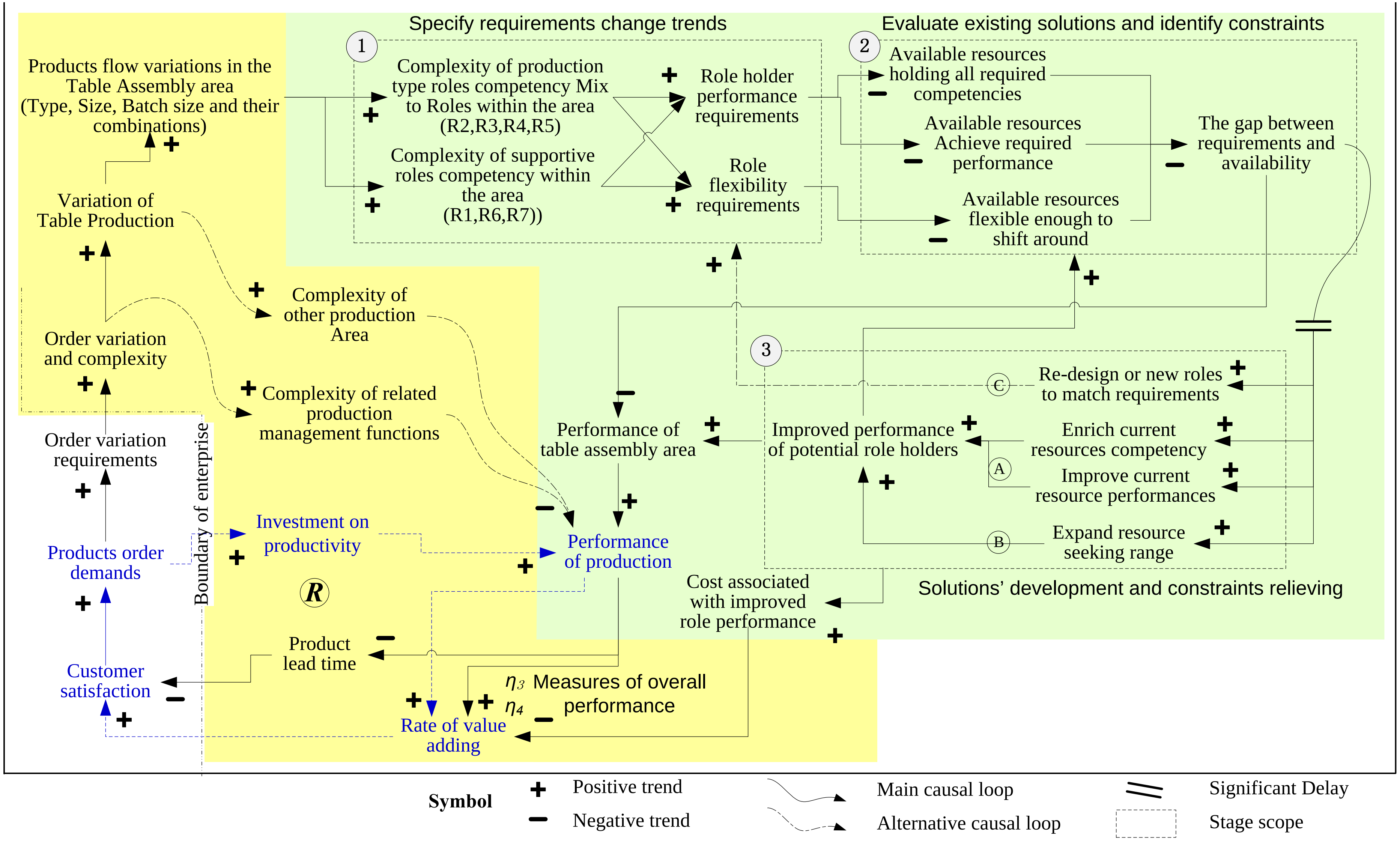


Figure 7.1 **Causal loop dynamics analysis with role modelling concepts**

Chapter 7

Impacts arising from outside the company were assumed to be requirements trends which in turn require an overall production and management system change or response. This kind of impact is extended in the developed CLM diagram to the table assembly area where the role based modelling exercise study was focused. The three numbered boxes were configured with respect to the following role modelling aspects: 1) Requirements, regarding products and production process; 2) Competencies, required by candidate role holders; 3) Potential solutions, from either the resource side or a requirements adjustment side. They are mapped onto the three principle phases proposed for role modelling that were assumed to be key during organisation design and change. The third segment covered those other entities within the enterprise boundary. They are concerned more about conventional thinking from process operation and financial implications arising from role related performance changes that impact on customer satisfaction. All segments presented are related to dynamic impacts on the table assembly area and related roles. Hence they help to position the table assembly section within a broader business and engineering context; which in general was assumed (a) could be specific to any given company and (b) would be characterised in part by previous static CIMOSA modelling. The importance of this is that dynamic evaluation of the case study role based modelling can be linked back to a wider enterprise change analysis.

7.2.2 CLM's causal impact analysis to R-BMM entities' dynamics

With reference to Figure 7.1, the CLM analysis was initiated at stage ①. Here a dynamic (or change) was assumed to require enhanced competency as well as capacity, to realise both direct roles associated with assembly work (R2, R3, R4, R5 that are needed to complete table assembly) and supportive roles (R1, R6, R7, necessary to prepare more complicated parts and components [R1]. Also these abilities need to be correctly assigned to the right work station [R6] to carry out correct packing; and to supervise and coordinate multiple roles to ensure balancing of loads for more complex resources [R7], etc.). As both of these types of role requirement increase, there would arise a need for enhanced performance from roles and (or role holders) and a need for greater flexibility to deal with increased changing requirements.

Regarding requirements change it was considered necessary to look for current availability of competency and capacity among resources, bearing in mind the following criterion: 1) collectively resources must hold all competencies of corresponding roles; 2) those resources holding required competencies must also be capable of achieving required performance levels related to each role; 3) among those limited resources, enough flexibility to shift their roles when necessary to deal with complex requirements change. However, in most cases it was assumed that such an availability trend will be opposite to the requirements change trend direction. This is because it was assumed that the pool of competencies and capacities will normally be constrained, hence the minus "–" is used aside with entry arrows of these entities (stage ② in Figure 7.1). As competency and capacity requirements grow and impact on a constrained resource, a gap between needed and available competency and capacity will grow. Without effective solutions to close the gap, the trend would lead to negative outcomes in terms of poorer overall table assembly performance.

At stage ③ consideration was focused on how role modelling could help cope with increased requirements. Three different types of option (A, B, C) were considered in this diagram case. Option A was to increase the current candidate resource's competency, or keep same competency but increased capacity with respect to their assigned role. Practical solutions in this case A may include providing professional training of staff and upgrading or improving the maintenance of current workstation machines. Option B was to seek to select alternative resources, to find candidate resources as improved potential role holders. For instance in case B, using an alternative workshop or product assembly area when available, would give new opportunities to cope with peaks in work requirements. Also recruiting new staff with abilities to perform new roles and related requirements could expand the abilities of a resource system, and might enable an organisation to expand outside its current boundaries. Option C was to consider ways of redesigning current roles. Here previously identified roles and their activity coverage were considered with respect to 'changing' requirements to adjust the way in which roles are assigned, possibly to create new roles where necessary and/or to reorganise role relationships and interdependencies. Option C, which was viewed as being role redesign or reconfiguration, was not any guarantee that changing requirements could be realised, but this was seen as another potential solution which could be evaluated through later quantitative simulation. The outcomes from choosing different potential solutions (Option A or B or both) indicated that if these solutions could work and would likely lead to positive impacts in terms of better performance from assigned role holders. If those resources were assigned roles in the table assembly area, contrasting with the negative impact to table assembly performance due to the gap increasing in section 2, now the performance could be improved with positive dynamic effect. And on the other side, these improved candidate resources would help to address the lack of availability found in section 2; thereby satisfying role requirements specifications via enhanced design of resource assignments or by simplifying requirements (through redesigning roles). Either can meet overall requirements but different outcomes result (in terms of time related behavioural performance and process costs for instance).

Through CL impact analysis in the table assembly area and by deploying role based modelling to support table assembly production performance improvement, this study assumed that overall production performance development could be achieved despite potential negative impact and risks arising from more complex production requirements if the solution development could be achieved successfully, as listed in stage ③ of Figure 7.1, either taking single options or combined deployment of multiple options. However it was also understood that it was necessary to prove this point through more quantitative analysis and/or practical implementation and experimentation. Such improvement would help to reduce product lead time and thereby avoid customer dissatisfaction. However bearing in mind that potential solutions to role performance improvement would be likely to lead to increased cost for different reasons, such as the need to retrain current staff or recruit new staff, upgrade or purchase new workstations or CNC machines, expand stock shelf for extra stocks etc, correspondingly the cost of performance improvements would also need to be evaluated. Hence the need for simulation modelling was assumed to quantify benefits and costs of redeploying a constrained set of resources in alternative ways.

On the other hand, discussion with FFL managers made it clear that many decisions and planning functions in response to change dynamics requires a detailed understanding of discrete events as orders for tables are placed on the table section and as varying order quantities and types essentially compete for the available time of a constrained set of resources. This causes difficult to predict delays and queue sizes. This was seen to necessitate the development and systematic use of simulation models which can quantify as well as qualify dynamic impacts.

7.3 SIMULATION MODELLING SOFTWARE

UGS Tecnomatix™ Plant Simulation® software was designed to support analysis and design optimisation of production systems. It was observed that information about modelled entities contained within previously constructed case study CIMOSA EMs (such as processing activities, activity routing, and resource/material flows) and about relationships between those modelled entities specified as causal relationships coded using a CLM, could be reused and recorded into a computer executable format. This was assumed to be the key as it would enable quantitative and statistical analysis of 'in context' time-based behaviours of alternatively designed process-resource production systems. It follows that this research aimed to consider how the reuse and recoding of information contained in EMs and CLMs can enable organisation design and change decision making and analysis, over and above that possible via discrete event simulation modelling alone. It is not the purpose of this thesis to describe specific characters of the Plant Simulation software tool. But necessarily its general capabilities and functions will be explained with reference to case study model building, model experimentation and analysis carried out by the author.

Plant Simulation is a so called MDI (multiple-document interface) application software. Figure 7.2 shows a snapshot of the software interface it provides. It shows some opened object windows on the top of a common parent window.

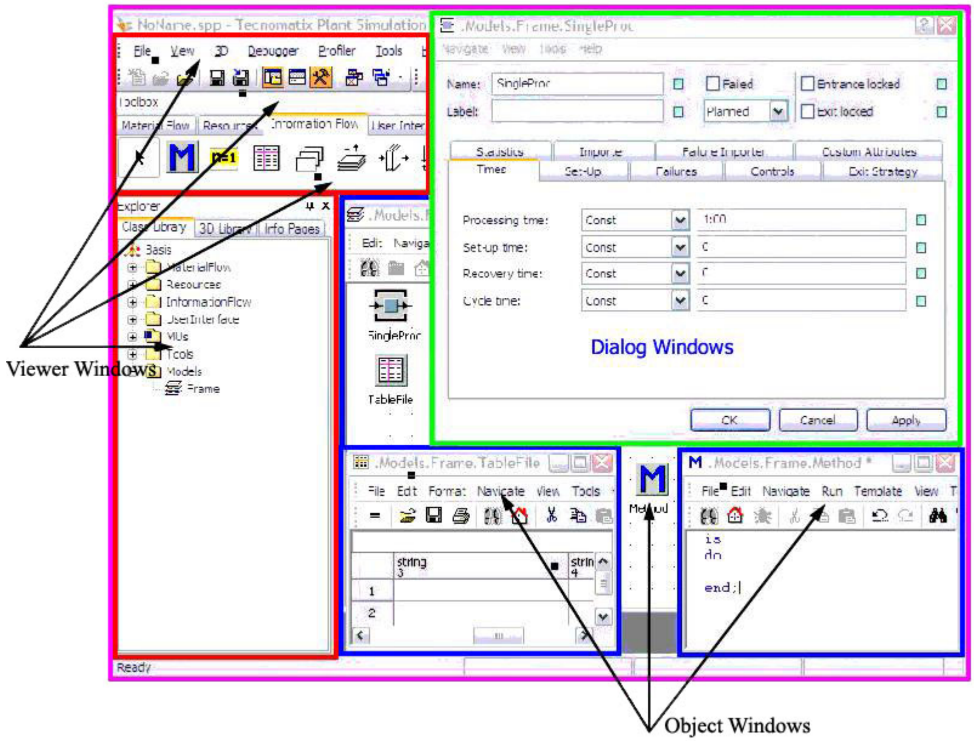


Figure 7.2 Snapshot of Plant Simulation software interface

Viewer Windows (red framed) include the Explorer, Menu Bar, Standard Toolbar, Simulation Toolbar, Debugger Toolbar, Toolbox and Console. These offer software operation control buttons and model structure building entities.

Dialog Windows (green framed) are the main container of material flow objects, the moving objects, the resource objects, the information flow objects and the user interface objects. After a principle model structure has been built, most data input and configuration operations are completed with this type of window.

Object Windows (Blue framed) Objects are the principle configurable unit, each of them is designed using an object specification window. Figure 7.2 shows two object windows (blue framed). Left one specifies Table objects and the right one defines a Method objects programming code editing window.

7.4 SIMULATION MODEL EXPERIMENTAL DESIGN

Well designed model experiment environments are essential to enable Plant Simulation to be used to quantitatively evaluate the performance and behaviour of systems based on current role decompositions and candidate resource's role assignments. Also use the results to contrast and compare current system configurations with possible future (to be) alternative role decompositions and resource assignments. Hence it was decided that experimental design might usefully be structured and informed by understandings obtained from 'causal' impact links among different role modelling elements.

7.4.1 Change Dynamics in Table Assembly Realisation System

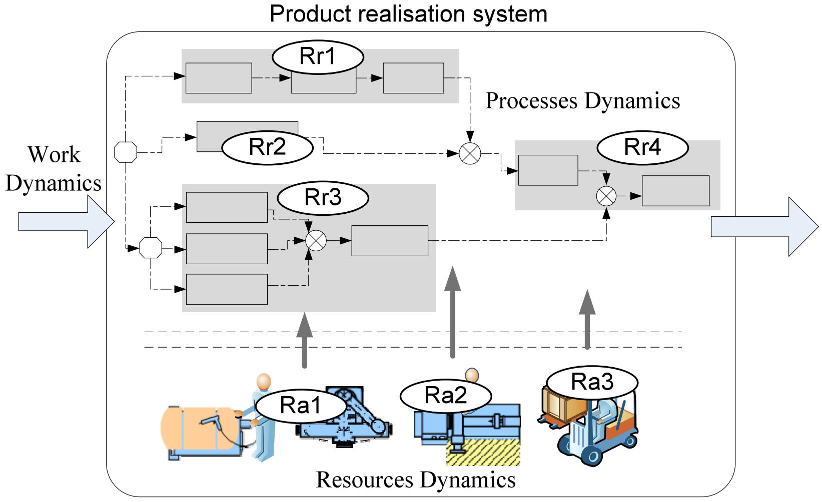


Figure 7.3 Change dynamics types within product realisation system

Figure 7.3 illustrates a model of change types that was developed as an abstraction of typical product realisation systems. This abstraction was proposed by Weston (2005) and was found to usefully represent the FFL case, in the table assembly workshop area. Role related concepts defined in the last chapter are applied with reference to this diagram with its assembly process, activities and involved resource system elements (people, machines and support tools in this case). The three dynamic aspects of this assembly realisation system were:

- *Work Dynamics:* Work is generated from outside the realisation system (i.e. is generated by some external entity to the table assembly section). In reality the source could be a customer order or be initiated by R&D engineers when they develop new products and release them for production. External occurrences of customer orders are normally processed through production planning and scheduling, where they are re-grouped or batched according to the product types and quantities ordered into a production order specification, with due dates, etc. This kind of processing into production orders will raise a *Work dynamic, which in general will be a* variable *Work pattern* that is input to the realisation system.
- *Process Dynamics:* To process such workloads, the 'product realisation system' can either utilise a current process network, with its 'as is' distributed activities and precedence links between activities, or alternatively it may be necessary to re-organise the current process structure to realise new work patterns. This aspect of change therefore concerns a specific activity group, flow routing and related operation time information; which may be derived from CIMOSA models. As the process network and its decomposition into roles is changed usually this will induce a change in role competency requirements.
- *Resource Dynamics:* Resources assigning to roles within the system are impacted on by both *Work dynamics* and *Process dynamics* as they are assigned responsibilities to complete work.

Here it is necessary to ensure the competency they possess (to accomplish specified work types) and their capacity (to accomplish specified work rates) matches work pattern requirements.

Cui and Weston [2008] had further analysed how *Work dynamics* could be specified in terms of required product types (classified in terms of their differences in processing requirements), required production volumes (which may or may not be predictable) and their production mix:

- *Product Variance (PV)* was defined as the change between ‘aspects of products’ within a ‘product class’ or within a ‘particular group of product classes’. Whether it is PV within a product class or across multiple product classes depends upon the ‘scope of products’ input to the production system being designed. [Cui and Weston, 2008].
- *Volume Dynamic (VD)* is defined as the change in the number of same product input to the system in unit time. Inter-arrival Frequency (IF) can characterise a particular input rate, so that change in inter-arrival frequency can characterise the VD where VD = ($IF_n - IF_{(n-1)}$). IF will rely on the number of products required by customers and due dates. IF will also depend upon the way in which planning and control functions are carried out. In a given time window typically a given number of products may need to be realised by a given production system [Cui and Weston, 2008].
- *Product Mix Dynamic (PMD)* is the change in mix (i.e. specific types and their quantities) of products that are input to the production system in a given time window, covering both above dynamics. PMD is [$PM_n - PM_{(n-1)}$] and can change the product scope and quantities that need to be processed in a given time window. The rate of change of PM will impact on the rate at which a given production system needs to be configured (or reconfigured) and programmed (or reprogrammed) [Cui and Weston, 2008].

7.4.2 Dynamic Scenario Instance Matrix for Experimental Input Design

Before simulation models can be verified, executed and redesigned, appropriate information needs to be input to the modelled production system. The input data can be categorized as an *experimental input.* Structural design of the model of the production system can vary to demonstrate different production system configurations and different scenario instances. But when executing the system model, structural design choices should be kept fixed, while different measures of performance are objectively applied. To provide a systematic way of interpreting *Change Dynamics* (as defined in the last section) that occur within the simulation software modelling environment and to enable building, configuring and testing system behaviour, the following scenario instance matrix table was created to characterise the different simulation model experimental designs deployed during this research study.

Table 7.1 Variable experiment change matrix template

Sc. No.	Work Dynamics						Process Dynamics (PD)		Resource Dynamics (RD)	
	Product Variation(PV)		Volume Dynamics (VD)		Product Mix Dynamics (PMD)					

Variation Applicability

Variation setting specification

Table 7.1 indicates the format of the scenario matrix. Each simulation model and its related scenario and therefore experimental set up can be characterised using such a table. Each designed scenario is numbered (Number of scenario set, plus the scenario instance). The three aspects of change dynamics defined in last section are listed in the table. The first Work dynamic includes three optional variable settings. Under each setting of Work dynamics, the other two dynamics aspects may be relevant (i.e. where a corresponding change is needed) or independent (no additional change being necessary). Variation applicability uses 'Y' or 'N ' to indicate whether this variable element will be changed in the specified experimental design scenario. If yes, specific variation descriptions will be defined.

Here it was understood that the three different sources of dynamics have different spheres of impact. For example the set of variables linked to customers typically have dynamic behaviours that are hard to predict and cannot easily be controlled. While variables that occur within the ME boundary, are either induced by external change, or are actively triggered by internal sources (e.g. by planning and production policy change, by staff training completed or new production facilities purchased and installed). Other variables are to some extent controllable and arguably are the main potential aspects of the ME that can be concentrated on during simulation experiments to achieve improvement.

In reality, many changes in variables and their impacts may occur in a largely synchronous manner but with various related delays. But in the simulation experiments the aim would be to minimise impacts of multiple parameter change to simplify results analysis and interpretation. Thus the experimental design was about simulating different scenarios so that resultant behaviours can be compared and changed accordingly; thereby to focus modelling of possible As-Is situations on developing improved dynamics aspects of possible 'To-Be' system designs and their related possible situations.

7.4.3 Experimental Design of the FFL Table Assembly Simulation Model

To guide the design of modelling experiments, historical data about FFL table production was elicited and this helped gain an understanding about likely propagated impacts arising from parameter change. Also model construction was heavily influenced by relationships between modelled entities defined during Enterprise modelling and Role based modelling so as to determine how elements of real production data may be related back to FFL business information (such as cost and value) as a whole. Three sets of experimental scenarios were conceived to investigate impacts of alternative 'role decompositions, 'resource assignments' and 'configurations of role-resource system couples', as discussed in the following sections.

7.4.3.1 Product historical data review

In reality, over 300 type products, with different specifications, are assembled in the table assembly area of the FFL company. With the aim of simplifying experimentation it was observed that these 300 products can be consolidated into 7 table families. This consolidation was made on the basis that products within each family had very similar processing operations, times and routes. However the orders received for each product are very distinctive and generally the quantities needed are uncertain. Orders for four of the consolidated table type families amounted to approximately 85% of the total production; in terms of order quantities and processing time. Amongst these four table families, some share similar sub-assembly steps even though they may belong to different table families. For scenario design, therefore these four types of table (as shown in Figure 7.4) were selected as the prime subjects of analysis as they were known by the case company management to have a dominant influence on production behaviours:

DL4 – (representative of DL1-5); DL6 – (representative of DL6-8);

PT3 – (representative of PT1-5); FT6 – (representative of FT1-7).

Figure 7.4 Table family products in experiment scenario

Having consolidated FFL products into family groups next it was necessary to collect and deploy realistic historical data over a sufficient period of time to enable the management to view simulation results with confidence. The following is a list of data types and sources that were elicited from FFL historical documents and were reflected upon during scenario design and later simulation model building. This includes:

- From work aspect – Product orders receiving patterns;
  Product batch/mix policy;
- From process aspect – The routing of parts and components go through these operations;
  Time associated with setting up, processing, motion and delivery;
- From resourcing aspect – Staff available associating to operations;
  Different skill level staffs to specific products and operations;
- From financial aspect (revenue and cost) -- products sales price and staff unit labour costs.

7.4.3.2 Scenario Set 1 ('As Is' Production System)

Scenario set 1 was designed in accordance with the following bulleted points:

- Four products were modelled, namely: DL4, DL6, FT6, and PT3. Each product involved a scenario sub-set.
- Designed to only *Work Dynamics* changes within the defined simulation timeframe.
- For each product, three type *Work Dynamics* are designed: a) parameters kept constant; b) Interval time varies; c) Incoming volume varies.
- DL4, DL6 and FT6 share the same process routing (i.e. all require R2, R4, R5); Role 3 (the Framemaker role) is not applicable for PT3 but it is required for the other three table types.
- 5 operators are assigned to work at fixed workstations.

Table 7.2 Experimental Scenario Set 1

Sce. No.	**Work Dynamics**						**PD**		**RD**	
	PV		**VD**		**PMD**					
S1-1a	N	DL4	N	Interval 30 min, batch size 1	N		N	Process Role R2,R3,R4,R5	N	5 Operators, fixed WC
S1-1b	N	DL4	Y	Interval 10-50 min; batch size 1	N		N	Process Role R2,R3,R4,R5	N	5 Operators, fixed WC
S1-1c	N	DL4	Y	Interval 30 min; batch size 1 to 5	N		N	Process Role R2,R3,R4,R5	N	5 Operators, fixed WC
…				…				…		…
S1-4a	N	PT3	Y	Interval 30 min, batch size 1	N		N	Process Role R2,R4,R5	N	5 Operators, fixed WC
S1-4b	N	PT3	Y	Interval 10-50 min; batch size 1	N		N	Process Role R2,R4,R5		5 Operators, fixed WC
S1-4c	N	PT3	Y	Interval 30 min; batch size 1 to 5	N		N	Process Role R2,R4,R5	N	5 Operators, fixed WC

Table 7.2 shows a part of the scenario set, completed one attached in Appendix V. This scenario set compared behaviours for the selected multiple products, One product and one change aspect corresponds to the simplest case of table assembly processing, but this rarely happens in the real production environment. However such a simplification can make simulation modelling feasible;

can clearly quantitatively differentiate between behaviours of selected table products; and can provide comparison benchmarks for later more complex change scenarios.

7.4.3.3 Scenario set 2 ('As Is' Production System)

Scenario set 2 is an extension of scenario set 1 and is described by Table 7.3. Also this second scenario is characterised as follows:

- Different ways of mixed multiple products input to the production system for each scenario case;
- Sub-set 1, different percentages of two product types are input;
- Sub-set 2, within work dynamic aspect, in addition to PV changes, VD also changes, made product mix dynamic (PMD) change;
- Sub-set 3 different product mixes are input which induces process routing change, involving change to roles, hence both *Work dynamics* and *Process dynamics* aspects are changed.

Table 7.3 Experimental Scenario Set 2

Sce. No.	Work Dynamics						PD		RD	
	PV		VD		PMD					
S2-1a	Y	FT6, DL6	N	30 min, batch size 1	N	25-75% Random	N	Process Role R2,R3,R4,R5	N	5 Operators, fixed WC
S2-1b	Y	FT6, DL6	N	30 min batch size 1	N	50-50% Random	N	Process Role R2,R3,R4,R5	N	5 Operators, fixed WC
S2-2a	Y	DL4, DL6	Y	Interval between 10 to 50 min	Y	25-75% Random	N	Process Role R2,R3,R4,R5	N	5 Operators, fixed WC
S2-2b	Y	DL4, DL6	Y	Interval 30 min batch size 1 to 5	Y	50-50% Random	N	Process Role R2,R3,R4,R5	N	5 Operators, fixed WC
S2-3a	Y	PT3 FT6	Y	Interval between 10 to 50 min	Y	25-75% Random	Y	R2,R3,R4,R5 or R2, R4,R5	N	5 Operators, fixed WC
S2-3b	Y	FT6 DL6 PT3	Y	Interval between 10 to 50 min	Y	33-33-33% Random	Y	R2,R3,R4,R5 or R2, R4,R5	N	5 Operators, fixed WC

Scenario set 2 introduces more complex scenario cases of assembly processes. This second scenario set includes multiple products, where each sub-set is designed with: different product family mix possibilities; a variable volume dynamic (via interval time change and interval batch size change); and random input of products with variable percentages. The dynamics introduced by scenario set 2 imitates real case order fluctuations that were known to impact on the FFL table assembly system. Such changes directly impact actual instants of workload, operation time and resource utilisations. Scenario set 2 assumes that no specific batch planning was used; rather product types and volume are input at random, dependent upon their order receiving sequences.

7.4.3.4 Scenario set 3: (To-Be production system redesign 1)

Earlier in section 7.4.1 both process change (regarding possible role change) and resource change were classified as internal variables. Therefore, internal change is the norm due to self-awareness within the system, rather than change being induced by external factors. One key constraint regarding resource utilisation when computer exercising As-Is scenario sets was that the location of operators was fixed to a single work station. But in reality staff may not always work at the same location; also may not always be available to carry out required work loads on time.

When considering this from R-BMM view, fixed assignment of operators to certain work stations would restrict role assignment options; even if staff are available and have sufficient competencies to be candidate holders of multiple roles. Hence the main objective of scenario set 3 is to maintain the input patterns work loads and product mix complexity (i.e. the same as for As Is sets 1 and 2), but to focus behavioural study on how new (possible To-Be) production system configurations will behave in the future following system re-design in the form of resource system change (such as to allow operators to move to different locations; on the condition that they 1) know how to work at multiple workstations (i.e. they possess the required competencies) and 2) have done the current job allocated to them and are in a waiting state (i.e. available to be re-assigned as the holders to different roles). Table 7.4 illustrates the design of scenario set 3 different role assignment solution to evaluate how FFL table assembly will behave compared with As-is status. The following bullet points further characterise scenario set 3:

- Keep multiple products mix input to each scenario case;
- S3-1, S3-2 S3-3 and S3-4 respectively are based on S2-1b, S2-2a, S2-3a and S2-3b;
- resource system assignment to roles is designed to enable operators to move flexibly among different workstations.

Table 7.4 Experimental Scenario Set 3

Sce. No.	**Work Dynamics**						**PD**		**RD**	
	PV		**VD**		**PMD**					
S3-1	Y	FT6, DL6	N	30 min batch size 1	N	50-50% Random	N	Process Role R2,R3,R4,R5	Y	Flexible operator locations
S3-2	Y	DL4 DL6	Y	Interval between 10 to 50 min	Y	25-75% Random	N	Process Role R2,R3,R4,R5	Y	Flexible operator locations
S3-3	Y	FT6 PT3	Y	Interval between 10 to 50 min	Y	25-75% Random	Y	R2,R3,R4,R5 or R2, R4,R5	Y	Flexible operation locations
S3-4	Y	FT6 DL6 PT3	Y	Interval between 10 to 50 min	Y	33-33-33% Random	Y	R2,R3,R4,R5 or R2, R4,R5	Y	Flexible operation locations

Scenario 3 introduces further complexity into the production system because staff relocation depends not only upon their availability, but also because their applicability as a role holder will also vary with different products. Therefore scenario set 3 was designed to predict, using simulation, how both individual and collective roles will be performed differently when flexibility is exercised in respect of viable role holders.

7.4.3.5 Scenario 4: (To-Be production system redesign 2)

Section 7.2.2 reported on the use of CLM to analyse different ways of achieving production systems optimisation potential. In addition to concentrating on resource aspect solution seeking as scenario set 3 designed , option C in section 7.2.2 (also indicated in segment ③, Figure 7.1) identified 'Role Re-design' as an alternative potential means of achieving production system improvement. Concentration on the analysis of existing roles it was observed that roles can be re-designed through re-structuring and re-configuring associated process segments (activity groups), thus substantially changing required competencies. This may induce different ways of using valuable and constrained resources that can lead to production system performance improvements. Hence this scenario design is to deploy Role re-designed production system into Plant Simulation model, to provided a quantitative test and supportive proof about above optimisation solution outputs under a particular set of circumstances. For best comparison, working item input patterns should remain the same as for S2-3b and S3-4. This scenario set design feature is as follows:

1) Work item incoming pattern and simulation duration remained the same as 2-3b and 3-4;
2) process routing and operations may change according to new table assembly system designs;
3) re-designed roles apply to operation activities;
4) a flexible role assignment policy was still applied;

Table 7.5 Experimental Scenario 4

Sce. No.	Work Dynamics						PD		RD	
	PV		VD		PMD					
S4	Y	FT6 DL6 PT3	Y	Interval between 10 to 50 min	Y	33-33-33% Random	Y	Re-designed role set	Y	Flexible operation locations

7.4.4 Scenario Design Link to CLM

The design of the three scenario sets can be interpreted in respect of a link to the CLM diagram (see Figure 7.1). The design of scenario sets 1 and 2 relate to different instances of 'Specifying requirements change'. While Scenario set 3 relates to option B 'expand resource seeking range' in section 3; Scenario 4 designed option C through "role re-design" attempting. These experimental designs illustrate that the qualitative CLM provided useful guides for consistent quantitative simulation model design. The scenario sets covered both external and internal experimental change issues.

7.4.5 Expected Simulation Results

The preceding simulation model development and experimental design was expected to enable measurement, comparison and analysis of the current behaviour of the FFL table assembly system under the specified scenario conditions. This approach was designed to discover and quantify the impacts of new understandings about the FFL table assembly system which could not be readily discovered in the real system where in reality many parameters change on an ongoing basis. When so doing the following Key Performance measures were expected to be determined:

- The number of tables assembled (for each table type) during a fixed model execution period, as a measure of overall product generation within a given time frame;
- A statistical analysis of key workstations' behaviour, including working time, blocked times, waiting percentage;
- An evaluation of the utilisation of human resources, and specific workstation related technical resource usage;
- Assuming financial data availability, to calculate revenue generation and production costs.
- Overall comparison between As-is and To-be experimental design to provide quantitative production system performance testing results

7.5 CREATING SIMULATION MODELS OF FFL TABLE ASSEMBLY

Having (1) gained knowledge of the selected simulation software; (2) reused structured information generated during EM, (3) used the CLM to determine like causal impacts and related control and controlled variables, and (4) thus designed a set of experimental simulation model scenario, the author constructed a number of Plant Simulation models of the FFL's table assembly system. The purpose of these models was to conduct quantitative and statistical measurement of role behaviours and comparative performances of alternative role holders under different modelled scenarios.

7.5.1 Model Construction

Figure 7.5 illustrates the overall appearance of the FFL table assembly model frame. This frame graphically represents the table processing routes and flows; this was achieved by picking standard Plant Simulation building blocks by using menus and instruction fields. The model layout maintained structural similarity with that of the corresponding EM Activity Diagram (Figure 5.10).

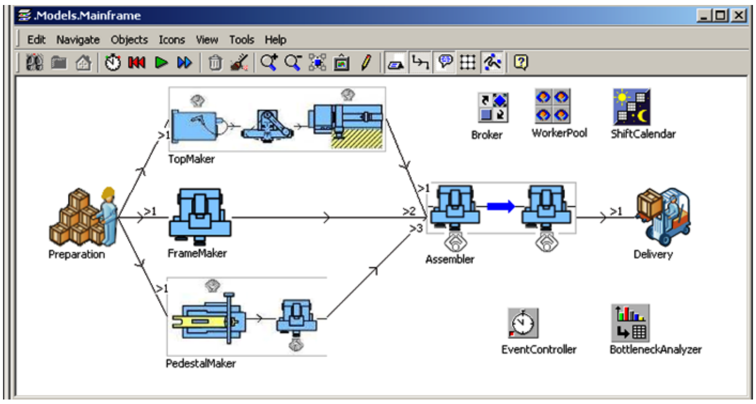


Figure 7.5 Table assembly section simulation model layout

The chosen Plant Simulation software tool provides a 'frame' type modelling construct, which enables description of a specific material flow distribution policy without excessive visual clutter. In the model, five model frames are used to form the overall model frame, as illustrated by Table 7.6.

Table 7.6 Main building block with customised icons in the model

Building block	Default icons	Customised icons	Associated roles
Model Frame			R1- Preparation
			R2 - TopMaker
			R4 - PedestalMaker
			R5 - Assembler
			R6 - Internal transport
Single Proc			R3 - Framemaker

Each of these frames specify one role. In addition, one *Single Proc* building entity was used to specify the Framemaker role. More detailed information are specified within each frame. Customised icons are used to build more visually descriptive model interfaces. The other building block types included in the model are also linked with the R-BMM entities, as explained in Table 7.7, and can be understood from the software usage view, but also from role modelling entities perspective within the simulation environment.

Table 7.7 Building blocks link to R-BMM entities

Building block	Default icons	Software description	Associated R-BMM entity
WorkerPool		The place where workers stay when waiting for a job.	Resources Pool (human resource)
Broker		It coordinates with Exporter and Importer, is the go-between for services offered and services required.	Responsible for assigning roles
Source		Produces MUs according to designed incoming feature.	working items incoming
Workplace		The actual place at the station, where the worker performs his job.	Role holder assignment location
Worker		Represents a operation staff who performs a table making job at a Workplace.	Candidate role holder(s)

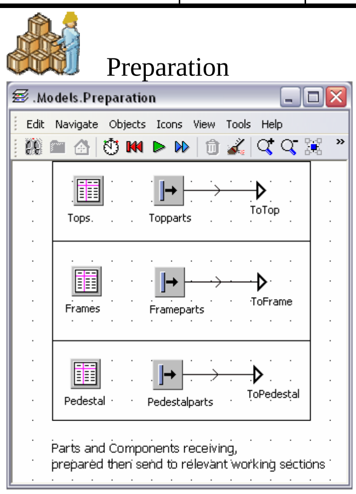
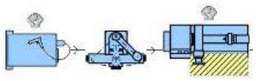


Figure 7.6 Preparation frame

Preparation frame: as shown in Figure 7.6, this frame generated all table parts, catalogued them into different *Sources*, namely: Top, Frame and Pedestal, and sent them to different sections of the assembly workshop. *Source* is a generic Plant Simulation building block which is designed to behave as an input to a model process or a set of operations. *Source* provides a dialog window to specify related parameters. Those worksheets provide detailed parts information as an external database support function, including specifying part types and part features.



Topmaker

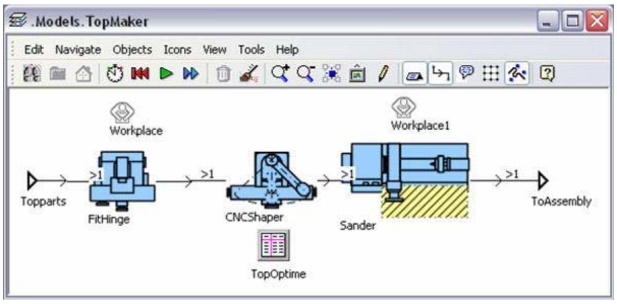
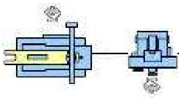


Figure 7.7 TopMaker frame

TopMaker Frame: as shown in figure 7.7, this required three operational steps with the first and third involving mainly manual work. The second step is an automated CNC operation. *TopOptime* lists the specific operation time of each step for each different product type.



Pedestalmaker

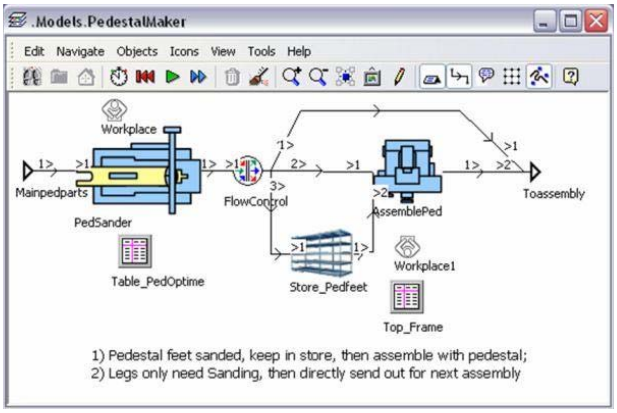


Figure 7.8 Pedestal Frame

Pedestal Frame: as shown in figure 7.8, was used to model the receiving and processing of pedestal parts or legs. Bearing in mind among the four tables in the scenario design, only PT3 and DL4 tables have both pedestal and pedestal feet, while the other two types only have legs that need to be sanded before they go to assembly. The required competencies of any holder of this role include: an ability to sand all parts; to identify table type part differences; to assemble pedestal tops and feet (of PT3 and DL4); or to sand shaped legs (of DL6 and FT6). Staff as candidate holders of to this role must possess all these competencies to be able to work at this section, as in the FFL table assembly reality (in its As-is form) these operations are all done by single operator.

Internal transport

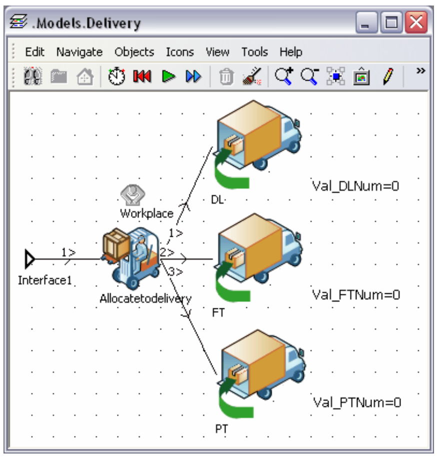


Figure 7.9 Delivery Frame

Delivery Frame: as shown in Figure 7.9, this frame is used to simulate the final checking and packing of assembled tables, then to allocate them to different stores for delivery according to their type. The four case type tables belong to 3 product families. Therefore there are three outputs from this model segment. The delivery role is defined as the functional competency to perform 'Internal deliveries'. The three outputs are symbolised by a customised icon using the building entity 'Drain'. They are represented by three number type variables, as listed on the right side of each of them. These variables trace and display dynamic changes in the output of relevant table products.

7.5.2 External Data Input Interpretation and Parameter Configuration

Having created the model structure and encoded previous enterprise modelling and role modelling elements into Plant Simulation model entities, the next step taken was to input data derived during previous modelling stages, including historical and statistical information into modelled entities. Plant Simulation provides several ways to input data, they include manual input via object dialog windows; programming code input; and external data importing. The following illustration covers two main aspects of input data types.

7.5.2.1 Work item entry specification information

Table parts coming from the three 'Source' entities (named Tops, Frames and Pedestal) that are located in the Preparation frame, are called Moving Units (MUs) as they are 'moving' through workstations. The incoming parts pattern was specified through use of an object window by opening each Source as illustrated on the right-hand side of Figure 7.10.

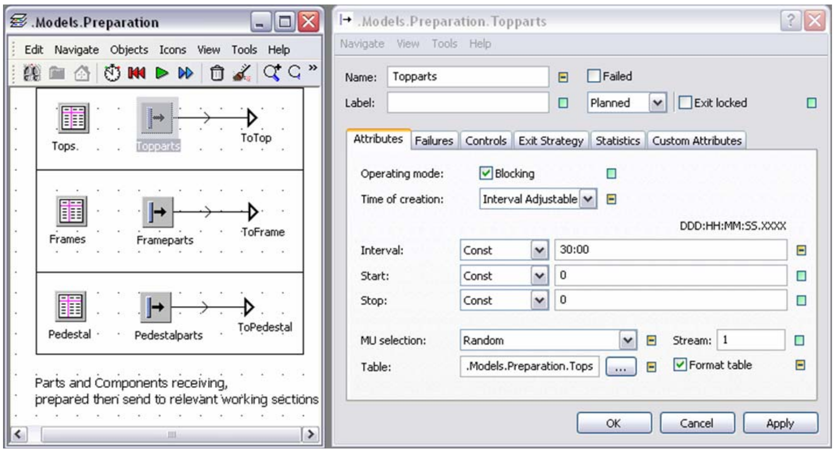


Figure 7.10 Illustration of data input: receiving parts – Preparation Role

7.5.2.2 Active resources involved

Operation staff and automatic machines are the main active resource types used for table assembly. (1) Plant Simulation collected all operators into a *Worker Pool, and* specified their 'capable service abilities' (with respect to operators' possessed competencies). (2) Manual operations were coupled with workstations through *Workplace* and configuration window to specify the service required (with respect to competency required). (1) and (2) were set for model execution, Plant Simulation used *Broker* to seek and compare the required services from (2) and the services contained in (1); if a match is found, the relevant worker is potentially available to be assigned the role at that workstation. By this means, all candidate role holders (who can provide required services to a certain workstation) listed and to inform management decision making. The left part of Figure 7.11 demonstrates that a specific service required at a workstation; and the right side is the *WorkerPool* worker service list.

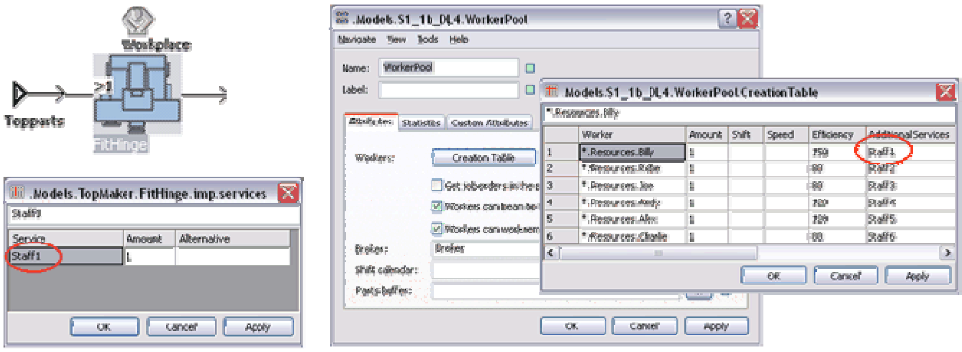


Figure 7.11 Example of resource specification

Operation data for machines was specified within each workstation. Plant Simulation detailed workstation configurations with respect to their setup and processing times, break down rate, as well as their entry and output control logic. In addition these parameters were specified separately and attributed to different products; Staff skill levels were differentiated by use of a comparative ratio relative to a standard operation speed. Figures 7.12 illustrates a snapshot of resource data input for TopMaker of the table assembly section.

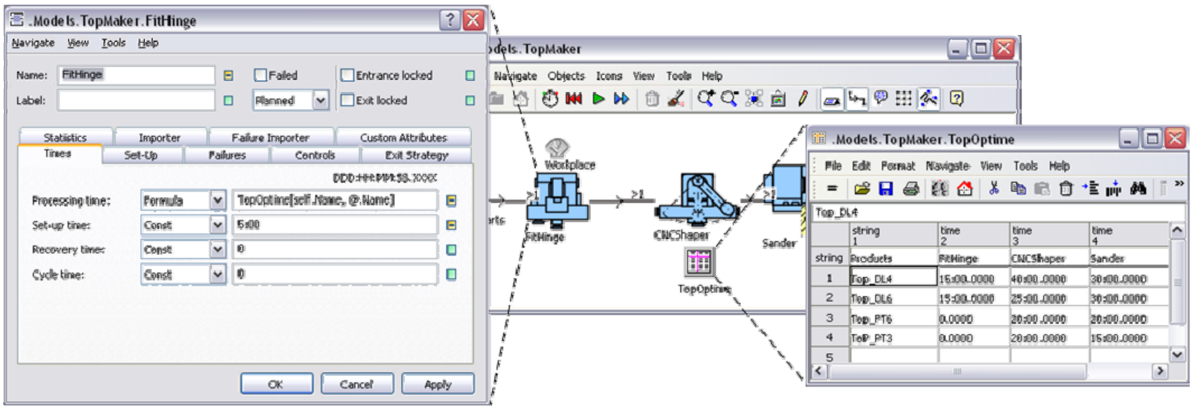


Figure 7.12 Example of operation data input – the TopMaker role

7.6 MODEL EXECUTION AND RESULTS ANALYSIS

After the model structures have been created, and programmed into Process Simulation Models and relevant data has been input, the model of the FFL table assembly system could be run to simulate assembly system behaviours over selected periods of production time. This enabled the tracing of work item flows through the model, passing them through model steps with the designed routing. This naturally involves resources carrying out work within their assigned roles. To obtain results, this requires the recording and presentation of total outputs of products; calculating the total value; and recording resource utilisations and processing costs.

7.6.1 Simulation Model Execution and Results Explanation

Figure 7.13 is a snapshot of the model scene recorded during execution. Table parts are received, as working items with defined entry patterns from Preparation. These MUs were operated on and sub-assembled, travelling through the parallel and sequential paths of the process network. Operations are carried out by operators and machines, as dynamic and multiple assignment of resources (as act as holders of one or more roles). Completely assembled tables are then transported out of the modelling scope.

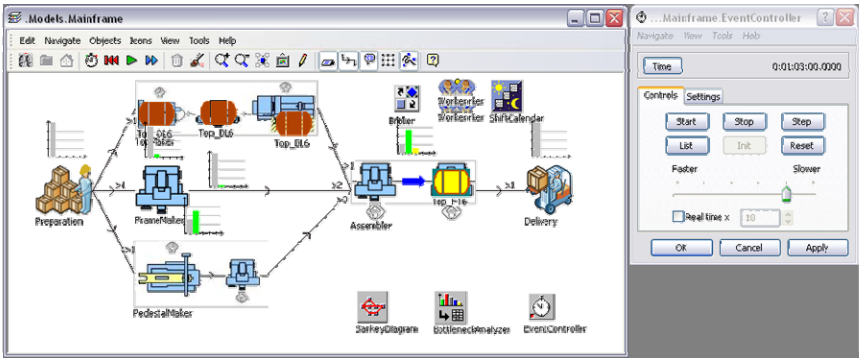


Figure 7.13 Snapshot to model simulation execution

By using the dynamic trace function, during model running, the real time workflow routing through each workstation (with their related working load and resource utilisation) was indicated using visual graphical patterns. These data are recorded in the model, until the model running ends. Then statistical functions of Plant Simulation provide an ability to conduct further quantitative analysis. The model was proven to usefully encode assembly duration as reasonable period, and to make available abundant numbering for results analysis. At the end of the designed '3 calendar month simulation period' of model execution, the designed model outputs are aggregated into a set of tables. Table 7.8 – Table 7.11 gives a partial illustration of the results, more comprehensive results lists are attached in Appendix VI.

Table 7.8 summarises results as the table assembly system model simulates production operations that generate products and displays the total volume of tables produced at the end of simulation period. With support of sale price information, the results list also provides a measure to the overall value added by the table assembly section, when viewed as a segment of FFL's overall production system.

Table 7.8 Assembled table and value generation within 3 month

Scen.	Volume produced & value generated								
	FT6	Value	DL6	Value	PT3	Value	DL4	Value	Total Value (£)
S1-1a							287	56252	56252
S1-2b			318	50562					50562
S1-3c	359	70364							70364
S2-1b	99	9801	93	14787					24588

S2-2a			164	26076			43	8428	34504
S2-3a	241	23859			83	9877			32076
S2-3b	63	6237	61	9699	79	9401			23757
S3-1	148	14652	134	21306					35958
S3-2			246	39114			76	14896	54010
S3-3	275	27225			82	9758			35343
S3-4	102	10098	130	20670	119	14161			42549
Based on market sale price: DL4 £196; DL6 £159; PT3 £119; FT6 £99									

From the results it was necessary to compare not only the value generated, but also to take corresponding costs of production into consideration. Taking a human resource as an example, the statistical function in Plant Simulation was used to compute resource utilisations at workstations where roles apply. The simulation model can hold three states (*Working, Waiting and Blocking*). Hence it was used to compute the time for which the complete assembly system (and its individual workstations) is actively working (i.e. in *Working* state), to realise a direct value adding contribution. While for the other two states, human cost is still incurred but no value is added. Table 7.9 and 7.10 give a comparison of a set of statistical data respectively under Scenario cases 2-3b and 3-4.

Table 7.9 Resources utilisation percentage (Scenario 2-3b, As-Is)

Workstations (Roles) / Status	**Top maker**			**Frame maker**	**Pedestal maker**		**Assembler**	
	Hinge	Shaper	Sanding		Sander	Pedassembler	ToptoFrame	FrametoPed
Working	13.02	12.91	12.91	49.89	50.05	49.95	5.14	16.44
Waiting	31.58	38.17	42.28	50.11	0	0	4.97	1.99
Blocking	55.40	48.91	44.81	0	49.95	50.05	89.90	81.57

Table 7.10 Resources utilisation percentage (Scenario 3-4, To-Be)

Workstations (Roles) / Status	**Top maker**			**Frame maker**	**Pedestal maker**		**Assembler**	
	Hinge	Shaper	Sanding		Sander	Pedassembler	ToptoFrame	FrametoPed
Working	17.49	17.49	17.49	48.63	85.75	85.51	11.00	28.58
Waiting	48.03	63.39	66.73	40.88	0	12.29	46.92	2.70
Blocking	34.48	19.12	15.78	10.49	14.25	2.20	42.09	68.72

Bearing in mind that during R-BMM case study work it was observed, that most staffs hold multiple competencies (refer to Table 6.7, chapter 6), then as candidate role holders, they have potential to be flexibly assigned to roles. Comparing the three working states in Table 7.9 with Table 7.10, the case of dynamically deploying staffs (To-be solutions in scenario 3-4) produced significant increase in efficiency (percentage in working state) and corresponding waste (the sum of waiting and blocking states) decrease. Such an improvement to whole table assembly performance is indicated as a table assembly volume and a value generation increase respectively S2-1b to S3-1, S2-2a to S3-2, S2-3a to S3-3 and S2-3b to S3-4 see Table 7.11. where same colour coded pairs are used to aid the comparison.

To simplify the evaluation, labour costs in the simulation were calculated based on the use of 5 practiser level staff (£8/hour labour cost) working over 3 months in total this equated to a total labour cost of £28800. Total value generated against cost of the table assembly section, under the different scenario cases, are listed in Table 7.11. Here performance indicators ***η1*** and ***η2*** identified in section 6.3.7 of chapter 6 were calculated. This predicts a similar impact of using flexible role assignment solution: higher working efficiency leading to higher ratio of value/cost being achieved.

Table 7.11 Paradigm of value added and cost comparison in simulation

Scenario	Value added(£)	Labour cost(£) *	η1 (to Role 5 - Assembler)	η2
S2-1b	24588	28800	0.178	0.854
S2-2a	34504	28800	0.196	1.198
S2-3a	32076	28800	0.470	1.114
S2-3b	23757	28800	0.135	0.825
S3-1	35958	28800	0.285	1.249
S3-2	54010	28800	0.340	1.875
S3-3	35343	28800	0.552	1.227
S3-4	42549	28800	0.275	1.477
* Simplified labour unit cost: as Practiser level £8/hour				

7.6.2 Analysis of Multi-role Interoperation

It was stated that the roles identified in the FFL table assembly area are inter-related (Figure 6.6, section 6.4.1 Chapter 6). This was verified by the simulation models' behaviours and results. When analysing behavioural outcomes with only solo role it was made evident that the capability to usefully support current production system improvements was constrained. Through simulation model re-design, construction and execution, dependencies of multiple roles can be analysed from the following aspects:

1) Logical sequential, parallel and/or hierarchical structured roles can be configured during the production system design phase. From the simulation model structure, the building entities have clearly indicated connection among them; this being determined by the structure designed. Within model building entities, the detailed *specification object window* configured these interactions that are linked through *Entry Control* and *Exit Control* tab mechanisms of the simulation tool. The existence of structural constraints imposed during design stage can be both beneficial and restrictive on behaviours and are of significant consideration issues during process network and associated roles set design.

2) Restrictions on the type and amount of resources assigned to roles and acted as role holders during production system execution phases also were observed to influence behaviours as generally expected. During simulation model execution, resources (in this case, operational staff and machines) are either fixed allocated (Scenario set 1 and 2) or dynamically allocated (Scenario set 3) to roles associated to modelled workstations . Resources can be given either single or multiple assignment

instances to different roles throughout the assembly area during the simulation period; the dynamics of those role holders are modelled in terms of different working states (Working, Waiting, or Blocking) across the simulation model scope. Hence the inter-operation of multiple roles will in general be constrained by resource (type and amount) availability and utilisation. This aspect also offers potential for resource configuration improvement options such as by introducing additional resources, in flexible assignments leading to optimised distribution, and high utilisation etc.

3) The deployment of a multiple role structure and resourcing policy should also lead to 'balanced' production. For multiple roles and multiple resources a badly designed multiple role structure and candidate role holder distribution policy would very probably lead to i) some simply competency needs or low work load workstations are designed with high competency or capacity requirement. ii) Such inefficient design wouldn't appear obvious until role assignment implementation, highly skilled staff members may be error-allocated to those workstations. Consequently highly skilled role holders then appear to behave badly and have a low efficiency but receives a high payment. Hence role based production system design, accurate role and its required competency configuration need compound with candidate role holder design/planning, so as to create a balance utilised process – resource (role – role holder) production system, to achieve appropriate resource dynamical assignment.

7.7 PRODUCTION SYSTEM OPTIMISATION THROUGH ROLE RE-DESIGN

The simulation model results were analysed and were observed to usefully support decision makers (such as assembly system planners or assembly system designers); providing them with improved and quantitative understandings about the performance of the modelled (As-Is and To-Be) production systems. Also the analysis provided decision makers with quantitative information about alternative configurations of roles and role holders. The following subsections illustrate some of the results analysis carried out in respect to the experimental sets.

7.7.1 Role Re-design in FFL Table Assembly Section

Role re-design was considered to need detailed evaluation involving the use and development of earlier process decompositions of the table assembly processes determined during the creation and use of activity diagrams (as part of the FFL EM). Also from the work efficiency results indicated in Table 7.9 and 7.10, it was observed for the 'as is' table assembly system that the 'Top Sanding' operation which is part of Topmaker Role and operations identified as Role Assembler both had a poor utilisation. Later this was also found to be the case even with a flexible distribution of staff to roles. However with reference to different sub-assemblies of tables (which reassure separate process segments and role criteria) the alternative decomposition approach investigated the resourcing of elemental activities within each sub-assembly. For example Topmaker Role and Assembler Role were studied in terms of their required competencies. Those competency requirements with similarity were grouped, while maintaining the same functional output. Following which a re-designed role network with alternative decomposition analysis was developed and is shown in figure 7.14. The main structural and temporal logic changes, and the new role coverage were determined with reference to the following:

- The ‘Top sanding’ activity was split with the rest of table top work (EA7232, EA7233) which re-designed the Topmaker Role (R2);
- Table parts sanding work was distributed but now gathered as a Sander role (R3);
- Assembly work involved in the frame, pedestal, and the main assembly work were aggregated into the Assembler role (R4);
- Raw material receiving, preparation, parts and sub-assembly transport work were combined into a Distributor role (R1).

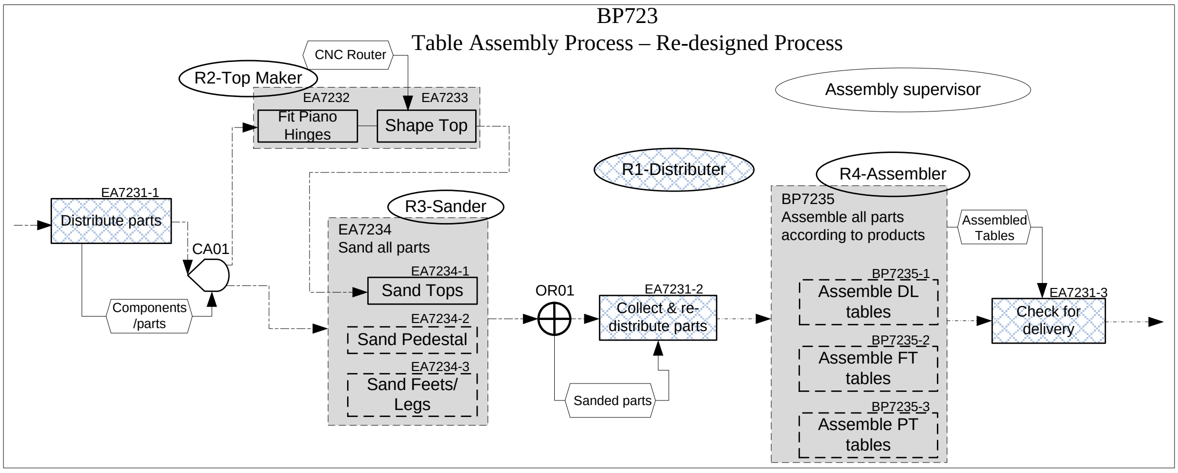


Figure 7.14 Role re-design of the table assembly process

From the process structure, it can be observed that more parallel operations exist in the ‘To-Be’ assembly system case. This enables more work items to be realised concurrently. However, effective parallel operation largely relies on whether the assigned resource holder has the required competencies and is flexible enough to work across re-designed multiple work locations. In addition, this option would be more efficient when a sufficient number of resources exist to support parallel working.

7.7.2 Table Assembly System Re-design

The re-designed decomposition of roles, shown in Figure 7.14 and described in Section 7.7.1, was expected to achieve enhanced assembly performance. But this requires a testing to prove via quantitative simulation. Overall production volume, value and cost results, as well as overall assembly efficiencies were used here as key measurement indicators, but does not include those same named roles whose covering operations already changed. Therefore a new simulation model was built and run over a 3 calendar month period. The outputs are listed in Table 7.12 – 7.14.

From table 7.12, it can be observed that the volume of each type of assembled table as well as total value, has significantly increased in comparison to earlier 'To-Be' solution results (Scenario 3-4) and were more than doubled compared to the original 2-3b case.

Table 7.12 Assembled table and value generation within 3 month (re-designed)

Scen.	Volume produced & value generated								
	FT6	Value	DL6	Value	PT3	Value	DL4	Value	Total Value (£)
S4	147	14553	148	23532	131	15589			51054
Based on market sale price: DL4 £196; DL6 £159; PT3 £119; FT6 £99									

Table 7.13 Resources utilisation percentage (re-designed)

Workstations (Roles) / Status	Top maker		Sander (Average)	Pedestal assembler	Assembler	
	Hinge	Shaper			ToptoFrame	FrametoPed
Working	18.33	18.33	27.50	45.83	11.91	34.67
Waiting	51.09	63.22	64.20	52.52	43.75	9.22
Blocking	30.58	18.45	8.30	1.80	44.35	56.11

Table 7.14 Value added and cost comparison in simulation (re-designed)

Scenario	Value added(£)	Labour cost(£) *	η1 (to Role 5 - Assembler)	η2
S4	51054	28800	0.343	1.773
* Simplified labour unit cost: as Practiser level £8/hour				

With respect to evaluating three working state behaviours, Table 7.13 indicates the working percentage to the Hinge and Shaper under Role Topmaker and these are nearly same as for the result in scenario 3-4. However the new Sander role had significant improvement as did the newly re-configured Assembler role. Consequently the role re-design had improved the resource utilisation and contributed to enhanced overall performance of the new system; even the working efficiency of Pedestal assembler in the new system appeared to decrease. Such improvement are indicated through the comparison to the green, yellow and blue color coded table cells in Table 7.9 and 7.10; the improvements with respect to indicators ***η1*** and ***η2*** is in table 7.14.

7.8 SUMMARY OF THE SIMULATION MODELLING WORK

By systematically building, specifying and running a simulation model of FFLs table assembly system it proved possible to use the R-BMM to facilitate an evaluation of impacts of alternative work flows and work patterns through alternatively designed processes-resource couples. This provided a quantitative evaluation modelling method to 'replicate existing' and 'predict possible future' resource behaviours when they were assigned roles and exercised via specific work pattern scenarios. The main importance of this chapter and its expansion and enhancement of pervious phases of the R-BMM was to use discrete event simulation to program, run and analyse the potential of new modelled production system configurations. When so doing it enabled: 1) responses to multiple simulation scenarios (including products type and number random mix) to be determined; 2) Variable activity group processing, with possible configuration changes to match scenario change, and logical control by pre-defined production states; 3) multiple roles to be simultaneously applied as distributed activity groupings (also in response to requirements change); 4) dynamic modelling of impacts of resource distribution across the model scope.

Model structures and data simplifications were developed and deployed which significantly reduced the modelling building time and effort, while maintaining a reasonable approximation to the reality being modelled. But model complexity was observed to be one essential factor when balancing modelling difficulty and ability to accurately represent reality. Also using the simulation software was found to need a deep understanding of the specific simulation programming language, which also was found to restrict the scope and detail that can be modelled with the available effort and time of the modeller. In this simulation model application, the author believes that there are outstanding issues that need to be considered about how to balance the modelling effort and the acceptability of modelling simplifications, particularly where production systems modelling involves a larger scope and scale.

However the outputs of simulation models with their statistical tools and the designed measurement indexes, provided a way of benchmarking current and possible future performances. Thus potential improvement options, in support of decision making, can be provided by comparing modelled results with actual performances and future outcomes. Consequently it was known that: (a) only relatively simple simulation models could be exercised in practice, therefore either the scope or depth of any SM would need to be systematically restricted; or (b) in general SM creation should be well structured to reduce the time and effort involved in replicating real world behaviours (in support of model validation) and predicting the effect of candidate change to the real world.

CHAPTER 8

Research Reflection and Extension

In this chapter the author reflects on the research conducted during this PhD study. Particularly it considers how new modelling ideas conceived and incorporated into the R-BMM have the potential to support complex production system's design. Also considered are possible constraints on a generalised application of the R-BMM. Discussion includes a consideration of 1) how the developed knowledge and technique was deployed in case study modelling, 2) aspects of lessons learned from methodology development and application and 3) how the lessons learned can instruct possible further development and improvement. The reflection is made in relation to (a) detailed modelling of an actual production system of limited scope and (b) relative conceptual modelling of an actual production system of significantly wider scope.

8.1 RESEARCH REFLECTION

This section will reflect on a number of aspects of the research conducted. Each aspect considered is summarised into figure 8.1. This reflection has four viewpoints: (1) 'Knowledge contribution'; (2) 'Benefits obtained', by applying the knowledge and by conducting analysis in respect of case study modelling work; (3) 'Skills' needed to realise (1) and (2) and related 'Cost' incurred during case study application; and (4) 'Constraints & Limitations' found during current methodology development and application. On considering the overall research aims and objectives, a successful research achievement (shown as blue arrows in figure 8.1) should tend to 'expand' the top sections but 'compress' the sections at the bottom. Presented in this way, reflections on the main research work carried out in chapters 5 to 7 are summarised into figure 8.2, which gives an explicit description and summary. Figure 8.2 graphically reflects on the main research work and the relative benefits observed in respect of the three main existing modelling approaches CIMOSA, CLM, SM, when used individually and in combination as part of the newly developed R-BMM.

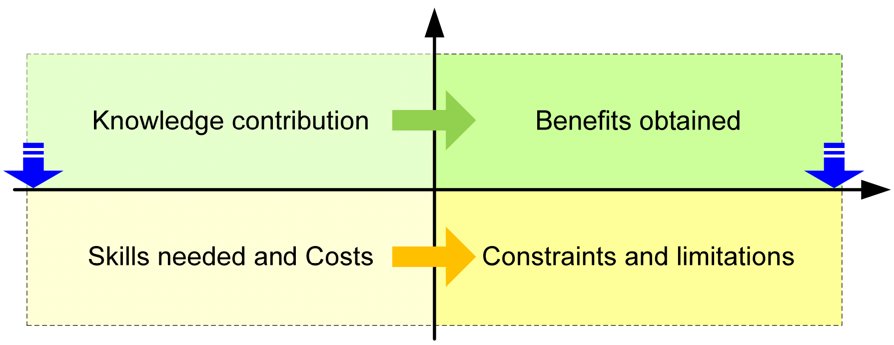


Figure 8.1. Research reflection format

Enterprise Modelling (CIMOSA and RPM)

- Systematic decomposition and explicit modelling approach;
- Process control logic improved;
- Method to classify process types provided.

Role Based Modelling Methodology (R-BMM)

- Role concepts identified in manufacturing system domains;
- Role concepts overlaid onto process segments;
- Modelling methods to specify competencies from requirement and possessed aspects.
- Method to assign resource system elements to specified roles;
- EM entities link to CLM and simulation modelling.

Causal Loop diagram Modelling (CLM)

- Graphical dynamic method of analysing causal effects relationship, especially among R-BMM entities (Roles – Competencies – Role holders);
- Guidance method for the design of simulation model experiments

Simulation modelling via using PlantSimulation© (SM)

- Systematic approach to SM design and experimentation;
- Quantified simulation of behaviour of modelled entities (e.g. role holders) ;
- Quantified behavioural prediction of alternative manufacturing system configuration

B1

- Support provided to determine the level of modelling detail required;
- Facilitate definition of manufacturing system segment structures, process sequences and resource information needs;
- Enable locations of value adding processes and give focus for improvement.

B2

- Explicit organisation decomposition into a network of roles;
- Human and technical resource system can be flexibly configured by optional competency specifications.
- Application of R-BMM provide basis for the lifecycle engineering of manufacturing system.

B3

- CLM allows qualitative inter-connection between the requirements and solutions;
- Change dynamics helps design potential resource system improvement options;
- Improvement options lead to better experimental design and simulation models.

B4

- Enabled quantitative behaviour simulation of modelled manufacturing system;
- Helps contrast alternative people and machine resource system configuration;
- Helps design improvement options to support decision making.

Skills needed

- Intensive knowledge of enterprise organisation required;
- General and intensive process oriented modelling skills needed;
- Large amount of case study company data required;
- Data modelling (to capture, store and process multiple type of data for modelling);
- Graphic modelling software;
- Concern to model both human and machines.
- Computer programming ability during simulation modelling

Main costs during application

- Time consumed – Repetitive data collection; model diagram building; model delivery; verification, correction and rework;
- Case study company personnel and resource support and collaboration;
- Software purchasing, training and licensing.

1) Data acquisition

- Required data collection is time consuming;
- There may be lack of complete and equivalent data available to support case study;
- No standard data collection template was made available;

2) Model building & analysis

- Manual modelling is very time consuming as there is a lack of software based model set building and execution;
- R-BMM does not model all reality (e.g. psychology, culture); but develops fit for purpose of modelling
- No formal approach for model verification incorporated into R-BMM;

3) Knowledge re-usability

- R-BMM is probably wide applicable but the models may not be
- Limited application testing

Figure 8.2. Research Reflection Summary

8.1.1 Reflection Discussion

The methodology developed added knowledge into the academic field. Particularly it was shown to enable the unified use of pre-existing modelling technologies; such that when they were deployed in an integrated fashion they delivered additional modelling capabilities relative to their singular use. The advantages realised via the methodology included: explicit and consistent use of modelling decompositions, means of explicitly specifying competencies, a way of diagramming and qualifying dynamic causal effects, which together with the formal decomposition and competency specification capabilities, provided a systematic method of designing simulation experiments and related scenarios that occur in complex and changing production systems. Essentially the methodology was shown to provide a new means of creating discrete event, computer executable models of real production situations, such that those situations can be made characteristic of the business environment in which they currently operate or in the future might need to operate in.

As a consequence the benefits listed in the right top segment of figure 8.2 were delivered into a specific real case manufacturing company. Here knowledge held by various company personnel, about the many processes, resources and work flows through the enterprise could now be marshalled and targeted at a specific case situation of importance to the company, such that system modelling and developmental design could be accomplished with realistic parameter inputs and parameter changes. Also the analysis afforded could be done at a level of detail which was useful and yet was practically achievable, i.e. was not overly complex from a modelling point of view.

However it was observed that some general and specific skills are needed for methodology development and its later application in any specific case study ME, which involves academic, managerial and technical abilities. Indeed the present author experienced some key issues that need to be understood and addressed to enable effective use of the methodology and the need to improve future case studies and applications. Any lack of skill in respect to any specific aspects, was seen to be important as it would result in large amounts of time and effort being spent to grasp those skills and to work effectively to deliver the modelling outcomes required. However it was observed that a skills analysis, and a related analysis of the effects of given skills, could only be partially carried out during this study. A complication here is that the author was not only trying to conceive and develop a new approach to doing something difficult but was also trying to test the new approach being developed, so as to deliver useful results for some would be customers in the enterprise being modelled.

Because of the different skills sets needed it is envisaged that there should be at least three types of stereo-typical actor involved here, namely: the researcher creating the new approach; the modeller doing the modelling for the case company; and the customer of the models with probable responsibility for finding a solution to some business, design/engineering, management or planning problems. The author felt able to reflect knowledgably on the researcher perspective by considering the time and cost involved in methodology development. He found he could also make a useful assessment of costs and time which would likely be consumed from the modeller viewpoint but could only make an educated guess about the customer perspective, especially as customers can have many roles (which is the case because of the potential power of the developed methodology as it can support customers performing a wide variety of roles).

8.1.2 Costs Trail in the Case Study

Acted as ‘researcher’ and ‘modeller’, the present author spent the following periods of time on research and project work:

1) 1 month to learn about Enterprise Modelling and become proficient with using its concepts.
2) 1 month to learn about DES Simulation Modelling and become a proficient simulation modeller.
3) 6 months to gain an understanding of the state of art in the application of modelling technologies in support of manufacturing systems engineering.
4) 9 months to iteratively conceive, develop and document the R-BMM.
5) 3 months to build, verify, then develop the EM of the case company.
6) 4 months of iterative case study simulation modelling, experimental design, specifying company data needs and developing data input method into models during experiments, and results generation.
7) 2 months of reflecting on, documenting and reporting results.

Through discussion with case study personnel it was also estimated that as customers of the models created during this study they spent the following periods of time as follows:

a) 0.5 month specifying the problem in a form suitable to the modeller.
b) 1.5 months aggregating existing historical data and measuring new data needed by the modeller.
c) 1 month validating models & model behaviours, and interpreting results generated by the modeller.

Also observed was that the PlantSimulation© software itself cost:

S) £4000 to purchase with a new annual licence renewal cost of £2250.

From the foregoing estimates, related project costs were categorized and estimated as follows:

Modelling facility creation cost: (which would be available also to analyse other similar problems)

1) + 2) + 3) + 4) = 17 person months = (estimated at £80 K)

+ S) = £4000 + £2250 (assuming software used full time for this purpose)

Sub-Total £86,250 --------- C1

Modeller costs of specific production system modelling work reported in the thesis:

5) + 6) + 7) = 9 person months = (estimated at £42 K) --------- C2

Customer Costs in respect of specific production system modelling work reported in the thesis:

a) + b) + c) = 3 person months = (estimated at £14 K) --------- C3

Hence *Total Modelling Cost* of all case study project work: C1+C2+C3 = £142K

The author understood the total modelling cost (of £142K) should be compared with the cost of any alternative way of achieving the same outcomes, i.e. improvements to the case study assembly systems of a similar scale. For the case study problem, the author knew of only two possible alternative methods; namely (1) by use of a very experienced and competent production engineer, possibly working in conjunction with an experienced production planner or (2) by a modeller, advised by the customer, using Discrete Event Simulation modelling on its own. However it is questionable whether either of these methods could have generated the same insights into the problem. It was also seen deciding whether this cost would be an effective one depends upon many factors, the benefits of the modelling outcomes need to be assessed, this was very difficult to do in this case.

8.2 REUSABILITY TEST OF THE NEW METHODOLOGY

Bearing in mind the aforementioned research reflections, The present author convinced an extended application of the methodology is necessary. This section reported such an application by means of "Scoping Exercise". This scoping exercise was conceived to have three main purposes, namely (1) to illustrate that the concepts incorporated into the R-BMM are not specific to single case study only, but are more generally applicable; (2) to test the methodology in respect of a significantly wider scope production system (so as to investigate possible scalability problems); (3) to illustrate that the benefits claimed in the reflection on the previous case study by deploying R-BMM can also be achieved in different applications. This scoping exercise was also planned to lead a study into a comparative illustration of the use of the R-BMM, the structured approach to integrating use of EM, CLM and SM, relative to their singular use, as well as other state of the art modelling approaches.

Due to constraints on time and sufficient data availability, FFL remained as the case study company. However FFL also wanted to further test the methodology in their organisation; by re-using R-BMM on larger scale and wider scope covering whole production and support sectors in the company, to achieve potential extra benefits. The expected benefits include decreasing modelling efforts and costs – if they involve as modeller; and predicting the potential to improve overall production system performance (i.e. to achieve more output with less resource).

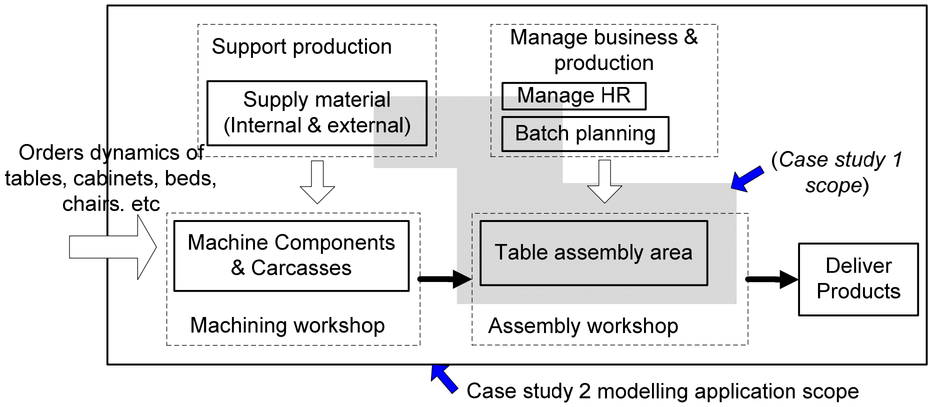


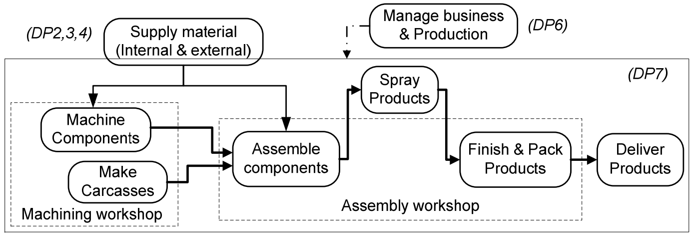
Figure 8.3. General modelling scope of the scoping exercise

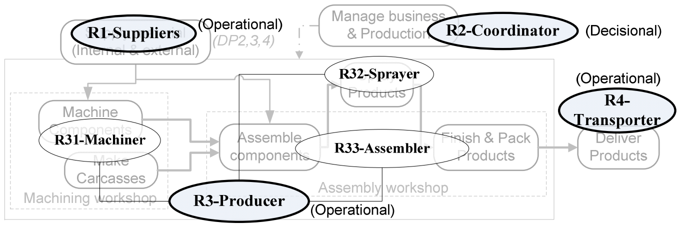
Figure 8.3 interprets ground work thinking of the aims and purpose of the scoping exercise. It gives an overall picture of the whole FFL manufacturing and its support system. It also indicates the difference of modelling scope and scale of the two case studies. The grey area was the scope of first case studied and modelled, which only covered the process in the table assembly area of assembly shop and some support entities, and only modelled a limited type of table assembly work. Comparatively in this exercise the scope expanded to the whole manufacturing system, and covering multi-type product families, i.e. tables, cabinets, beds, chairs etc.

Bearing in mind the purposes, by following each stage of R-BMM listed in left column of Table 8.1, the main modelling work carried out within the case study 2 by the author is summarised in the middle column. In the right hand side column, the included diagrams and tables illustrate in outline how the stages of the R-BMM were followed. The integrated deployment of R-BMM approach displayed in Table 8.1 can be read by following aspects:

- The abstract activity diagram F8.3-1 defines the process oriented structure of the manufacturing system under study, refer to benefit B1 in Figure 8.2;
- Diagrams and tables created during ST1 to ST4 generated a new organisational decomposition of the FFL enterprise in the form of a network of roles, which was naturally linked to a new graphical, enterprise wide conceptual model of the FFL resource system configuration. The modelling work outputs in these stages collectively realised the benefits B2 stated in Figure 8.2.
- Simulation modelling during ST 5 to ST7 cover the complete cycle from model design, verify, date input, execution, results analysis and update. Different organisation structures and production resource system configurations can be tested to compare how they would impact overall on system behaviour and performance of the FFL enterprise, so as to verify the realisation of potential benefits B3 & B4 shown in Figure 8.2

Table 8.1 FFL the scoping exercise summary

<table>
<tr><th colspan="3">Phases & Stages</th><th>Modelling work description</th><th>Modelling method application illustration</th></tr>
<tr><td colspan="3">Stage 0</td><td>Abstract activity diagram developed which covered DP 7, 2, 3, 4 and 6), i.e. the complete production chain of the FFL enterprise, shown as F8.3-1.</td><td>

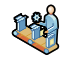
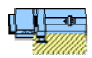
F8.3-1</td></tr>
<tr><td>ST 1</td><td rowspan="2">Requirements Capture</td><td></td><td>Four abstract roles identified in F8.3-2, overlaid with F8.3-1; Role dependencies specified</td><td>

F8.3-2
Role dependencies
R1 & R2 both are supportive to R3
R3 is supervisory to R31,R32, R33
R3 & R4 are sequential;
R31, R32 & R33 are partly parallel</td></tr>
<tr><td>ST 2</td><td></td><td>Competency required by roles to fulfil operational, supportive and managerial tasks.
Competencies are specified via a qualitative description. (Illustrated in the table)</td><td>
<table>
<tr><th>Role</th><th>Illustration of competencies required by identified roles</th></tr>
<tr><td>R1-Suppliers</td><td>Process requirements; prepare and deliver right raw material, components and tools</td></tr>
<tr><td>R2-Coordinator</td><td>Enable business planning; Enable process orders and release picking lists;
Enable provide financial support to main production work</td></tr>
<tr><td>R3-Producer</td><td>Enable production planning and scheduling;
Enable balancing of incoming production tasks;
Enable balancing of resource distribution according to production schedule;
Enable organise and implement products realisation with customisation and good quality</td></tr>
<tr><td>R31-Machiner</td><td>Enable identify different parts and components and complete machining work as required</td></tr>
<tr><td>R32-Sprayer</td><td>Enable identification of different parts and components, complete spray work as required;
balance oven usage with mixed products</td></tr>
<tr><td>R33-Assembler</td><td>Enable assemble & finish part, component and sub-product into final products as required</td></tr>
<tr><td>R4-Transporter</td><td>Enable identify, allocate, transport and deliver all complete products to customers</td></tr>
</table></td></tr>
</table>

ST 3 — Conceptual Design

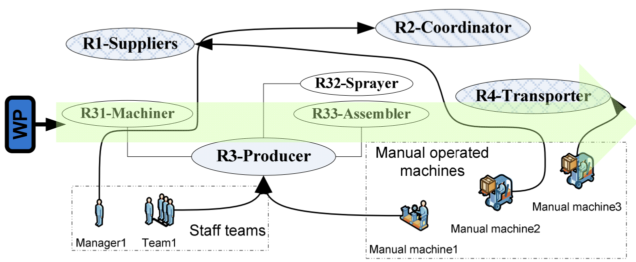
- Examples of human and technical resource system are listed.
- Multiple resource types, are grouped and organised differently, thereby they provide different aggregated competencies

Optional resource type – Resource pools examples

Production teams (Sanders, cabinet door makers etc.)		Manual operated machines (Legs machining station; driller etc.)	
Automatic Machines (CNC shaper; Painting oven, etc.)		Jigs, fixtures and support tools	

ST 4 — Conceptual Design

- Design a production scenario
- Select a resource system configuration and assign them to allocated role network

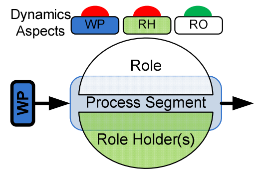


F8.3-3

- Assumed low volume but high product variation demand as incoming work pattern.
- Candidate role holders from members of 'Production teams' and 'Manually operated machines' as selected and assigned to roles.

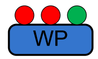
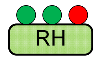
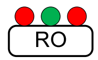
ST 5 & ST 6 & ST 7 — Detailed Design, Deployment Simulation and Improvement

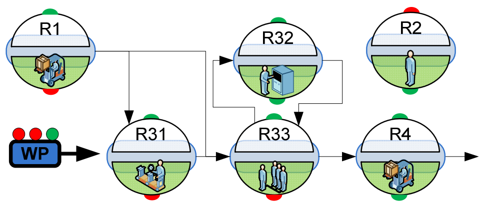
- Covered simulation steps of: Conceptual design, Programming design, Design verification, Experimental design, Data input, model execution, result analysis and their update cycle.
- Experimental design was configured from component type W-R-R unit as F8.3-4, illustrated in the table; scenario design can be some combination of all aspects and their instances.
- Simulation models were built and behaviours analysed. The resource system shown in F8.3-3 can be flexibly deployed, such as with options F8.3-5A or F8.3-5B, in response to change in dynamics at different period of time.



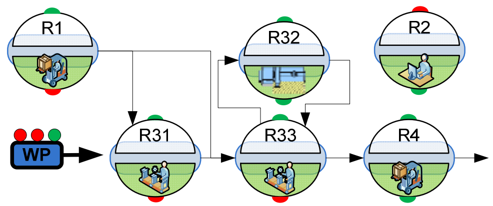
F8.3-4

- Three main dynamic aspects, each can have multiple dynamics states;
- Red highlight means dynamics applicable to that aspect, while green means not applicable.

Aspects	Dynamic instance description
	PD – among multiple product types or multiple products families VD – within same product type. MD – the mix of above two.
	Dynamics of resource amount Dynamics of unit resource productivity Dynamics of resource organisation structure
	Dynamics of role coverage; Dynamics of competency required by role; Dynamics of roles dependency.



F8.3-5A High flexible/low workload resource system



F8.3-5B High automated/high workload resource system

The author considered ways of quantifying benefits of applying the R-BMM approach in the two FFL case studies. However this was very difficult to do in any convincing way, especially as it had proven impossible to only fully develop one single case study which had a somewhat limited scope. It was felt that this might become feasible if the scoping exercise had been expanded to enable an evaluation of benefits in the overall production shops of the case company. From the scoping exercise it was evident that the approach might be used many times to maintain or improve the company performance as its trading conditions changed and significantly reduce the modelling time and efforts in re-use. This was seen to provide another possible reason why the approach could prove fruitful, as the development i.e. Modelling facility creation costs (circa £86K) in previous case study might be spread over a number of projects. For example by ongoing R-BMM modelling the cost of labour in the complete enterprise might be reduced by 15%. As therefore as the case company employs 45 shop floor workers, on the shop floor alone this could equate to a person saving of 6.75 times £30 K per annum = circa 202K per annum, hence it may have proven possible to have a good payback on the investment made.

Further opportunities were envisaged in that the R-BMM could have applications in many manufacturing companies of different sizes and in different industries, which would give rise to economies of scope of modelling application by spreading the development costs. In such cases different optional developments may also become possible, such as employing the modeller near full time (possibly as an industry consultant), or to develop the R-BMM and specific case models into a decision support tool. For some companies use of the R-BMM could lead to significant competitive advantage, so that a relatively short payback period might be achieved on the investment made in modelling production systems. This might particularly be the case for large MEs who are known to employ corporate modellers. For small companies alternative options might in the future to be to engage modelling consultants who have access to R-BMM ideas and techniques. Longer term it might also be appropriate for software vendors like Dassault or Technomatics to implement R-BMM and to package them as production planning and process improvement tools.

A causal loop model of impacts arising from the development of R-BMM was created and is shown in Figure 8.4. This illustrates how this knowledge contribution, and its consequent methodology application, needed skills, incurred costs and expected benefits can be linked and reviewed. Indeed figure 8.4 provides a CLM based means of summarizing impacts of different aspects of the case studiey and the foregoing reflection on them. An outcome from the overall loop can be to continuously develop and refine the new knowledge, then to test and verify that knowledge by applying it into more industrial cases. This would likely achieve more benefits and profits in return; while at the same time would address surmountable difficulties that constrain modelling outcomes and reduce skill requirements and incurred costs.

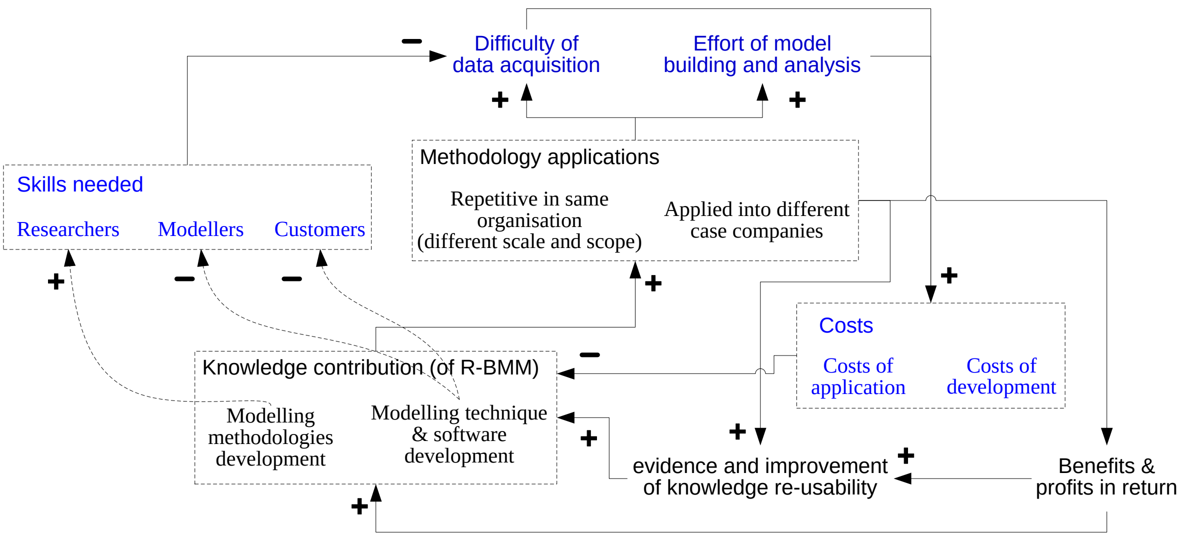


Figure 8.4. Inter-relationship impact of R-BMM and its application

8.3 RESEARCH DEVELOPMENT

When considering how to continue and sustain this research, the summary of constraints and limitations outlined in Section 8.1 were considered as guidance. Attention was focused on ways of further developing the modelling methodology conceived and developed during this study and to consider how to better integrate this methodology with other production systems engineering methods and concepts under development.

8.3.1 Role Categories to Support Role Identification

To enable detailed modelling and to ensure data availability, the first case study concentrated on a limited production system segment, in that the roles considered were restricted to operational types. However a broader application of the methodology in manufacturing industry would need to cover significant differences regarding role types. The author envisaged the future need for a role identification stage; during which the modeller can reference different role categories previously defined to achieve improved conceptual support and better systemisation of needed modelling activities. On reviewing typical process oriented requirements of manufacturing enterprises known to the author and his colleagues, the following role categories were defined within the groupings: interpersonal, decisional, informational and operational, as shown in figure 8.5. Within the four different role types only a few possible role examples are listed. Characteristic descriptions of these different roles in complex MEs are needed to populate these different categories. The author believes that this kind of classification of process-oriented requirements would facilitate the modeller during enterprise modelling phase (section 5.4, chapter 5) and make the interpretation and re-use of models more consistent.

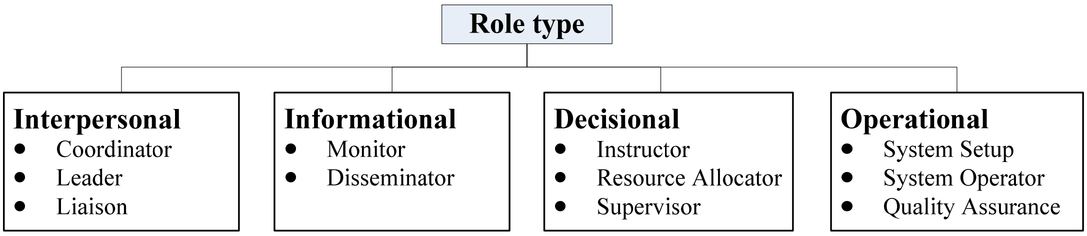


Figure 8.5. Proposed role type category and example roles

8.3.2 Improved Modelling of Resource Components- Role holder link to DPU concepts

The present author and his colleagues in the MSI Research Institute initiated the concept and subsequent development of so called Dynamic Producer Unit (DPU) modelling concepts [Ding 2007; Rahimifard 2007; Weston 2008; Weston and Cui 2008]. In their work a DPU is described as being a 'configurable', 'reusable', 'change capable' resource component of a manufacturing enterprises. This study has considered how use of the DPU concept (as a concept for modelling any type of active resource unit, including people, machines or IT systems) can be integrated into the R-BMM to improve and extend its application in industry. Figure 8.6 illustrates explicitly how the author envisages that DPUs (which describe actual resource entities) can be selected (from optional DPU candidates) and structurally linked via (optional binding structures), then assigned as role holders within any designed production system.

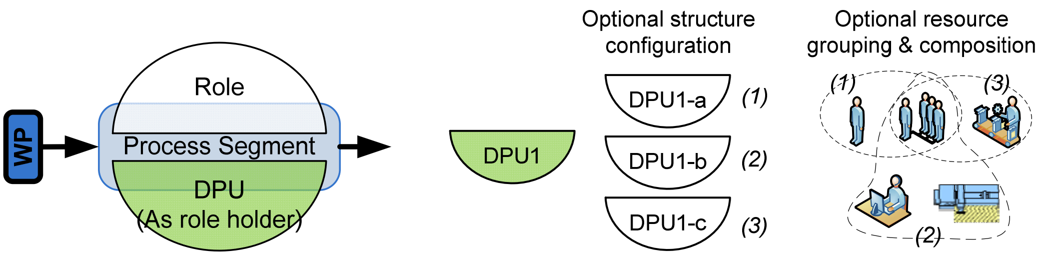


Figure 8.6. Conceiving of DPU combined use in R-BMM as role holder

One significant benefit of introducing DPU concepts into the R-BMM is that, from the conceptual design stage onwards, DPUs can explicitly be attributed with 'competencies possessed' and 'binding structures', using suitable computational capabilities. This is because DPU description and construction has been conceived as being capable of computational presentation in support of systematic system modelling. Those computational features can therefore be referenced and re-used as model parameters and variables, when various types of resource system are configured during both EM and SM. Here the aim has been to establish a computational basis for modelling unitary DPUs in relation to work streams. This is considered to be particularly important when dealing with multiple product work streams, because the value of resource system parameters will likely change. Table 8.2 presents a possible 'DPU description card' and its illustrative use.

Table 8.2 Terminology explained: an example DPU description card

DPU ID	DPU1-1	DPU name	Table sub-assembler
Work item(s) type	Pedestal; pedestal feet (DL tables) Legs (FT tables)		
Unit(s) of work	Sand pedestal + 4 feet; Assembly 1 pedestal with 4 feet (for DL tables) Sand 4 legs (for FT tables)		
Rate of processing	15 min pedestal sanding + 5 min each pedestal foot sanding; (DL tables) 8 min sanding for each leg as standard (for FT tables)		
Quantity of work required	1 pedestal and 4 pedestal feet(for DL tables); 4 legs (for FT tables)		
Achievable work rate	13 DL pedestal set sanding; (Daily, single shift) 15 FT legs sanding; (Daily, single shift)		

8.3.3 Computerised Model Building & Model Development

As indicated in the research reflection, as yet there is a lack of computerisation of the R-BMM. Future improvements to facilitate data collection and improve efficiency of model building, and to enhance knowledge re-use, are already under development. A computer tool which facilitates RPM's CIMOSA model building is under development by the present author and his research colleague [Wahid and Ding, 2008]. This tool development has been heavily dependant on generating an advanced understanding of Microsoft Visio© and the Visual Basic programming language, with its powerful visual functionality. It was used as the platform to produce a tool that enables computerised CIMOSA model construction and application.. When complete the tool is expected to enable positive growth behaviours in the causal loop of Figure 8.4, by possessing the following features:

- Embedded CIMOSA principles; into model entities which can be displayed and accessed by users to reveal detail;
- Efficient model building through a drag and drop interface with pre-defined constructs and associated 'attributes';
- Capture of the modellers decisions and process related measures. These can later be exported to generate required inputs to discrete event simulation packages.

The tool was designed based on the RPM's graphical modelling framework. Its model diagrams are constructed from a stencil, as illustrated by Figure 8.7, with formal attributes assigned to each modelling entity by realising the following modelling steps:

1. Populate diagram with information;
2. Populate diagram with constructs and attributes as per needs of the modelling level and its associated CIMOSA principles;
3. Create 'parent-child' links, as per the defined process decomposition;
4. Export to an HTML format for wider use and presentation.

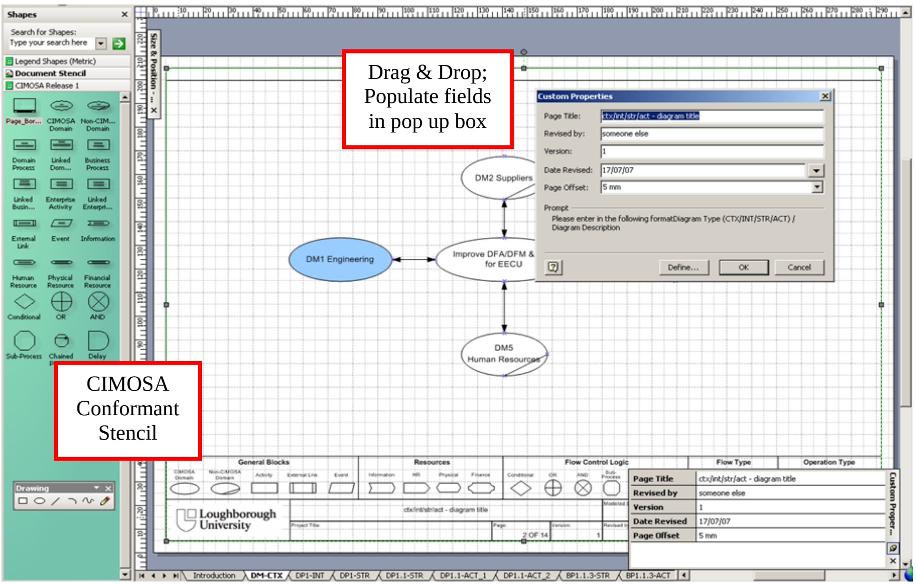


Figure 8.7. Computerised CIMOSA building tool snapshot (in developing)

CHAPTER 9

Research Conclusion and Further Development

This chapter concludes this overall research by considering the contributions made by the methodology development and detailed case study testing. Hence research novelty and contributions to knowledge are discussed in realised benefits during industry case application. The chapter also considers possible future potential research in general.

9.1 COMPLYING WITH THE RESEARCH DEVELOPMENT PLAN

The research conducted complied essentially to the plan shown as a backbone procedure in Figure 4.3.

1. Early in the research, concentration was on gaining a broad understanding of modelling techniques and manufacturing systems engineering requirements. This helped to define the research scope and focus from both academic and industrial perspectives.
2. The understanding was gained mainly from two sources, namely: the literature and numerous project practices. The main thrust of the literature review was to gain a state of the art understanding of what previous authors had achieved by modelling manufacturing systems and to understand the limitations they had uncovered.
3. The core methodology was developed based on research objective identification and plan design. Stepwise multiple modelling approaches deployment and development, by support of demonstrative and illustrative case data. The methodology was developed from initial partial contributions to a subsequent more integrated configuration. This phase took very significant time and efforts, and is the main body of whole research.
4. In addition to the stepwise methodology developed and applied on the case study, the results achieved were reflected upon, to seek and to assess the potential suitability of the methodology for broader application in different ME sectors.

9.2 MAIN PRACTICE APPROACHES IN CASE STUDIES

The main case study was carried out to facilitate methodology testing and methodology development. The chosen case company possessed manufacturing characteristics required to facilitate testing and development; in terms of manufacturing system characteristics complexity and change with respect to products and their needed processing structures and human resource systems. The two cases were studied with different scope and at a different level of abstraction. In this way it was judged that the two cases could provide credible examples of the modelling methodology deployment, evaluation, verification and review. The main outcomes from the two cases studies were as follows:

1. Through initial meetings and discussion with the case company's management team, the deployed modelling techniques and concepts allowed explicit knowledge capture about the case company in terms of its key production processes, variance in its product flows and its resourcing requirements at different abstraction levels.
2. From 1 it proved possible to systematically identify business problems in the company which could be addressed by coherently deploying a suitable set of modelling techniques.
3. Company case data was then collected on a step by step basis to detail and then model the focal area of company concern using static and dynamic modelling technologies. The models drill down from a top level focussed on strategic and business issues to a detailed production system section view which could support factual decision making.
4. The Enterprise, causal loop and simulation models created were then used to evaluate and analyse current production and performance levels in both qualitative and quantitative terms. Collectively the models developed graphically and numerically presented the case company as a value stream map with associated resource utilisation. The models produced were novel relative to other case study modelling work reported in the literature. Model results were fed back to the case company management team and were verified as an effective representation of reality.
5. Model outputs highlighted and analysed the current status of production system segments in the case study company. Potential optimisation and improvement solutions were then developed, simulated, discussed to predict outcomes of possible new future strategies for the case company.

9.3 MAIN OUTCOMES FROM THE MODELLING METHODOLOGY DEVELOPMENT

The three main modelling approaches namely (1) Extended Enterprise Modelling – based on RPM's CIMOSA diagrams, (2) Role Based Modelling and, (3) Dynamic & Simulation Modelling, were deployed in a new and integrated way. Also studied was a use of configurable resource unit systems (termed Dynamic Producer Units or DPUs) as a means of unifying the methodology development. Case study testing largely overlapped methodology development. The main modelling concept and methodology achievements are summarised in table 9.1. The methodology systemised the design and building of case study models, the use of which were tested in respect of different possible scenarios of application.

Table 9.1 Main concepts and methodology achievement

Research objectives and aims	Main concepts and methods achievement
Specify modelling concepts with a capability to represent requirement characteristics of people/technical resource system; and their association to ME processes	New concepts were developed to enhance requirements identification to the new modelling approach: • Role concept: functional objective to structured and bind together (company activities and organised groups of activities). • Competency concept: a capability attribute attached to roles, from both required and possessed view points. The former specifies the requirements to achieve identified roles, the latter supports resource system design and planning. • Role holder & DPU concept: used to decompose resource systems into configurable units, capable of carrying out dynamic work.
Specify systemic methods for capturing, reusing and updating models of characters of people and technical resource systems in terms related to the work they need to do.	• Development concentrated on Role based modelling as new modelling approach. This provided a way of integrating the use of the three modelling methodologies. (Namely EM, CLM and SM) into the coherent R-BMM approach. • Best capturing process-resource system characteristics. • The framework, structure and methodology was fleshed out to enable model reuse in support of (1)analysing different scenarios of one ME and to different MEs; (2) capturing current and enable update models to trace future status change.
Instrument the modelling concepts, framework, and the methods conceived, via a unified use of EM, CLM and SM techniques	• Developing the existing RPM approach to CIMOSA modelling, as the primary process-resource system information capturing tool from a requirement point of view. Improvements centred on: better classified process and resources, improved logic control attribution to activity networks. • Developed a unified role based modelling approach to analyse and represent EM process segments of concern, then to create R-BMM conformant competency specification and behaviour indicators to support resource system design. • Built CLMs and SMs (Plant Simulation) to quantify key aspects of system planning, testing and evaluation for different process-resource system configurations when subject to different dynamics.
Apply and test primary uses of the modelling approach, in complementary scenarios of work pattern change faced by typical MEs.	• First case study used as demonstration through new modelling approach development. The new concepts, methods and technique deployed to the case study focused on one detailed level production system segment. Both external and internal dynamic aspects impact elements of the production system segment applied and multiple system behaviour instances tested. • Scoping exercise used same company, but emphasised on different modelling abstraction level and scope. Main purpose was on the new modelling approach deployment to test methodology re-usability. Case study model work was more on descriptive and qualitative rather than detailed and quantitative modelling..

9.4 RESEARCH NOVELTY AND CONTRIBUTIONS TO KNOWLEDGE

The following were delivered as contributions to academic knowledge in the research field:

- A new perspective on role based modelling concepts was conceived and developed as part of this study. This sought to explicitly describe process oriented roles and structural relationship between those roles, as a formal decomposition of a process network, which itself is described by hierarchically and temporally ordered sets of activity relationships. Key to this idea is that the ordered sets of activities have previously been defined by using an EM approach to elicit ME knowledge from various ME knowledge holders.
- The new role modelling concepts were further developed with a view to explicitly defining ‘competencies’ and ‘capabilities’ that can be associated with roles in two complementary respects. One respect was conceived to explicitly define ‘role requirements’: in terms of ‘needed competencies and capacities’ to fulfil that role. The second respect was to explicitly characterise the ‘competencies and capabilities’ that potential role holders possessed and could bring to bear on roles, should they be selected and assigned to a role (and its given set of role requirements).
- The contribution made by separating ‘role requirements’ and ‘role holder’ explicit definitions were two fold. (1) If allowed a ‘clean separation’ was to be maintained between ‘ME processing requirements’ and ‘candidate ME resource system solution designs’; so as to conform with well proven general systems engineering practice. (2) It allowed consistent abstract representation of both ‘human’ and ‘technical (machine and IT System) resource systems’; so that the R-BMM can be applied to design a spectrum of system types ranging from manual, through semi-automated to fully automated resource systems.
- The role based modelling ideas developed in this thesis, and particularly the ideas related to explicitly defining role holder requirements later led the author’s research colleagues in MSI to develop and deploy DPU concepts (Weston et al 2008) as a coherent means of formally representing ‘resource system components’.
- A series of new methodologies were conceived and developed to utilise and integrate the deployment of the multi-modelling approach. This covered both static and dynamic modelling from both structural process design and behavioural resource system modelling aspects. As part of these developments:.
    - Process classification was used to enhance the current EM method; so as to identify processes in terms of contribution to value addition.
    - Control logic nodes were developed so that each node type can be further customised or configured to improve the EM’s ability to explicitly represent complex activity flows.
    - Role identification made role based modelling create a coherent link from EM; and configuration methods provided role modelling beyond current describing responsibility constraint, expanded to evaluate resource capability, thus connected requirements with

solutions. In addition, the method generated criterion to compare and measure resource system with their capacity.

- Role holder and resource pool construction and late DPU concept link has become a new thinking to integrate process modelling into a reference framework that covers static modelling, role related modelling and dynamic modelling. Content in the framework unified the capture of multi-modelling information, utilise and re-use them during multiple models formation.
- Capability and feasibility assessment are key indicators to new modelling concepts and methodology. The multiple modelling approach was tested in respect of two industrial case studies involving different production system types and scenarios. Through creation, analysis and assessment of set models using the new approach, the concepts and methodology has improved the academic establishment of reconfigurable and flexible ME production system design and improvement.

9.5 WEAKNESS OF CURRENT RESEARCH PROGRESS

Certain weaknesses related to the methodology development and deployment thus far, were observed. To state them could direct future research effort and guide ongoing research improvement.

9.5.1 Methodology Weaknesses Observed.

When deploying the methodology developed so far, each dataset created and used for the three main modelling approaches (i.e. EM, CLM and SM) are largely separated and utilise their own documentation type. Therefore currently there is a lack of a means of defining a standard model data format. A consequence of this is significant duplication of effort in model formation work and potential lack of model format consistency. As the modelling approach was a new conceptual development, most of data sharing and re-use in this research was based on manual transfer and duplication, which inevitably extended the time and effort involved in combined multiple modelling approach deployment. Currently only the simulation modelling aspects of the R-BMM were well supported via computer software support, which made the simulation models fully computer executable. The other modelling techniques used were only paper based.

9.5.2 Constraints on Methodology Implementation in the Case Study Work

Current MEs and their production systems are very complex and are subjected to ongoing change. So to understand, model and analyse process and resource systems with a close enough approximation to reality will involve very significant time and effort. Especially time consuming and complex is simulation model building and execution. This needs detailed study and significant data support to model close enough to reality. Implicitly therefore the case studies models and their deployment was only a partial test of the new modelling approach. A number of assumptions and model scenario simplifications needed to be made during model structuring and data input. They were considered to maintain an acceptable reality level, but they and the chosen level of modelling abstraction all impact on the performance of the model. Only one case company was chosen and only two cases were studied and modelled. Therefore it may be argued they do not sufficiently benchmark broad ME industry sectors and their variable production characteristics. Also the second case involved only conceptual modelling and did not involved complete quantitative simulation modelling. Nonetheless within the constraints of a simple PhD study the author believes that useful groundwork research has been done which can potentially lead to a step change in industry practice within engineering production systems.

9.6 FUTURE RESEARCH DEVELOPMENT

From the above summary of research achievements and weaknesses, there is some further work under development and suggested by the present author. To classify these would help to keep the sustainable ability to relevant research progress. Compared with the more specific further research work proposed in last chapter, here the further work is discussed in more generic terms.

9.6.1 Develop Better Computerised Model Building Environment

As discussed previously a much improved model building environment is required which will save significant time and effort when life cycle engineering ME systems. Based on case study findings the author believes that such a computerised development can realise improvements in the following respects:

- Visual and semantic static system structure representation – This aspect is required mainly for model documentation purposes and could be realised via enhanced Enterprise Modelling. Graphical models have proven to be effective in presenting complex ME system structures. This aspect might best be supported by some software tools possibly using a graphical interface such as Visio.
- Explicit and flexible support for data capture, storage and re-use – This aspect is concerned with how to best gather, store and categorise captured data, so as to efficiently facilitate reuse and sharing among different modelling stages. This aspect can probably be improved by using a database software tool. Collected data can be saved in a third party database tool using a standard compatible format, such as an MS excel work sheet(.xls; .mdb; .dbf), text file type data (.csv; .txt) and website executable language data(.xml; .html), etc. However such a candidate database tool will need extra customised design to achieve the required functions.

- Computer executable simulation model building. Compared with the required software support to the first bullet point aspect, this aspect is required to deal with more dynamic model generation. Hence data stored in a database needs to be efficiently invoked and input into simulation models, to support utilise semi-automatic and rapid simulation modelling building based on a consistent format. Plant Simulation® simulation model in this research has been proved a good tool in this aspect. However further improved utilisation of other alternative software tools may prove fruitful.
- Quantitative model analysis – after simulation models have been built they require efficient execution in support of life cycle engineering experimentation. Experimental results need to be quantified to enable design analysis of complex production systems; from their current status (As-Is) to alternative predicted future states (To-Be); so that production system design, implementation and improvement can be achieved.

9.6.2 Wider Industrial Application

The foregoing analyses of research achievement indicated that the new modelling approach needs to be deployed into a broader range of industrial applications, in order to:

(1) verify the suitability and effectiveness of the modelling principles, in terms of their capitalization to enable: data collection, models building efficiency, modelling results outputs observation, ongoing testing, requiring model reuse. and

(2) to realise significantly improved production systems design and operations and significant savings in time and cost in support of all life-phases of production systems use in different industry sectors.

Figure 9.1 presents conceptually how such a new modelling approach might support manufacturing enterprise management and operation application into a company and could be organised into multiple levels as indicated in the diagram. Work could start from a level which best reflects any given company's overall project aims. Such a start point for modelling is indicated in the diagram as the blue split arrow, on the right hand side. Each level corresponds to different main objectives, along with relevant responsible person needs to support the required engineering activities. Also listed are key modelling entities relevant to these levels. Modelling implementation goes deeper along with company involvement and support, on each level modelling work of jointly associated with modelling information and company practice information which should be shared and exchanged for best project efficiency. Results and analysis from lower levels can be linked and feedback to higher levels.

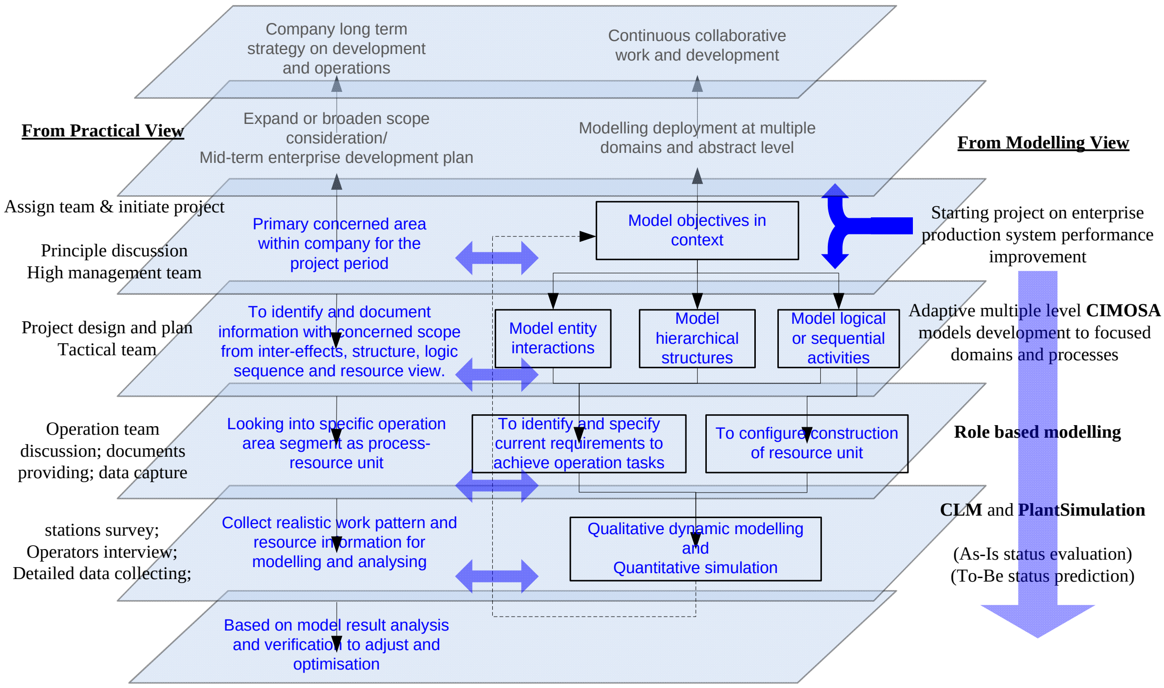


Figure 9.1 Enhanced modelling approach for future industrial application

Reference

Aburub F., Odeh M., Beeson I, (2007), 'Modelling non-functional requirements of business processes', *Information and Software Technology*, in press

Aguair M.W.C., and Weston R.H., (1995), 'A model-driven approach to enterprise integration', *International Journal of Computer Integrated Manufactruring, 8(3)*, pp2235-2245

Ajaefobi, J.O., (2004), Human Systems Modelling in Support of Enhanced Process Realisation, PhD Thesis, Loughborough University, UK.

Ajaefobi, J.O. and Weston, R.H., (2005), "Modelling Human Systems in Support of Process Engineering", Proceedings of the International Conference On Human Aspects in Production Management , Karlsruhe, Germany, pp3 - 16

Ajaefobi, J.O.and Weston.R.H., (2006), "Human systems engineering instrumented by modelling techniques", *INCOM'2006 - 12th IFAC Symposium on Information Control Problems in Manufacturing*, Saint Etienne, France

Ajaefobi J.O., Weston R.H.,Chatha K.A., (2006), "Predicting the performance of candidate human systems within specific work contexts", *International Journal of Computer Integrated Manufacturing,* 19:7,651 — 662

AMICE, (1993), "CIMOSA: open system architecture for CIM", Springer

Axlerod, R. (1997). 'The complexity of cooperation.' Princeton, NJ: Princeton University Press

Ashfort, B.E.,(2000). Role Transition in Organisational Life: An Identity Based Perspective, Lawrence Erlbaum Associates, Mahwah N.J.

Ashkenas R et al., (1995), The Boundaryless organization: breaking the chains of organizational structure. San Francisco: Jossey-Bass Publishers, 1995.

Bahill A.T., **Dean, F.F.**, (1999), 'Discovering system requirements', in **Sage A.P**. and **Rouse W.B.** (Eds), *Handbook of Systems Engineering*, John Wiley & Sons, 175-220

Bahill, A.T. and Gissing, B., (1998), 'Re-evaluating systems engineering concepts using systems thinking'. *IEEE Transactions on Systems, Man and Cybernetics,* Part C: Applications and Reviews, Volume 28, Number 4, pp. 516-527.

Ball P.,(1996), 'Introduction to Discrete Event Simulation', University of Strathclyde

Banathy B.H., (1996), 'Designing Social Systems in a Changing World: Contemporary Systems Thinking', Springer

Banks J., Carson J.S., Nelson B.L., (1996), Discrete-Event System Simulation, Prentice-Hall, Upper Saddle River, NJ

Barad M., (1992), 'mpact of some flexibility factors in FMSs— a performance evaluation approach', *International Journal of Production Research 30 (11),* 2587–2602

Barber M.I., Weston, R.H., (1997), 'Scoping Study on Business Process Reengineering: Towards Successful IT Application', *International. Journal of Production Research*.

Bar-Yam Y, (1996), "Dynamics of Complex Systems", Addison-Wesley

BCSSE, (2007), Human-System Integration in the System Development Process: A New Look, National Academic Press, US

Benjaafar S., (1994), 'Models for performance evaluation of flexibility in manufacturing systems', *International Journal of Production Research 32 (6),* 1383–1402.

Bennis, W. (1996), *Changing Organisations,* New York: McGraw Hill.

Bernus P., Nemes L., Edited By (1996), 'Modelling and Methodologies for Enterprise Integration', Chapman and Hall, London, ISBN: 0 412 756307

Bernus, Peter (2003), Organisation Design, Handbook On Enterprise Architecture, Bernus et al (Editors), pp 574-594, Springer-Verlag, Berlin.

Bernus,P., Nemes.L., (1997), 'The Contribution of the Generalised Enterprise Reference Architecture to Consensus in the Area of Enterprise Integration', Proc ICEIMT97, **Kosanke, K**., **Nell J**.(Eds) Springer Verlag, Berlin, pp. 175-189

Blackburn J., (1991), 'Time-Based Competition Business' One Irwin, Homewood, IL

Boccara N., (2004), "Modeling Complex Systems" , Springer Ltd.

Boer F.S.d., Bonsangue, Graf M, S. and de Roever W.-P., (2003), Formal Methods for Components and Objects, Springer- Verlag, Berlin

Bouchhima F., Nicolescu G., Aboulhamid M. and Abid M., (2005) Proceedings of the 16th International Workshop on Rapid System Prototyping (RSP'05) 1074-6005/05

Browne, J., Dubois D., Rathmill K., Sethi S. P. and Stecke K. E., (1984), 'Classification of flexible manufacturing systems'. *The FMS Magazine,* 2 (2), 114-117.

Bubler, C., (1996), 'Workflow management system as renterprise engineering tools, in *Modelling and Methodologies for Enterprise Integration*, by Bermus, P., 1996, Chapman & Hall, London, ISBN: 0-412-75630-7

Butlergroup, (1996), 'Management Guide – Workflow', [http://www.butlergroup.co.uk/subs/manguides/workflow/]

Byer, N.A.,(2003), Team Systems Engineering and The Role of Enterprise Modelling Technologies, PhD Thesis, Loughborough University, UK.

Caballero D., Molina A. and **Bauernhansl T. A.**, (2000), 'Methodology to evaluate enterprises to become members of virtual industry clusters', in **Camarinha L.M., Rabelo H.** (Eds.), *E-business and virtual enterprises: Managing business-to-business cooperation* (pp. 443–454). Dordrecht Kluwer Academic Publishers.

Capra, F. (1996) 'The web of life: a new scientific understanding of living systems' (1st Anchor Books ed). New York: Anchor Books. p. 30

Carrus, B.J. and Cochran, D.S., (1998), "Application of a design methodology for production systems." Proc. of EDA 98 Conf., July 1998, Maui, Hawaii. Chryssolouris, G. (1992). Manufacturing Systems: Theory and Practice. New York: Springer-Verlag.

Cattell, R.B.,(1957), Personality and Motivation: Structure and Measurement, World Book, N.Y.

Cellier, François E.,(1991), Continuous System Modelling, Springer-Verlag, New York, New York

Chatha K.A., (2003), 'Multi-process Modelling Approach to Complex Organisation Design', PhD thesis, Loughborough University

Chatha, K.A., Weston, R.H. and Pourtafreshi Monfared, R., (2003), 'An Approach to Modelling Dependencies Linking Engineering Processes', Proceedings of the *Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture* , 217 , 2003, pp 669-687

Chatha K. A. and Weston R. H., (2005), 'Combined Enterprise & Simulation Modelling in Support of Process Engineering', *Int. J of Computer Integrated Manufacturing*, Vol., 18 No. 8, pp 652-670.

Checkland P.,(1981), Systems Thinking, Systems Practice, Wiley

Cho Y. H. (1998) Role-based approach to business process simulation modelling and analysis

Choobineh F., (1988), "A framework for the design of cellular manufacturing systems", *International Journal of Production Research*, Vol 26, Issue 7, p1161 - 1172

CIMOSA Association, (1993), 'CIMOSA—Open System Architecture for CIM', *AMICE-ESPRIT consortium, 2nd Ed. Vol.1 1993, Springer-Verlag, Berlin*

CIMOSA Association, (1996), 'CIMOSA—Open System Architecture for CIM', *Technical Baseline, Version 3.2,* private publication

Cochran, D.S., (1994), "The design and control of manufacturing systems. PhD thesis. Auburn, AL: Auburn Univ.

Cochran, D.S., (1999). 'The production system design and deployment framework', SAE Technical Paper 1999-01-1644. Proc. of 1999 SAE Int'l Automotive Mfg. Conf., May 11-13, 1999, Detroit.

Colquhoun G.J., Baines R.W, Crossley R., (1993), 'A state of the art review of IDEFO', *Int. Journal of Computer Integrated Manufacturing*, 6 (4)

Computers industry engineering Vol.35. Nos 1-2, pp 343-346 Elsevier Science Ltd.

Consortium AMICE Eds., (1993), 'CIMOSA—Open Systems Architecture for CIM', 2nd revised and extended edition, Research Report, ESPRIT Project 688r5288, Springer Verlag,, ISBN 3-540-56256-7.

Consortium AMICE, **CIMOSA**, (1993), 'Open system architecture for CIM', Springer-Verlag, Berlin

Correa H. L., (1994), 'Linking Flexibility, Uncertainty and Variability in Manufacturing Systems', London: Avebury

Correa H.L., Slack, N., (1996), 'Framework to analyze flexibility and unplanned change in manufacturing systems', *Computer Integrated Manufacturing Systems* 9 (1), 57–64

Cox P.T. and Song B., (2001), A Formal Model for Component-Based Software, NSERC of Canada, Research Grant RGPIN124-99.

Coyle R.G. and Wolstenholme E.F.,(1981), 'Development of system dynamics as a rigorous procedure for system description'. Work paper, Bradford University System Dynamic Research Group**.**

Crainer, S.,(1996), 'That was the idea that was', *Management Today*, pp.38-41

Creswell, J. W. (1998). 'Qualitative inquiry and research design: Choosing among five traditions', Thousand Oaks, CA: SAGE Publications.

D'Souza D. F. and Wills A.C., (1997). *Objects, Components, And Frameworks with UML – the Catalysis Approach*, Addison-Wesley, Reading, Mass.

Daenzer F., Huber F.,(1985) Systems Engineering, Verlag Industrielle Organisation.

Davenport T.H., (1993), 'Process Innovation: Reengineering Work Through Information'

Davenport T.H., Short, J.E., (1990). 'The new industrial engineering: Information technology and business process redesign', *Sloan Management Review* 31 (4), 11–27.

Debn´ar R., Kuric I, (1998), "Simulation - Tool for Productivity and Profit Increasing". INFORWARE

De Meyer A., Nakane J., Miller J. and Ferdows K.,(1989), 'Flexibility: the next competitive battle', *Strategic Management Journal*, Vol. 10 No. 2, pp. 135-44.

Denzin, Norman K. and Yvonna S. Lincoln, (1994), "Handbook of Qualitative Research", Thousand Oaks, CA: Sage

De Toni A., Tonchia S., (1998), 'Manufacturing flexibility: a literature review', *International Journal of Production Research*, vol. 36, no. 6, 1587-1617

Detty R.B. and Yingling J.C., (2000), Quantifying benefits® of conversion to lean manufacturing with discrete event simulation: a case study, int. j. prod. res., vol. 38, no. 2, p429-445

Didic M, Neuscheler F, Bogdanowicz L, Klittich M, (1993), 'Mc-CIM: Execution of CIMOSA models', in: *Proceedings of the 9th CIM-Europe Annual Conference*, Amsterdam

Douglass B. P., (2000), *Components, states and interfaces, oh my!*, Software Development,

Doumeingts, G., Vallespir, B. Darracar, d. And **Roboam, M**.,(1987), 'Design Methodology for Advanced Manufacturing Systems,' Computers in Industry, Vol. 9, No. 4, pp. 271-296.

Doumeingts, G., Vallespir, B., Zanettin, M., and **Chen, D**.,(1992), GIM, GRAI INTEGRATED METHODOLOGY, A Methodology for Designing CIM Systems, Version 1.0, Unnumbered Report, LAP/GRAI, University Bordeaux 1, Bordeaux, France .

Drucker, P.F. (1988), "The coming of the new organization", *Harvard Business Review*, Vol. 66 No.1, pp.45-53.

Ericsson A. and Erixon G., (1999), 'Controlling Design Variants – Module Products Platforms', Society of Manufacturing Engineers, Michigan, USA, ISBN: 0-87263-514-7

Ferdows K. and Meyer, A.D., (1990), 'Lasting improvements in manufacturing performance: in search of a new theory', *Journal of Operations Management*, Vol. 9 No. 2, pp. 168-84.

Fine, C.H. and A.C. Hax, (1985); Manufacturing Strategy: A Methodology and an Illustration, Interfaces, 15, No. 6, pp. 28-46.

Fox M.S., Gruninger M., (1998**),** 'Enterprise Modelling', American Society of Artificial Intelligence, pp109-121

Franchini L., Caillaud E., Nguyen P., Lacoste G.,(1999), 'Planning and scheduling competences: towards a human resource management in manufacturing systems', *International Journal of Agile Manufacturing* 2 (2) pp247–260.

G. Schreiber, H. Akkermans et al., (1999), The Common KADS Methodology, MIT Press

Geller, H., (1994), *Position. Rolle. Situation. Zur Aktualisierung soziologischer Analyseinstrumente*, Opladen: Leske + Budrich

GERAM, (1999), Generalised Enterprise Reference Architecture and Methodology, Version 1.6.3 IFIP-IFAC Task Force

Giddens A., (1988), 'Die Konstitution der Gesellschaft. Grundzüge einer Theorie der Strukturierung', Frankurt/New York

Grobe-Rhode M. and Mann S., (2004), 'Model-based Development and Integration of Embedded Components: an Experience Report from an Industry Project', *FESCA 2004 Short Paper*

Gössler G. and Sifakis J., (2005), 'Composition for component-based modeling', *Science of Computer Programming* 55(23005) p161–183

Grover V. and Malhorta M.K, (1997), 'Business process reengineering: A tutorial on the concept, evolution, method, technology and application', *In Journal of Operations Management*, No.15.

Gruber, T. (1993), 'A Translation Approach to Portable Ontologies,' *Knowledge Acquisition 2*, p199-220.

Guerrero A, Darlington J, Weston R H, Case K, Harrison R, (2008), 'Development of a new learning methodology for discrete event simulation by reutilising previous software experience', *proceeding of the 6th International Conference on Manufacturing Research* (ICMR08)

Gupta D., (1993), 'On measurement and valuation of manufacturing flexibility', *International Journal of Production Research* 31 (12), 2947–2958

Halpin T., (1996), 'Business rules and Object-Role modeling', *Database Programming and Desig*n, vol. 9, no. 10, pp. 66-72.

Halpin T., (1998), 'Object-Role Modeling (ORM/NIAM)', *Handbook on Architectures of Information Systems*, Springer, Heidelberg

Hammer M., (1990). 'Reengineering work: Don't automate, obliterate', *Harvard Business Review* July/August, 104–112.

Hammer, M. (1996), Beyond Reengineering: How the Process-Centered Organization Is Changing Our Lives, HarperBusiness, New York, NY,

Hammer M., Champy J., (1993), 'Reengineering the corporation: A manifesto for business revolution', Harper Collins. New York.

Harrison R, West A.A., Weston R.H., Monfared R.P., (2001), 'DistributedEngineering of Manufacturing Machines'. Journal Engineering Manufacture, Part B2 pp215:217–31.

Harzallah M. Vernadat F.(2002), 'IT-based competency modelling and management: from theory to practice in enterprise engineering and operation', *Computer in Industry* 48 pp157-179

Harzallah M., Vernadat F., (1999), Human resource competency management in enterprise engineering, in: 14th IFAC World Congress of Information Control in Manufacturing, Beijing, China

Hayes R.H., Wheelwright S.C., (1984), 'Restoring Our Competitive Edge: Competing Through Manufacturing', Wiley, New York.

Hayes, N. (2002), Managing Teams: a strategy for success. Thomson Learning, London.

Hayes, R.H.,Wheelwright,S.C.,Clark, K., (1988), *Dynamic Manufacturing*, Free Press, New York, NY,

Hemosillo Worley J., Chatha K.A., Weston R.H., Aguirre O. and **Grabot B.**,(2005), 'Implementation and Optimisation of ERP Systems: A Better Integration of Processes, Roles, Knowledge and User Competences', *Computers in Industry*, 56(6), 620-638. Edited by B. Grabot and V. Botta-Genoulaz.

Hendrick H.W.,(1997), Organisational Design and Macro-ergonomics. In G. Salvendy (Ed.) *Handbook of Human Factors and Ergonomics* (New York: Wiley), pp595-637.

Hill, T. (1995); Manufacturing Strategy: Text and Cases, MacMillan, London

Hollingsworth D., (1995)**, '**The Workflow Reference Model', TC00-1003 - Issue 1.1, WfMC

Hollingsworth D., (2004), 'The Workflow Reference Model:10 Years On', WfMC

Hunt J.W., (1992), *Managing People at Work: a manager's guide to behaviour in organisations*, 3rd Edition, McGraw-Hill, London.

Hyun J., Ahn B.H., (1992), 'An unifying framework for manufacturing flexibility', *Manufacturing Review* 5 (4), 251–260.

ICAM, (1981), 'US airforce integrated computer computer aided manufacturing(ICAM) architecture' part IIVolume IV - Functional Modelling(IDEF0), Airforce material lab., Wright patterson AFB, Hoio 45433

Jablonski, S. and Bussler, C., (1996), 'Workflow Management: Modelling Concepts, Architecture and Implementation', International Thomson Computer Press, ISBN: 1-85032-222-8

Kateel G., Kamath M. and Pratee D., (1996), An overview of CIM Enterprise Modelling Methodologies, *Proceedings of the 1996 Winter Simulation Conference, p1000-1007*

Kathuria R., Partovi F.Y., (1999), 'Work force management practices for manufacturing flexibility', *Journal of Operations Management* 18 (1), 21–39

Katie Callan K., Sieimieniuch C., Sinclair M., (2006), 'A case study example of the role matrix technique', *International Journal of Project Management* 24 pp506–515

Katz R., Kahn R.L, (1966), The Social Psychology of Organizations, Wiley & Sons

Katz R.L. 'Business/enterprise modelling' In: *IBM Systems Journal*, Vol. 29, No.4, pp. 509-525

Khalil S N and Weston R H, (2008), 'Human system modeling in support of manufacturing engineering activities', *the proceeding of 6th International Conference on Manufacturing Research (ICMR08)*, Brunel University, UK

Klein M., (1996), 'Challenges and directions for EI: a distributed AI perspective', in *Modelling and Methodologies for Enterprise Integration*, Edited by **Bernus P.** & **Nemes L.**, Chapman & Hall, London, ISBN: 0-412-75630-7

Kiepuszewski B.,ter Hofstede A.H.M. , and van der Aalst W.M.P. (2003)
'Fundamentals of control flow in workflows', *Acta Informatica*,
39(3), p143-209

Kornwach K., Jacoby K., (1996), ‘Information. New questions to a multidisciplinary concept’,. Akademie Verlag, Berlin

Kosanke K., (1994), ‘Status of EP 7110 AMICE and CIMOSA evolution’, Technical Report

Kosanke K., (1997), ‘Comparison of Enterprise Modelling Methodoliges’, in *Information Infrastructure Systems for Manufacturing* Edited by **Goossenaerts J., Kimura F**, Chapman & Hall, London, ISBN: 0-412-75630-7

Kosturiak J., (1999), ‘Simulation in production system life cycle’ *Computers in Industry* 38 159–172

Kotsiopoulos I.L., (1996), ‘Objects and Environment in Dynamic CIMOSA Models’, in *Modelling and Methodologies for Enterprise Integration*, Edited by **Bernus P.** & **Nemes L.**, Chapman & Hall, London, ISBN: 0-412-75630-7

Kramer R.M., Tyler T.R., (1995), ‘Trust in Organizations: Frontiers of Theory and Research’. Berkeley, CA, Sage Publications IPA, Stuttgart

Krzepinski A, (1993), ‘Ein Beitrag zur methodischen Modellierung betrieblicher Informationsverarbeitungsprozesse’, Doctoral Thesis, University of Karlsruhe

Kueng P., (1997), "Workflow Management Systems – still few operational systems". *ACM SIGGROUP Bulletin*, Vol.18, No.3, pp32-34.

Lander E. and Liker J.K., (2007), "The Toyota Production System and art: making highly customized and creative products the Toyota way", *International Journal of Production Research, Vol. 45, No.16, p3681–3698*

Laszlo, E. (1996). 'The systems view of the world: A holistic vision for our time (Advances in systems theory, complexity, and the human sciences)'. Cresskill, NJ: Hampton Press.

Law M.A., Keaton W.D.,(1991) Simulation Modeling and Analysis, 2nd edition, McGraw-Hill

Lawrance P., (1997), ‘Workflow Handbook – 1997’, John Wiley & Sons Ltd, England, ISBN:0-471-96947-8

Leeuw A. D. and Volberda H. W., (1996), ‘On the concept of flexibility: a dual control perspective’, Omega, 24 (2), 121- 139.

Leymann F. and Roller D., (2000), ‘Production Workflow: Concepts and Techniques’, Prentice-Hall, Englewood Cliffs, NJ.

Lindemann G.(2002) The Role Concept for Agents in MultiAgent system, Trzebiatowski, Ines Münch

Mandelbaum M., (1978), ‘Flexibility in Decision Making: An Exploration and Unification’, PhD thesis, Dept. of Industrial Engineering, University of Toronto, Canada.

Maonfared R.P., (2000), ‘A Component Based Approach to Design and Construction of Change Capable Manufacturing Cell Control Systems’, PhD thesis, Loughborough University

Mariotti S., (1995), ‘FlessibilitaÁ : lezioni e limiti della `lean production’, *Economia & Management*, 21 (2), 30-43.

Mark S. F., Gruninger M., Zhan Y., (1994), ‘Enterprise Engineering: An Information Systems Perspective’, *Proceedings of the 3rd Industrial Engineering Research Conference*, Atlanta GA

Martin J.N., (1997), ‘System Engineering Guidebook – A Process for Developing Systems and Products’, CRC Press, Inc., ISBN:0-8039-7837-0

Maxwell J. A. (1996), ‘Qualitative Research Design: An Interactive Approach’, Thousand Oaks, Sage Publications.

Mayer, R., Keen, A., Browne, D., Harrington, S., Marshall, C., Painter, M., Schafrik, F., Huang, J., Wells, M., and Hisesh, H. (1995), 'IDEF4 Object-oriented Design Method Report', Wright-Patterson AFB, Ohio. AL/HRGA.

Mayer, R., Benjamin, P., Menzel, C., Fillion, F., deWitte, P., Futrell, M., and Lingineni, M. (1994), 'IDEF5 Ontology Capture Method Report,' Wright-Patterson AFB, Ohio, AL/HRGA.

McClelland D., (1973), Testing for competence rather than intelligence. American Psychologist, 28, 1-14.

McCormack, K.P., Johnson, W. (2000), Business Process Orientation: Gaining the E-business Competitive Advantage, CRC Press, Boca Raton, FL, .

McCormack K. and Rauseo N., (2005), "Building an enterprise process view using cognitive mapping", *Business Process Management Journal* Vol. 11 No. 1 p63-74

McCormack, K.P. (1999), "The development of a measure of business process orientation", paper presented at the European Institute for Advanced Studies in Management: Workshop on Organizational Design, Brussels, .

Medsker, G.J., Campion, M.A. (1997), Job and Team Design. In G. Salvendy (Ed.) *Handbook of Human Factors and Ergonomics* (New York: Wiley), pp450-489.

Mertins K. and Jochem R., (1998), 'Integrated Enterprised Modelling: Refrence Architecture and Methodology', in **Molina A. Kusiska A. and Sanchez J**., 'Handbook of Life Cycle Engineering: Concepts, models, technologies', Kluwer Academic Publishers, UK ISBN:0-412-81250-9

Merton, R.,(1957), 'The Role-Set: Problems in Sociological Theory', *British Journal of Sociology*, VIII, pp106-120

Metropolis N. and Ulam S., (1949), 'The Monte Carlo Method', *Journal of the American Statistical Association*, volume 44, number 247, pp335–341

Microsoft Corporation, (1995). The Component Object Model Specification, Version 0.9 [online]. Available http://www.microsoft.com/Com/resources/comdocs.asp

Mills H.D., (1975), 'The New Math of Computer Programming', *Commun. ACM* 18(1): p43-48

Mills H.D., (1976), 'Software Development'. *IEEE Trans. Software Eng*. 2(4): p265-273

Mills H.D., (1983), 'Software Productivity', Little Brown, Boston

Mintzberg, H., and Heyden, L.V., (1999), 'Organigraphs: Drawing how companies really work', p87-94

Molina A., Kusiak A., & Sanchez J. M., (1999), 'Handbook of life cycle engineering: Concept, methods and tools', Dordrecht: Kluwer Academic Publishers.

Molina A, and Medina V., (2003), "Application of enterprise models and simulation tools for the evaluation of the impact of best manufacturing practices implementation", *Annual Reviews in Control* 27 p221–228

Monfared R.P., West A.A., Harrison R. and Weston, R.H., (2002), 'An Implementation of the business process modeling approach in the automotive industry, Proc. of Inst. of Mech. Eng. Part B', *Journal of Engineering Manufacture*, Vol.216

Neelamkavil F.,(1987), Computer Simulation and Modelling, p.324.

NELL, J. G., (2001), TC184 SC5 WG1 New-work-item proposal. Requirements for establishing manufacturing-enterprise process interoperability, WG1 N433 rev.2.

Nino Boccara,(2004), *Modeling Complex Systems* , Springer Ltd.

Noble M. A., (1995), 'Manufacturing strategy: testing the cumulative model in a multiple country context', *Decision Sciences*, Vol. 26 No. 5, pp. 693-721.

Object Management Group, Unified modelling language: Superstructure. URL: http://www.uml. omg.org/cgi-bin/doc?formal/05-07-04, August 2005

O'Connor, J. (1997). 'The Art of Systems Thinking: Essential Skills for Creativity and Problem Solving'. Thorsons, London.

Odell, J., Van Dyke Parunak H., Bauer B., (2000), 'Extending UML for Agents', in Proc.of the *Agent-Oriented Information Systems Workshop at the 17th National conference on Artificial Intelligence*, Gerd Wagner, Yves Lesperance, and Eric Yu (eds.), Austin, TX, pp.3-17

Olhager J., (1993), "Manufacturing flexibility and profitability", International Journal of Production Economics 30-31(1993) p67-78

Oliver, N., Wilkinson, B. (1992), *The Japanization of British Industry: New Development in the 90s*, Blackwell, Oxford,

Ortmann G., Windeler A., Becker A., Schulz H.J., (1990), 'Computer und Macht in Organisationen. Mikropolitische Analysen.' Opladen, Westdeutscher Verlag

Pandya, K.V., Karlsson, A., Sega, S., and Carrie, A., (1997), Towards the manufacturing enterprises of the future, International Journal of Operations & Production Management, 17(5), 502-521.

Parunak H., Van D., Odell J.,(2001), 'Representing Social Structures in UML', in Proc.of *the Agent-Oriented Software Engineering Workshop*, Agents 2001, Michael Wooldridge, Paolo Ciancarini, and Gerhard Weiss (eds.)

PBS, (2003), 'Performance benchmarking service'. http://www.mmtc.org/services/pbs/

Pidd M.,(1992) 'Computer Simulation in Management Science', John Wiley & Sons, Inc.

Pidd M.,(1998), Computer simulation in management science - fourth edition. Wiley

Poler R., Lario F. C., Doumeingts G., (2002), 'Dynamic modelling of decision systems (DMDS)'. *Computers in Industry*, *49*(2), 175–193.

Poli R. Framing Ontology—Part I, II 2004 [http://www.formalontology. it/Framing_first.htm].

Prahalad C.K., Hamel G., (1992),The core competence of the corporation, IEEE Engineering Management Review, pp5–14

Presley A.R., (1997), 'A Representation Method to Support Enterprise Engineering', *Industrial and Manufacturing System Engineering*, Arlington University of Texas

Quinn J B. (1992) Intelligent enterprise: a knowledge and service based paradigm for industry. Free Press, N.Y. 658.406/QUI.

Rahimifard A., Weston R.H. (2006), "The enhanced use of enterprise and simulation modelling techniques to support factory changeability" Accepted for publication in IJCIM

Ramey, T., and Brown, R., (1987), 'Entity, Link, Key Attribute Semantic Information Modeling: The ELKA Method, ms, Hughes Aircraft.

Raven, J., & Stephenson, J. (Eds.). (2001). Competence in the Learning Society. New York: Peter Lang.

Reithofer W., Naeger G., (1997), 'Bottom-up planning approaches in enterprise modelling - the need and the state of the art', *Computers in Industry* (33) 223-235

Reynal V., Cochran D.S., (1997). 'Axiomatic design of manufacturing systems. 2nd World Congress of Intelligent Mfg. Processes and Systems, June 10-13, 1997, Budapest, Hungary.

Robinson S.(2004), Simulation - The practice of model development and use. Wiley.

Robinson S.,(1994), Successful Simulation: A Practical Approach to Simulation Projects, McGraw-Hill International (UK) Ltd.

Rolstadås A., (1998), 'Enterprise performance measurement', *International Journal of Operations & Production Management*, 18(9), 989–999

Ross, D., (1977), 'Structured Analysis (SA): A Language for Communicating Ideas,' TSE 3(1), p16-34

Russell N., ter Hofstede A.H.M., van der Aalst W.M.P., and Mulyar N.(2006),. 'Workflow Control-Flow Patterns: A Revised View. BPM Center Report BPM-06-22'

Sackett, P. & Fan, I. (1989), 'The Control of a Flexible Manufacturing System by Short-term Goal Identification' , *International Journal Of Advanced Manufacturing Technology*, vol.4, p123-143

Sadoun B., (2000), "Applied system simulation: a review study", *Information Sciences*, Vol124, Issues 1-4, P173-192

Salvendy, G. (1992) 'Handbook of Industrial Engineering', A Wiley-Interscience Publications, John Wiley & Sons, Inc., USA, ISBN: 0-471-50276-6

Sarbin T.R, Allen V.L., (1968), Role theory, in: Lindzey G., Aronso E. (Eds.), seconded., Academy of Social Psychology, 1, pp. 488–567.

Schal T.(1996). 'Workflow Management for Process Organisations', *Lecture Notes in Computer Science*. Vol 1096, Springer-Verlag, Berlin

Scheer A.W., (1991), 'Architektur integrierter Informationssysteme- Grundlagen der Untemehmens-modellierung'. Springer

Schreiber, A. T., Akkermans, J. M., Anjewierden, A. A., De Hoog, R., Van De Velde, W., & Wielinga, B. J. (1999). Engineering of Knowledge: The CommonKADS Methodology. University of Amsterdam.

Scott, W.G. & Mitchell, T.R. (1976), Organisation Theory A Structural and Behavioral Analysis, Richard D. Irwin Inc. Illinois.

Senge P.M., (1990), 'The Fifth Discipline: The Art and Practice of the Learning Organization', Bantam Doubleday Dell Publishing Group, Inc

Sethi A. and Sethi S., (1990), 'Flexibility in manufacturing: a survey', *International Journal of Flexible Manufacturing Systems*, 2, 289-328

Shippmann, J. S., Ash, R. A., Battista, M., Carr, L., Eyde, L. D., Hesketh, B., Kehoe, J., Pearlman, K., and Sanchez, J. I. (2000). The practice of competency modeling, Personnel Psychology, 53, 703-740.

Siemieniuch C.E. et al, (1999), 'The Role of 'Partnership' In Supply Chain Management for Fast-Moving Consumer Goods: a Case Study', *International Journal of Logistics Research and Applications*, Vol 2, Issue , p87-101

Singh B., (1992), Interconnected roles (IR), a coordination model, MCC Technical Report.

Sjoberg, G., Williams, N.,Vaughan, T., & Sjoberg, A. (1991). The case study approach in social research. In Feagin, J., Orum, A., & Sjoberg, G. (Eds.), (1991).*A case for case study* (pp. 27-79). Chapel Hill, NC: University of North Carolina Press.

Slack N., (1983), 'Flexibility as a manufacturing objective', *International Journal of Operations and Production Management*, 3 (3), 4-13

Slack N., (1987), 'The flexibility of manufacturing systems'. *International Journal of Operations & Production Management*, 7 (4), 35-45.

Small Components Project, URL: http://www.voelter.de/smallComponents

Smith R.D., (1998), Simulation Article, Encyclopedia of Computer Science, Nature Publishing Group, ISBN 0-333-77879-0.

Smith R.D. (1999), "Simulation: The Engine Behind the Virtual World", eMatter

Sommerville I.,(1992),. Software Engineering, Fourth Edition', Addison-Wesley Publishing Company, Inc.

Spencer, L. M., & Spencer, S. M. (1993). Competence at Work. New York: Wiley.

Spur G., Mertins K. and Jochem R., (1996), Integrated Enterprsise Modelling, Beuth Verlag, Berlin

Steers, R.M & Black, S.J. (1994), Organisational Behaviour, HarperCollins N.Y.

Sterman J., (2000), *Business Dynamics: Systems Thinking and Modeling for a Complex World*, McGraw-Hill/Irwin

Stevens R., Brook P., Jackson K., and Arnold S., (1998), 'System Engineering – Coping with complexity', Prentice Hall Europe, ISBN: 0-13-095085-8

Storey, J. (1994), *New Wave Manufacturing Strategies*, Paul Chapman Publishing, London,

Strebler M., Bevan S., (1996), Competence based management training, Institute of Employment Studies, Report 302

Suh N.P., Cochran D.S., and Lima P.C. (1998). 'Manufacturing system design.' *Annals of the CIP*, v47, n2, pp627-639.

Sun Microsystems, (1997), *JavaBeans for Java Studio: Architecture and API*, White paper.

Szyperski C., (1999), *Component Software - Beyond Object-Oriented Programming*, Addison-Wesley

Szyperski C., (2002), Component Software. Addison-Wesley, 2nd edition

Teece D.J., Pisano G. and Shuen A., (1997), 'Dynamic capabilities and strategic management', *Strategic Management Journal*, Vol. 18 No. 7, pp. 509-33. Technology in Harvard Business School Press. Boston.

Tunalv C., (1992), 'Manufacturing strategy – plans and business performance', *International Journal of Operations & Production Management*, Vol. 12 No. 3, pp. 4-24.

Ulam S., Richtmyer R. D., and von Neumann J., (1947). *Statistical methods in neutron diffusion*. Los Alamos Scientific Laboratory report LAMS–551.

Upton D.M., (1995), 'What really makes factories flexible?' *Harvard Business Review* 73 (4), 74–84.

Valles-Rosales D.J., Nathan J.S. and Viswanathan V.,

Van Assen, M.F. (2000), 'Agile Based Competence Management'. *Int. J. of Agile Management Systems*. pp145-155. MCB Uni. Press.

Vernadat F. B., (2002). 'Enterprise modelling and integration (EMI): Current status and research perspectives'. *Annual Reviews in Control*, 26, 15–25.

Vernadat, F.B. (1996), *Enterprise Modeling and Integration: Principles and Applications*, Chapman & Hall, London

Voelter M., Schmid A. and Wolff E., (2002), *Server Component Patterns*, Wiley and Sons

Völter M., (2003), 'A Taxonomy for Components', *Journal of Object Technology*, vol. 2, no. 4, pp119-125.

Von Beck U. and Nowak J.W., (2000), **'**The merger of discrete event simulation with activity based costing for cost estimation in manufacturing environments', Proceedings of the 2000 Winter Simulation Conference

Von Bertalanffy, L. (1976). 'General system theory: Foundations, development, applications' (Rev. ed.). George Braziller.

Wagner J.A. & Hollenbeck J.R. (1992), Management of Organisational Behaviour, Prentice Hall, N.J.

Wahid B M, Ding C, Weston R H, (2008), 'A new tool development to improve enterprise model building and utilisation', *proceeding of the 19th international conference of Flexible Automation and Intelligent Manufacturing*, FAIM2008, Skövde, Sweden

Weston R.H., (1998), 'Manufacturing business systems requirements & current practices', *Manufacturing Business Systems Notes*, Loughborough University

Weston R.H., (1999)**,** 'A model-driven, component-based approach to reconfiguring manufacturing software systems.' In: MacCarthy B, McFarlane D, editors. *Special issue of International journal of operations and production management, responsiveness in manufacturing*, vol. 19(8), pp834–55.

Weston R.H., (2004), 'Coherent Models of Processes and Human Systems', *ICEIMT'04 Toronto*, Canada.

Weston R.H., (2006), "Simulating Dynamic Behaviours in Manufacturing Organisations", *Int. Conf. on Industrial Engineering and Systems Management*, IESM 2007, Beijing, China.

Weston R.H., Byer N., Ajaefob, J.O., (2003), 'EM in Support of Team System Engineering', *10th ISPE Conf. on C.E.: Research &Applications*, Madeira, pp 865-872, Swets & Zeitilinger, Lisse.

Weston, R.H., Guerrero A. and Chatha K.A., (2007), 'Process Classes Deployed in Manufacturing Enterprises', *Int. J. of Computer Integrated Manufacture*.

Weston R.H., Zhen M, Rahimifard A., Ajaefobi J., Ding C., (2006), 'Simulation Model Interoperability in Support of Complex Organisation Design and Change', ESM’2006

Weston, R.H., Zhen, M., Ajaefobi, J.O., Rahimifard, A., Guerrero, A., Masood, T., Wahid, B., and Ding, C. (2007), 'Simulating Dynamic Behaviours in Manufacturing Organisations', *IESM 2007 Int. Conf. on Industrial Engineering & Systems Management*, Beijing.

Weston R.H., Rahimifard A., Ajaefobi J., Cui Z., (2008), 'Model driven and change capable production system', *proceeding of the 6th International Conference on Manufacturing Research (ICMR08)*

Weston R.H., (2008), "Next generation manufacturing systems", Chapter 6 of Global Design to Gain a Competitive Edge, Springer, London

WFMC.(1999), 'Workflow Management Coalition Terminology & Glossary, Document Number WFMC-TC-1011, Document Status - Issue 3.0. Technical report', Workflow Management Coalition, Brussels

Williams T.J., (1992), ‘The Purdue Enterprise Reference Architecture’, Technical Report, Purdue Laboratory for Applied Industrial Control, Purdue

Wilson B., (1990), Systems: Concepts, Methodologies and Applications, 2nd ed., Wiley

Wirth N. (1971), 'Program Development by Stepwise Refinement', *Communications of the ACM, Vol. 14, No. 4, April 1971*, p221-227

Wisker G. (2001), Postgraduate research handbook, Palgrave Macmillan

Yaneer Bar-Yam, (1996),*Dynamics of Complex Systems*, Addison-Wesley

Yin, R.K. (2003). *Case Study Research Design and Methods*. (3rd ed.). Thousand Oaks, California: Sage, Publications, Inc.

Zachman J. A., (1987), ‘A framework for information systems architecture’. In: *IBM System Journal*, Vol. 26, No. 3, pp. 276-292

Zarifian P., (2002), La politique de la compe´tence et l’appel aux connaissances dans la strate´gie d’entreprise, in: Vers l’articulation entre Compe´tences et Connaissances, 1er Colloque du GCCGI, Nantes

Zhang Q., **Vonderembse M.A., Lim J.S.**, (2002), ‘Value chain flexibility: a dichotomy of competence and capability’, *International Journal of Production Research* 40 (3), 561–583.

Zhang Q., Vonderembse M.A., Lim J.S., (2003), ‘Manufacturing flexibility: defining and analyzing relationships among competence, capability, and customer satisfaction’, *Journal of Operations Management* 21 (2003) 173–191

Appendices

Appendix I Comparison of Enterprise Modelling Approaches

Table A1-1: Comparison of different approaches against organisation design requirements set.

Organisation Design Requirements		**CIMOSA**	**R.P. Monfared's Process Modelling Approach**	**IDEF3**	**IEM**
Process lifecycle		◔	◔	◔	◑
Multi-process oriented organisation structure enforcing decomposition principles	Multi-Process Oriented Structure	○	---	---	---
	Decomposition Principles	◑	◑	◔	◔
Generic process modelling language for generating semantically rich process specifications		◔	◑	◑	◑
Process modelling method to support process lifecycle		◑	◑	---	◑
Modelling concepts framework		◕	---	---	---
Exceptions handling		◔	---	---	---
Resource coordination		---	---	○	---

Coverage	● Very High	◕ High	◑ Medium	◔ Low	○ Very Low	--- No coverage

(Source: Catha, 2003)

Table A1-2 Modelling Framework Comparison - Life Cycle (Modelling Levels)

GERAM	ARIS	CIMOSA	GRAI/GIM	IEM	PERA
Identification	not defined	not defined	not defined	not defined	EBE (*) Identfication
Concept	not defined	not defined	not defined	not defined	EBE Concept Layer
Requirement	Operation Concept	Requirement Definition	Concept Level Analysis	Requirement Definition	EBE Definition Layer
Design	IT System Concept	Design Specification	Structure Level User Oriented Design	System Design	EBE Specification Layer
					EBE Detailed Design Layer
Implementation	Implementation	Implementation Description	Realisation Level, Technical Oriented Design	Implementation Description	EBE Manifestation Layer
Operation		(Operation)			EBE Operation Layer
System Change		Model Maintenance			Model Update

* EBE, Enterprise Business Entity

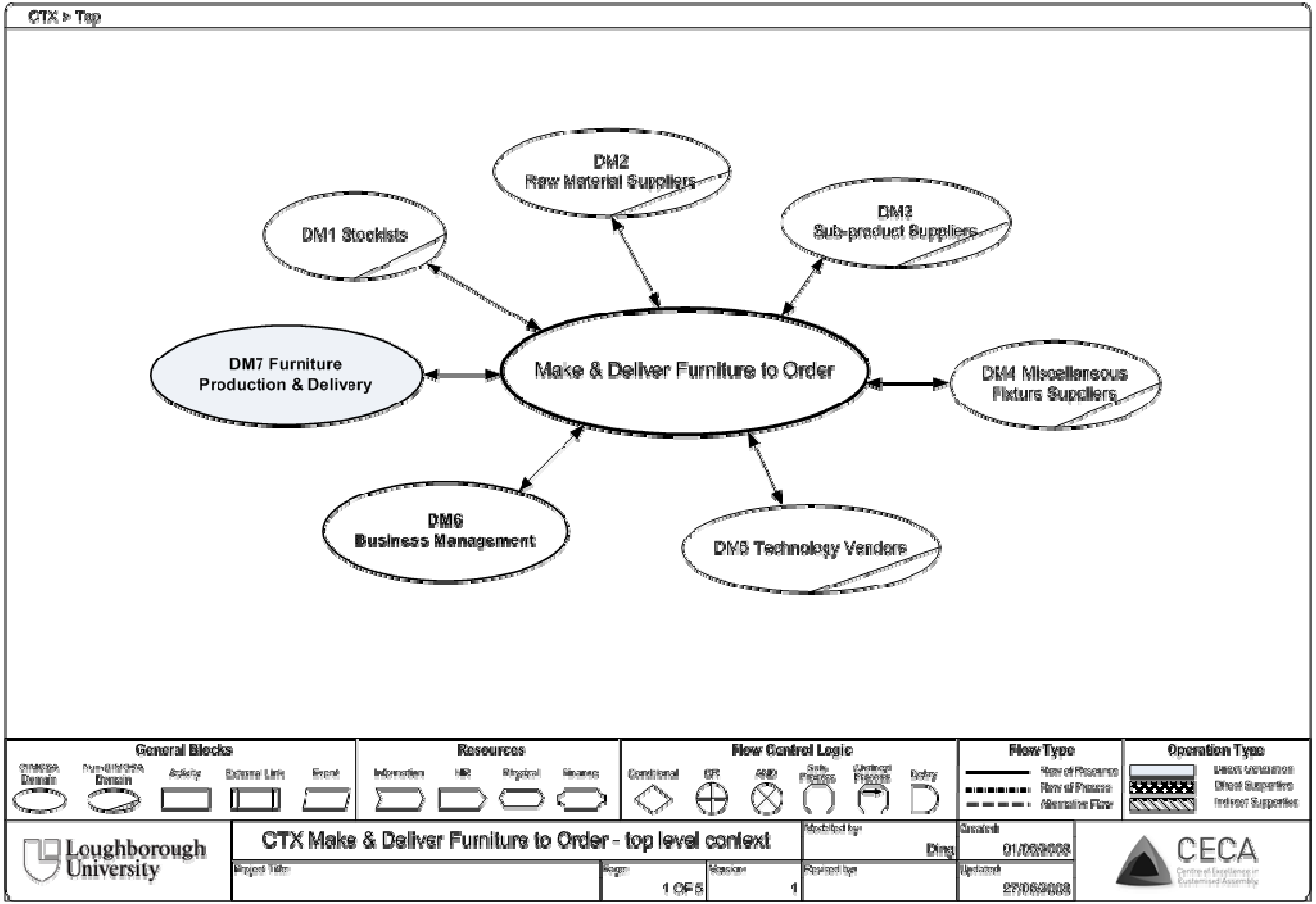
(Resource: Conference Proceeding of the DIISM'96)

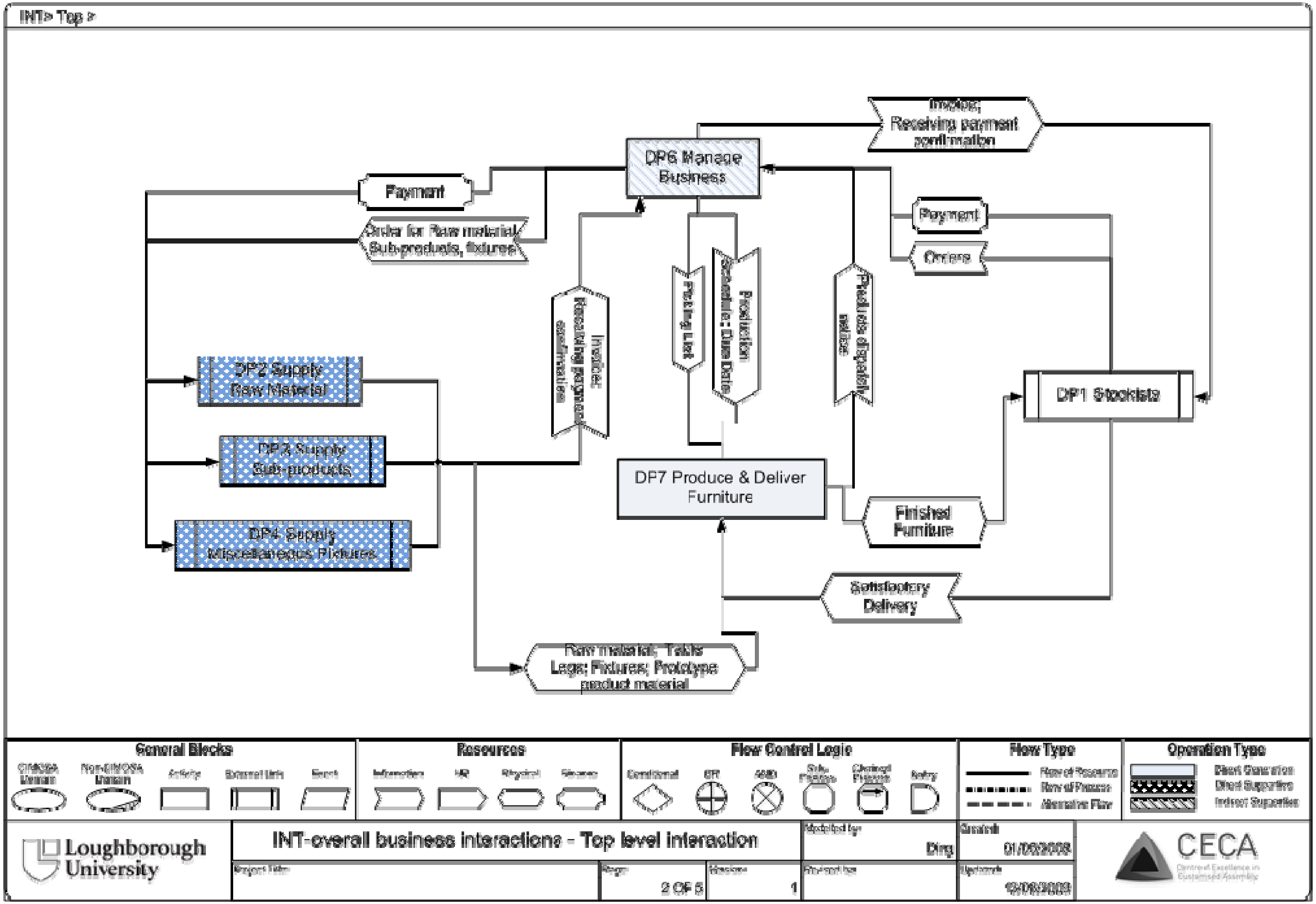
Table A1-3 Modelling Language/ Construct Comparison

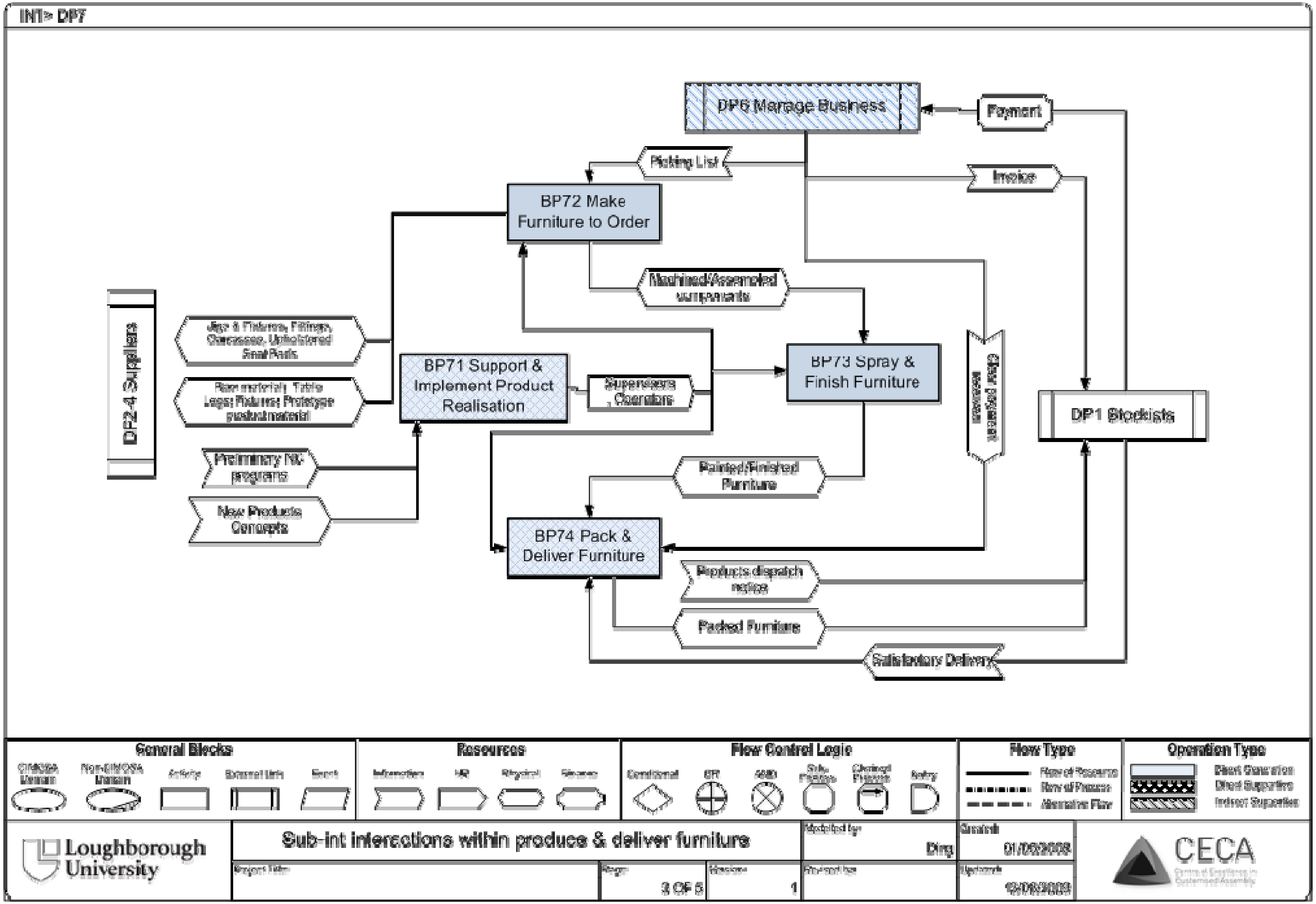
Modelling Constructs	ENV 12 204	ARIS	CIMOSA	GRAI/GIM	IEM	PERA
General Definitions	not defined	not defined	Engineering Environment, Operation Environment	Decis. System Inform. Syst. Phys. System, Bus. Domain	not defined	Enterprise Business Entity
Function View – Static	Enterprise Activity	Function	Domain, Enterprise Activity (Funct.Oper.)	IDEF0 Activity	Activity, Function, (Action)	Task Module
Function View – Dynamic	Bus. Process, Event, (Sequential Relationships)	Process Chain, Event, (Connectors), Cluster	Process (DP, BP), Event, (Behav.Rules)	not defined	Funct. Chain, Funct Auton. Unit, (Connect Constructs)	not defined
(Decision) View	not defined	not defined	not defined	GRAI Grid: Decision Level/ Centre/ LinkGRAI Net: Decision./ Not Dec Activity	not defined	not defined
Organisation View	Organisational Unit	Organ. Level, Organ. Unit, Attribute, Location, Network, NetworkNode, NetworkUnit, TechResource	Organ. Cell, Organ. Unit, Organ. Element	not defined	Object Class: Special Resource	not defined
Information View	Enterprise Object, Product, Order, Object View, Relation	Entity, Attribute, Relation, Terminology, Table, (Cardinality, Operators)	Enterprise Object, Object View, (Inf. Element), Relation, (Cardinality, Operators)	Information Model, Entity, Relation	Object Class: Product, Order , Relation (Operators)	not defined
Resource View	Capability Set, Resource	part of Organisation View	Capability Set, Resource / Functional Entity	not defined	Object Class: Resource	not defined
Number of Constructs	11	17	11	9	10	1

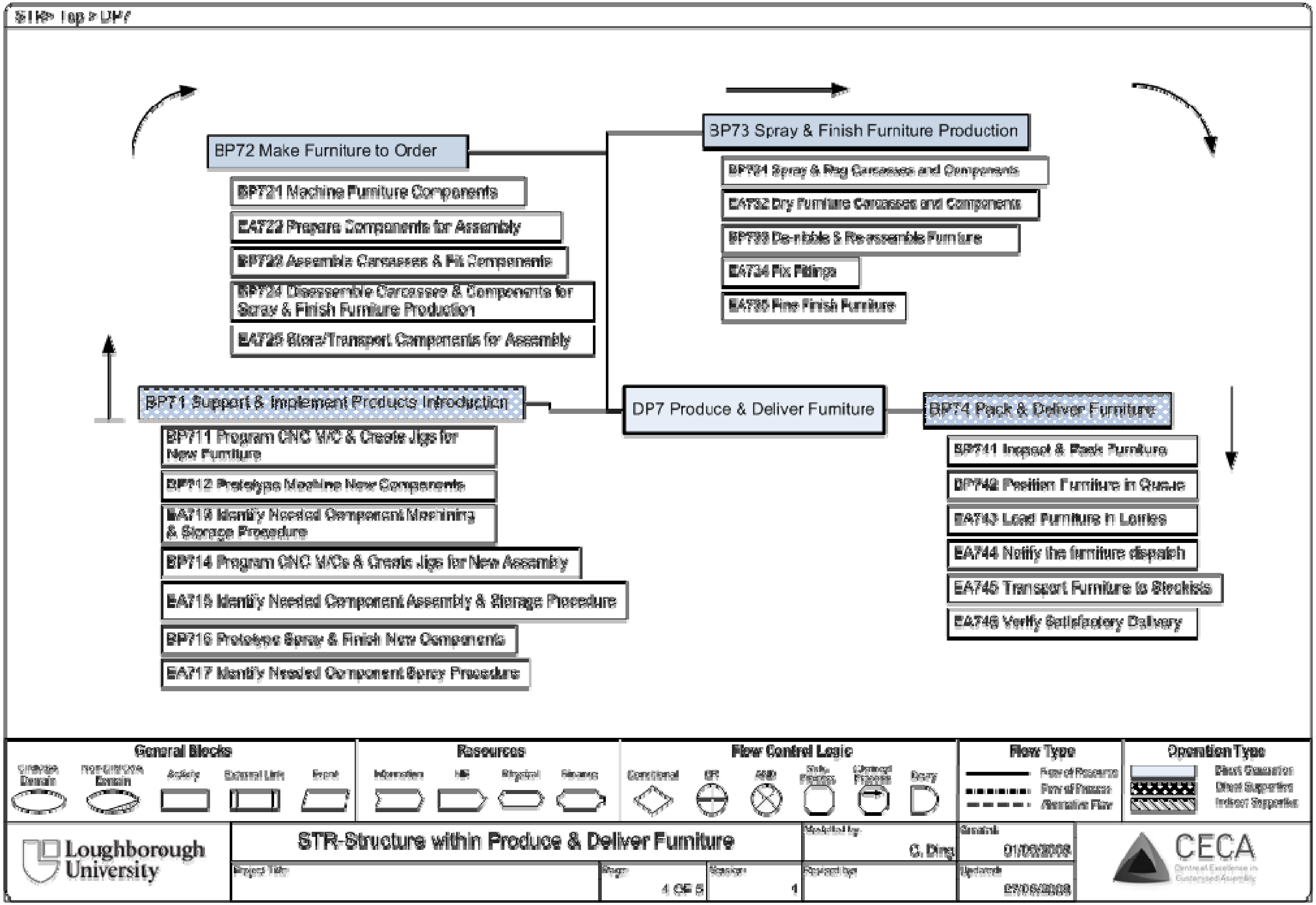
(Resource: Conference Proceeding of the DIISM'96)

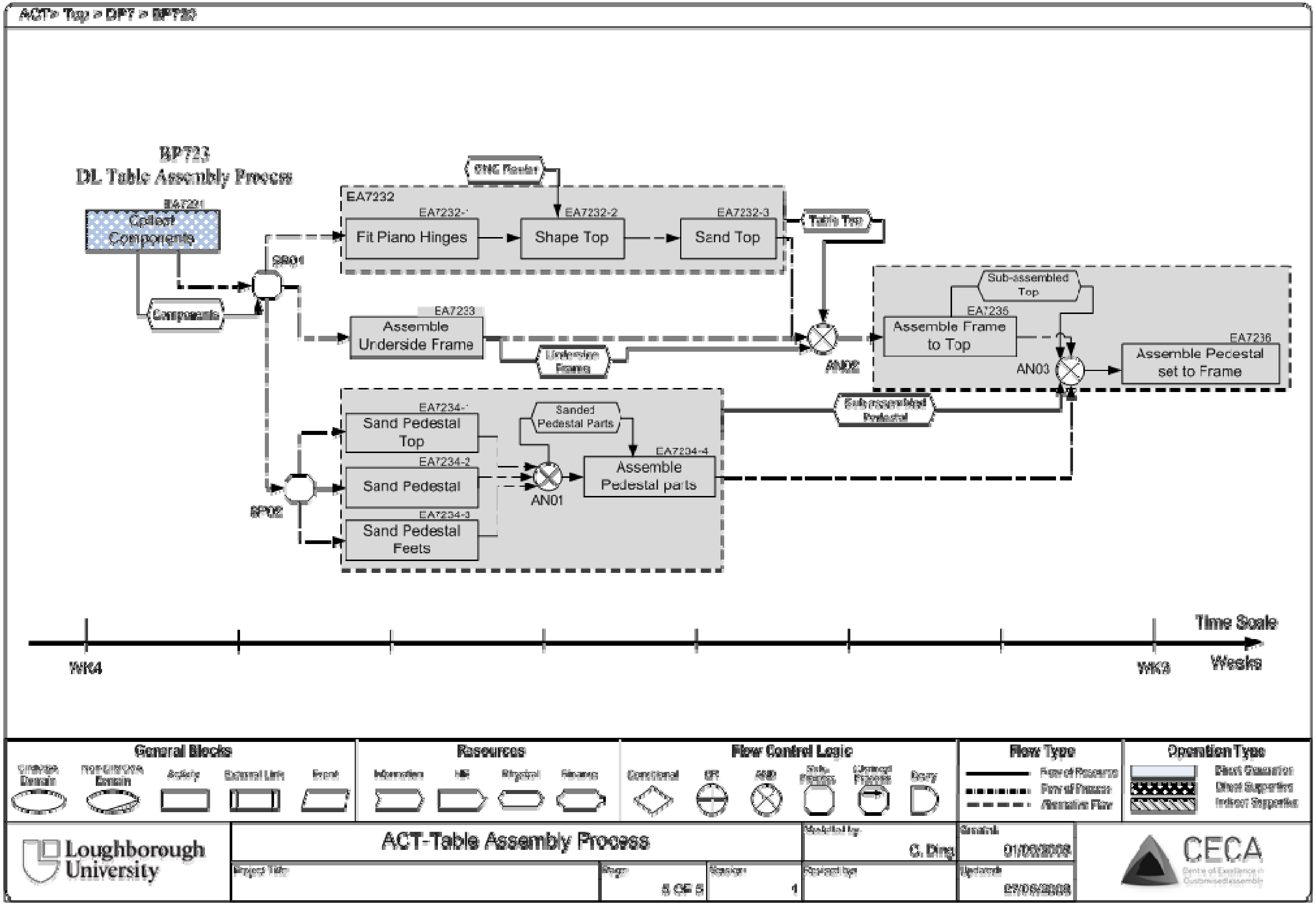
Appendix II Examples of CIMOSA Model Diagrams using improved logic control and model template




INT> Top >
DP6 Manage Business
Invoice; Receiving payment confirmation
Payment
Order for Raw material, Sub-products, fixtures
Payment
Orders
Invoice; Receiving payment confirmation
Picking List
Production Schedule; Due Date
Products dispatch notice
DP2 Supply Raw Material
DP3 Supply Sub-products
DP4 Supply Miscellaneous Fixtures
DP1 Stockists
DP7 Produce & Deliver Furniture
Finished Furniture
Satisfactory Delivery
Raw material; Table Legs; Fixtures; Prototype product material
General Blocks
Resources
Flow Control Logic
Flow Type
Operation Type
Loughborough University
INT-overall business interactions - Top level interaction
Dirg
01/06/2008
2 OF 5
1
12/06/2008
CECA


INT> DP7
DP6 Manage Business
Payment
Picking List
Invoice
BP72 Make Furniture to Order
Machined/Assembled components
DP2-4 Suppliers
BP71 Support & Implement Product Realisation
Supervisors Operators
BP73 Spray & Finish Furniture
DP1 Stockists
Preliminary NC programs
New Products Concepts
Painted/Finished Furniture
BP74 Pack & Deliver Furniture
Products dispatch notice
Packed Furniture
Satisfactory Delivery
General Blocks
Resources
Flow Control Logic
Flow Type
Operation Type
Sub-int interactions within produce & deliver furniture
Loughborough University
3 OF 5
CECA


STR> Top > DP7
BP72 Make Furniture to Order
BP721 Machine Furniture Components
EA722 Prepare Components for Assembly
BP723 Assemble Carcasses & Fit Components
BP724 Disassemble Carcasses & Components for Spray & Finish Furniture Production
EA725 Store/Transport Components for Assembly
BP73 Spray & Finish Furniture Production
EA732 Dry Furniture Carcasses and Components
EA734 Fix Fittings
BP71 Support & Implement Products Introduction
BP711 Program CNC M/C & Create Jigs for New Furniture
BP712 Prototype Machine New Components
EA713 Identify Needed Component Machining & Storage Procedure
BP714 Program CNC M/Cs & Create Jigs for New Assembly
EA715 Identify Needed Component Assembly & Storage Procedure
BP716 Prototype Spray & Finish New Components
EA717 Identify Needed Component Spray Procedure
DP7 Produce & Deliver Furniture
BP74 Pack & Deliver Furniture
BP741 Inspect & Pack Furniture
BP742 Position Furniture in Queue
EA743 Load Furniture in Lorries
EA744 Notify the furniture dispatch
EA745 Transport Furniture to Stockists
EA746 Verify Satisfactory Delivery
General Blocks
Resources
Flow Control Logic
Flow Type
Operation Type
Loughborough University
STR-Structure within Produce & Deliver Furniture
C. Ding
01/06/2008
4 OF 5
1
27/06/2008
CECA



BP723
DL Table Assembly Process
EA7231
Collect Components
Components
SP01
EA7232
EA7232-1
Fit Piano Hinges
EA7232-2
Shape Top
EA7232-3
Sand Top
CNC Router
Table Top
EA7233
Assemble Underside Frame
Underside Frame
AN02
Sub-assembled Top
EA7235
Assemble Frame to Top
AN03
EA7236
Assemble Pedestal set to Frame
EA7234-1
Sand Pedestal Top
EA7234-2
Sand Pedestal
EA7234-3
Sand Pedestal Feets
Sanded Pedestal Parts
EA7234-4
Assemble Pedestal parts
AN01
SP02
Sub-assembled Pedestal
Time Scale
WK4
WK8
Weeks
General Blocks
Resources
Flow Control Logic
Flow Type
Operation Type
Loughborough University
ACT-Table Assembly Process
C. Ding
01/06/2008
27/06/2008
5 OF 5
1
CECA

Appendix III Flow Control Logic specification template

Table A3-1 Conditional Node(CO) specification table

Conditional node No.	Forward entity when condition meet(Y)	Forward entity when condition doesn't meet(N)
CO01		

Table A3-2 Case Node(CA) specification table

Case node No.	Designed case list	Forward entity in thre case
CA01	Case 1(point or range)	EA0001
	Case 2(point or range)	EA0002
	Case n(point or range)	…
Exceptional	When none of above case could fit	EA0011

Table A3-3 OR Node(CA) specification table

OR node No.	Optional entry list	Release condition(s)	Forward entity
OR01	EA0001	The condition(s) which will trigger the release to exit, if any of entry meet it	EA0004
	EA0002		
	EA0003		

Table A3-4 AND Node(CA) specification table

AND node No.	Entry list	Aggregated elements list	Forward Entity	Coupled Node (if available)
AN01	EA0001	The elements coming from entries need to be collected through the node	EA0004	If there needs refer to Sub-process node
	EA0002			
	EA0003			

Table A3-5 Sub-Process Node(SP) specification table

Sub-Process No.	Previous Entity	Forward Entities	Delivered Products components
SP01	EA0001	EA0002	Items delivered by each forward entity
		EA0003	
		EA0004	
Comments: Describe "*What received from Previous Entity and how to distribute to Forward Entities*"			

Table A3-6 Chained-Process Node(CP) specification table

Chained-Process No.	Previous Entity	Forward Entity	Delivered Products components
CP01	EA0001	EA0002	Items delivered by each forward entity
		EA0003	
		EA0004	
Comments: Describe "*What received from Previous Entity and how to distribute to Forward Entities*"			

Table A3-7 Delay Node(DN) specification table

Delay node No.	Entity(ies) which can release delay	Condition to hold the delay	Forward entity after released
CO01	EA0001	How the delay caused and what is being waited to release the delay	

Appendix IV Role based resource system design case study tables

Table A4-1 Competency requirements specification

ID	Objects	Operation	Required Competency	CT	CCL	Role linked
RC01	Parts & components	EA7231	Identify parts & components	CT2	CCL2	R1
RC02	Parts & components	EA7231	Deliver parts to right sections	CT3	CCL2	R1
RC03	Top parts; hinges	EA7232-1	Fit hinge with table top parts	CT3	CCL2	R2
RC04	Top parts	EA7232-2	Able to operate CNC router	CT3	CCL3	R2
RC05	Top parts	EA7232-3	Manually sand table tops	CT3	CCL2	R2
RC06	Underside frame parts	EA7233	Identify frame parts & assembly	CT3	CCL2	R3
RC07	Pedestal tops; Pedestal; Pedestal feet	EA7234-1/2/3	Sand pedestal parts to satisfaction	CT3	CCL2	R4
RC08	Pedestal tops; Pedestal; Pedestal feet (Sanded)	EA7234-4	Assemble pedestal parts	CT3	CCL3	R4
RC09	Top parts; frame	EA7235	Assemble top & frame	CT3	CCL3	R5
RC10	Sub-assembled top; pedestal	EA7236	Assemble into whole table	CT3	CCL3	R5
RC11	Sub-assembled components		Identify components and transport	CT2	CCL2	R6
RC12	Assembled DL tables		Load tables and transport	CT2	CCL2	R6
RC13	Parts, components & assembly		Monitor assembly process	CT3	CCL3	R7
RC14	Work stations and tools; Operators		balancing machines and staff working load	CT4	CCL3	R7

Table A4-2 Competency possession distribution among resources

Role ID	RC ID	RP ID	Applicable to Resources											
			S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
R1	RC01	RP1	√				√						√	
	RC02		√			√							√	
R2	RC03	RP2			√					√	√			
	RC04				√				√					√
	RC05				√		√	√						
R3	RC06	RP3								√	√			
R4	RC07	RP4		√		√				√				
	RC08			√						√		√		
R5	RC09	RP5		√								√		
	RC10		√									√		√
R6	RC11	RP6						√					√	√
	RC12							√					√	
R7	RC13	RP7												√
	RC14													√

Table A4-3 Capability evaluation for candidate role holders of Role 1

RP ID	RP1	Associate Competency / Role			RC01/R1
Applicable Resources		S1	S5	S11	
Associate products	DL4	SL3	SL2	SL3	Skill level associated to products
	DL6	SL4	SL2	SL3	
	FT6	SL4	SL3	SL2	
	PT3	SL4	SL2	SL2	
RP ID	RP1	**Associate Competency / Role**			RC02/R1
Applicable Resources		S1	S4	S11	
Associate products	DL4	SL3	SL2	SL2	Skill level associated to products
	DL6	SL3	SL1	SL2	
	FT6	SL3	SL2	SL2	
	PT3	SL3	SL2	SL2	

Table A4-4 Capability evaluation for candidate role holders of Role 2

RP ID	RP2	Associate Competency / Role			RC03/R2-1
Applicable Resources		S3	S8	S9	
Associate products	DL4	SL3	SL1	SL2	Skill level associated to
	DL6	SL3	SL2	SL3	
	FT6	N/A			
	PT3	N/A			
RP ID	RP2	**Associate Competency / Role**			RC04 / R2-2
Applicable Resources		S3	S7	S12	
Associate products	DL4	SL3	SL2	SL2	Skill level associated to
	DL6	SL4	SL2	SL3	
	FT6	N/A			
	PT3	N/A			
RP ID	RP2	**Associate Competency / Role**			RC05/R2-3
Applicable Resources		S3	S5	S6	
Associate products	DL4	SL2	SL4	SL3	Skill level associated to
	DL6	SL3	SL2	SL3	
	FT6	N/A			
	PT3	N/A			

Table A4-5 Capability evaluation for candidate role holders of Role 3

RP ID	RP3	**Associate Competency / Role**		RC06/R3
Applicable Resources		S8	S9	
Associate products	DL4	SL2	SL2	Skill level associated to products
	DL6	SL3	SL1	
	FT6	SL4	SL2	
	PT3	N/A		

Table A4-6 Capability evaluation for candidate role holders of Role 4

RP ID	RP4	**Associate Competency / Role**			RC07/R4
Applicable Resources		S2	S4	S8	
Associate products	DL4	SL4	SL3	SL3	Skill level associated to products
	DL6	SL3	SL3	SL3	
	FT6	SL3	SL2	SL	
	PT3	SL2	SL1		
RP ID	RP4	**Associate Competency / Role**			RC08 / R4
Applicable Resources		S2	S8	S10	
Associate products	DL4	SL3	SL3	SL2	Skill level associated to products
	DL6	N/A			
	FT6	N/A			
	PT3	SL4	SL3	SL1	

Table A4-7 Capability evaluation for candidate role holders of Role 5

RP ID	RP5	**Associate Competency / Role**			RC09/R5
Applicable Resources		S2	S10		
Associate products	DL4	N/A	SL2		Skill level associated to products
	DL6	SL1	SL3		
	FT6	SL3	SL3		
	PT3	SL2	SL3		
RP ID	RP5	**Associate Competency / Role**			RC10/R5
Applicable Resources		S1	S10	S12	
Associate products	DL4	SL1	SL3	N/A	Skill level associated to products
	DL6	SL2	SL3	SL1	
	FT6	SL2	SL4	SL2	
	PT3	SL2	SL4	SL2	

Table A4-8 Capability evaluation for candidate role holders of Role 6

RP ID	RP6	**Associate Competency / Role**			RC11/R6
Applicable Resources		S6	S11	S12	
Associate products	DL4	SL3	SL2	N/A	Skill level associated to products
	DL6	SL3	SL3	SL1	
	FT6	SL4	SL3	SL2	
	PT3	SL4	SL3	SL1	
RP ID	RP6	**Associate Competency / Role**			RC12 / R6
Applicable Resources		S6	S11		
Associate products	DL4	SL4	SL3		Skill level associated to products
	DL6	SL4	SL2		
	FT6	SL3	SL3		
	PT3	SL3	SL2		

Table A4-9 Capability evaluation for candidate role holders of Role 6

RP ID	RP7	**Associate Competency / Role**		RC13 / R7
Applicable Resources		S12		
Associate products	DL4	SL3		Skill level associated to products
	DL6	SL3		
	FT6	SL4		
	PT3	SL4		
RP ID	RP7	**Associate Competency / Role**		RC14 / R7
Applicable Resources		S12		
Associate products	DL4	SL2		Skill level associated to products
	DL6	SL2		
	FT6	SL3		
	PT3	SL3		

Appendix V

Plant Simulation Experimental Design Scenario Set

Table A5-1 Experiment Scenario Set 1

Sce. No.	Work Dynamics						PD		RD	
	PV		VD		PMD					
S1-1a	N	DL4	N	Interval 30 min, batch size 1	N		N	Process Role R2,R3,R4,R5	N	6 Operators, fixed WC
S1-1b	N	DL4	Y	Interval 10-50 min; batch size 1	N		N	Process Role R2,R3,R4,R5	N	6 Operators, fixed WC
S1-1c	N	DL4	Y	Interval 30 min; batch size 1 to 5	N		N	Process Role R2,R3,R4,R5	N	6 Operators, fixed WC
S1-2a	N	DL6	N	Interval 30 min, batch size 1	N		N	Process Role R2,R3,R4,R5	N	6 Operators, fixed WC
S1-2b	N	DL6	Y	Interval 10-50 min; batch size 1	N		N	Process Role R2,R3,R4,R5	N	6 Operators, fixed WC
S1-2c	N	DL6	Y	Interval 30 min; batch size 1 to 5	N		N	Process Role R2,R3,R4,R5	N	6 Operators, fixed WC
S1-3a	N	FT6	N	Interval 30 min, batch size 1	N		N	Process Role R2,R3,R4,R5	N	6 Operators, fixed WC
S1-3b	N	FT6	Y	Interval 10-50 min; batch size 1	N		N	Process Role R2,R3,R4,R5	N	6 Operators, fixed WC
S1-3c	N	FT6	Y	Interval 30 min; batch size 1 to 5	N		N	Process Role R2,R3,R4,R5	N	6 Operators, fixed WC
S1-4a	N	PT3	Y	Interval 30 min, batch size 1	N		N	Process Role R2,R4,R5	N	6 Operators, fixed WC
S1-4b	N	PT3	Y	Interval 10-50 min; batch size 1	N		N	Process Role R2,R4,R5	N	6 Operators, fixed WC
S1-4c	N	PT3	Y	Interval 30 min; batch size 1 to 5	N		N	Process Role R2,R4,R5	N	6 Operators, fixed WC

Table A5-2 Experiment Scenario Set 2

Sce. No.	Work Dynamics						PD		RD	
	PV		VD		PMD					
S2-1a	Y	FT6, DL6	N	30 min, batch size 1	N	25-75% Randon	N	Process Role R2,R3,R4,R5	N	6 Operators, fixed WC
S2-1b	Y	FT6, DL6	N	30 min batch size 1	N	50-50% Randon	N	Process Role R2,R3,R4,R5	N	6 Operators, fixed WC
S2-2a	Y	DL4, DL6	Y	Interval between 10 to 50 min	Y	25-75% Randon	N	Process Role R2,R3,R4,R5	N	6 Operators, fixed WC
S2-2b	Y	DL4, DL6	Y	Interval 30 min batch size 1 to 5	Y	50-50% Randon	N	Process Role R2,R3,R4,R5	N	6 Operators, fixed WC
S2-3a	Y	PT3 FT6	Y	Interval between 10 to 50 min	Y	25-75% Randon	Y	R2,R3,R4,R5 or R2, R4,R5	N	6 Operators, fixed WC
S2-3b	Y	FT6 DL6 PT3	Y	Interval between 10 to 50 min	Y	33-33-33 % Randon	Y	R2,R3,R4,R5 or R2, R4,R5	N	6 Operators, fixed WC

Table A5-3 Experiment Scenario Set 3

Sce. No.	Work Dynamics						PD		RD	
	PV		VD		PMD					
S3-1	Y	FT6, DL6	N	30 min batch size 1	N	50-50% Randon	N	Process Role R2,R3,R4,R5	Y	Flexible operator locations
S3-2	Y	DL4DL6	Y	Interval between 10 to 50 min	Y	25-75% Randon	N	Process Role R2,R3,R4,R5	Y	Flexible operator locations
S3-3	Y	FT6 PT3	Y	Interval between 10 to 50 min	Y	25-75% Randon	Y	R2,R3,R4,R5 or R2, R4,R5	Y	Flexible operation locations
S3-4	Y	FT6 DL6 PT3	Y	Interval between 10 to 50 min	Y	33-33-33% Randon	Y	R2,R3,R4,R5 or R2, R4,R5	Y	Flexible operation locations

Appendix VI Plant Simulation model results

Table A6-1 Assembled table number, value and measure indicator **(Simulation period: 3 months)**

Scenario	FT6	Value1 (£)	DL6	Value2 (£)	PT3	Value3 (£)	DL4	Value4 (£)	Total Value (£)	*η1*	*η2*
S1-1a							287	56252	56252	0.816	1.953
S1-1b							287	56252	56252	0.816	1.953
S1-1c							286	56056	56056	0.816	1.946
S1-2a			317	50403					50403	0.986	1.750
S1-2b			318	50562					50562	0.986	1.756
S1-2c			318	50562					50562	0.986	1.756
S1-3a	358	70168							35442	0.991	1.231
S1-3b	359	70364							35541	0.991	1.234
S1-3c	359	70364							35541	0.991	1.234
S1-4a					410	48790			40590	269.270	1.409
S1-4b					410	48790			40590	269.270	1.409
S1-4c					410	48790			40590	269.270	1.409
S2-1a	57	5643	165	26235					31878	0.212	1.107
S2-1b	99	9801	93	14787					24588	0.178	0.854
S2-2a			164	26076			43	8428	34504	0.196	1.198
S2-2b			90	14310			106	20776	35086	0.184	1.218
S2-3a	241	23859			83	9877			32076	0.470	1.114
S2-3b	63	6237	61	9699	79	9401			23757	0.135	0.825
S3-1	148	14652	134	21306					35958	0.285	1.249
S3-2			246	39114			76	14896	54010	0.340	1.875
S3-3	275	27225			82	9758			35343	0.552	1.227
S3-4	102	10098	130	20670	119	14161			42549	0.275	1.477
S4	147	14533	148	23532	131	15589			51054	0.343	1.773

* Value adding based on sale price: FT6 £99; DL4 £196; DL6 £159; PT3 £119. labour cost based on 5 practicer level staffs, 3 month working. Total is £28800

Table A6-2 Resources utilisation within role covered process segment (Scenario 2-3a, As-Is)

Workstations (Roles) / Status	Top maker			Frame maker	Pedestal maker		Assembler	
	Hinge	Shaper	Sanding		Sander	Pedassembler	ToptoFrame	FrametoPed
Working	37.51	99.94	74.89	25.12	100	24.99	24.96	87.29
Waiting	0.02	0.05	25.10	0.79	0	75.01	74.96	12.69
Blocking	62.46	0.01	0.01	74.09	0	0	0.08	0.02

Workstations (Roles) / Status	Top maker			Frame maker	Pedestal maker		Assembler	
	Hinge	Shaper	Sanding		Sander	Pedassembler	ToptoFrame	FrametoPed
Working	37.51	99.94	74.89	25.12	100	24.99	24.96	87.29
Waiting	0.02	0.05	25.10	0.79	0	75.01	74.96	12.69
Blocking	62.46	0.01	0.01	74.09	0	0	0.08	0.02

Appendix VII Conference Paper at ICIEA2007

Role Based Modelling Approach to Designing Multi-product Systems

Appendix VIII Conference paper at DET09

Development of New configurable Process-resource Modelling Unit for Dynamic Manufacturing System Design

Role Based Modelling Approach to Designing Multi-product Systems

Chenghua Ding and Richard Weston
MSI Research Institute, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK.
E-mail: C.Ding@lboro.ac.uk

***Abstract* – A new approach to modelling roles in manufacturing organisations is described. Many companies seek to manufacture a variety of products with common resources. Hence complex decision making is required when seeking to match suitable human and technical resource systems to processes and workflows. The new approach uses Enterprise Modelling to explicitly define functional and flexibility competencies that must be possessed by suitable role holders. Also described is how Causal loop modelling can be used to reason about dependencies between different role attributes. The approach is targeted at the design and application of simulation models that enable relative performance comparisons (such as work throughout, lead-time and process costs) to be made and to show how performance is affected by different role decompositions and resourcing policies. The approach is illustrated with reference to a case study furniture making company.**

***Key words:* Enterprise Modelling, Resource System, Roles, Products Flows**

I INTRODUCTION

Manufacturing organisations are very complex yet need to function as dynamic systems, such that they remain competitive during their lifetime. Therefore when it is necessary to realise organisational change on any significant scale, consultative decision making is needed to conceive and agree upon improved ways of working. Many academic researchers have investigated and modelled complex organisations and their decision making. Their emphasis has covered many different aspects, but seldom has previous study considered ways of determining and accounting for all relevant aspects given a specific organisation and its changing working conditions. Without a more integrated view poor use of people and machine resources can result. Hence the authors are conceiving and testing the application of multi-perspective, multi-purpose models in support of various types of organisational decision making. One principle focus of their work is on combining the use of existing modelling approaches to externalise organisational knowledge typically vested in multiple decision makers. This paper will illustrate their approach with respect to a case study organisation.

II THE ROLE BASED MODELLING APPROACH

Previous modelling approaches have strengths and weaknesses. Hence the authors have sought to select some proven techniques and to use them in an integrated and systemised way to model static and dynamic aspects of complex manufacturing organisations. The main modelling methodologies and tools used include Enterprise Modelling (CIMOSA in particular) and Dynamic Systems Modelling (causal loop modelling and simulation software tools). The modelling techniques chosen are widely accepted individually and are known to have complementary strengths and weaknesses.

The case company employs circa 50 people to make around 350 types of high quality pine furniture products in response to orders received mainly from furniture stockists. Many of the case company problems revolved around their product dynamics: namely the time-varying mix and volumes of products ordered during any given timeframe. Therefore a key issue is to maintain competitive product quality, lead-times and cost despite constraints arising from a need to maintain a sufficiently competent and change capable set of human and technical resources. The company had previously experimented by implementing various organisational changes, alternative business and manufacturing policies and rules, new business systems and had sought to minimise waste and cost. However previously it had no analytical basis for change decision making.

A Stepwise modelling in the case company

Step 1: Context Modelling

Enterprise Modelling (EM) techniques were observed to usefully provide means of handling organisational complexity; by offering modelling concepts to decompose (general and specific) process networks into their component process segments. Also EM techniques provide means of documenting and visualising associated flows of activities, material, information, controls and so forth. [1] In the case company, the CIMOSA decomposition mechanism was used to ‘drill’ into complex problems to a sufficient level of modelling detail. The ‘table assembly’ process segment constitutes one of two main assembly processes realised in the assembly shop of the case company. The operation of this process segment had caused some concerns to the company management who required increased product throughput within this segment without increased investment in human and machine resource systems. Hence this segment was selected (along with other process

1-4244-0737-0/07/$20.00

segments not considered in this paper) as a subject of detailed modelling study. Firstly it was necessary for the modellers (the authors) to understand the normal operation of the assembly shop. Then it was necessary to collect historical information on product flows through the process segment and to directly observe operations, resource usage, process states and timings. Fig. 1 indicated a snapshot of a CIMOSA Activity Diagram captured to explicitly represent the assembly of one type of table (a Drop Leaf (DL) table). Activity diagrams of this type provided a backbone model to which Drop Leaf Table Assembly(DLTA) process information could be attached. Here standard CIMOSA modelling concepts were deployed but additional modelling concepts were conceived and used by the authors to describe Boolean Control Logic connecting activities. The purpose of this semantically enriched feature is considered in later section.

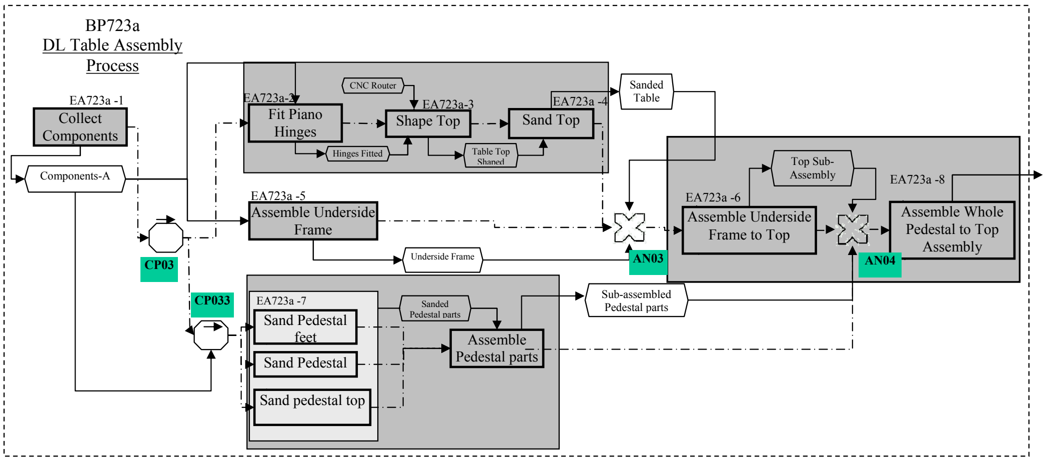


Fig 1 CIMOSA activity diagram: A segment of table assembly process

Step 2: Current Role Definition

During this modelling step, current roles of humans and machines in the table assembly process segment were observed and modelled explicitly. Here the use of CIMOSA model diagrams enabled systematic identification of competency requirements to the existing roles in DLTA: namely for 'Preparation', 'Top-maker', 'Frame-maker', 'Pedestal-maker', 'Assembler' and 'Internal Delivery' roles. The scope of these roles is shown by the grey blocks in Fig 1. In the real environment, role holders need to carry out all associated operations at specific times and at different distributed locations. The observed role specifications captured functional requirements of candidate role holders in a common format, bearing in mind that they form only a small part of a large and complex system. The attributes specified included role identifier, inputs, operations, functions, outputs, etc. When specifying roles at this stage, 'actual attributes of role holders' are decoupled from 'needed attributes of required roles'. The purpose of this separation is to enable comparative performances of alternative role holders to be modelled explicitly.

Step 3a: Define Existing Role Dependencies

Role dependencies were distributed in role-sets. As they are derived from the same parent CIMOSA model, defined sets of role requirements inherit well defined dependencies. Structural dependencies between roles can in general be coupled or decoupled. With reference to the main DTLA roles represented in Fig 1, the three components maker roles were observed to be decoupled after preparation, while all three became logically coupled to the Assembler role(i.e. the table top, underside frame and pedestal must be sub-assembled prior to final assembly). On the other hand, a higher level role is required to control and monitor instances of these roles. A 'Table Assembly Instructor' role holder must act in a superior role, that oversees the use of production planning information, to harmonise, instruct and facilitate interoperation between all lower level roles involved in the table assembly segment. Correct management of role dependencies is needed to ensure that the company as a whole operates efficiently. Such role dependencies created multi-level role network mechanism.

Step 3b: Analysis of Role Potential

In theory each DLTA role defined could operate (independently or collectively) in various ways. However as observed during Step 3a an activity structure (considered during Step 1) was overlaid onto DLTA roles. When production orders (derived from customer orders) are input to the assembly shop, specific requirements for table types, numbers off (of each table and component type) are defined along with their due dates. This in turn defines the needed instances of DLTA roles. At this point in time, in the real systems operation, suitable role holders need to be assigned to DLTA roles, so that they function and interact such that they meet production order requirements. It follows that suitable role holders need to be selected with reference to competencies required for each DLTA role that were previously defined during Step 2. For instance in the case company, larger DL

Tables have 5 pedestal feet, while smaller ones have 4; larger table tops need 3 hinges to fit parts together, smaller ones only need 2. Hence role holders assigned to the 'Pedestal Maker' and 'Top Maker' roles need to treat different DL table types differently. This highlights the importance of another competency requirement, i.e. the need for assigned role holders to be flexible ('programmable' in this case) such that product differences can be recognised and alternative actions taken. It follows that candidate role holders need at least two distinctive kinds of competency potential, namely functional and flexibility competency classes. Role holders assigned to roles must possess both competency types in multi-product systems. The actual need for flexibility arises because manufacturers seek 'economies of scope' by using a common set of resource to make a product range such that variations in customer demands can be averaged out to some extent. Only when actual work loadings are placed upon the overall production system and its specific process segments (the DLTA segment for instance), can multi-products work flows through any given process segment be specified; so that the suitability of a role design and its assigned role holders can be meaningfully assessed. This is because in the example real case, each role is loaded with different table types and sizes, which in turn needs different jigs, tools and setups before operations can commence.

Step 4: Assignment of Resources to Roles

From the previous analysis the present authors observed that any designed system of roles can only really be evaluated meaningfully when resources have been assigned as role holders and the configured sets of roles and role holders are loaded with specific work patterns. Also important to test is the ability of any designed set of roles and role holders to cope with change in actual work patterns. Hence the present authors devised a tabular method of assigning resources to roles and then to estimate and predict their abilities to perform adequately as role holders.

This tabulation was observed to be usefully divided into two stages. The first stage is concerned with an identification of suitable candidate resources. Typically more than one possible candidate role holder will possess the functionality and flexibility needed to perform a role. Hence optional combinations of resources could be assigned to any given task. However the process of drawing up a short list of suitable candidates should be well defined and easily traced. To systemise the static matching of resource competency potential to competency requirements of roles, candidate resources (and/or their combination) that possess needed competencies were grouped into common Resource Pools. Table 2 shows example Resource Pools. Here the authors chose to group resources in product oriented pools. In Table 2, for example, the 'Assembler' role for table type DL4 could be occupied by either an assembly staff 03 working manually or by an automated assembly machine. This means that in theory both of these resource types are viable role holders. Hence either can be placed into Resource Pool D01-RP2. By this means, with reference to specific roles the process designer can aggregate resources into pools, thereby generating explicit feedback at an early stage of analysis that candidate resources have potential to match differentiated role competencies, from functional and flexibility viewpoints. The data stored in these tables can readily be recorded into a database, and software can be created to systematically signal viable static matches between 'role requirements' and 'role holder potential competencies'. Subsequently decisions can be made to assign resources to roles. Table 3 illustrates such a list of candidate resource assignments to roles. The creation of this table was instrumented via the use of links specified by configuration information earlier defined. The last column lists selected resource assignments bearing in mind the multiple product realisation scenarios envisaged.

Step 5: Role verification with reference to value streams

When assigning specific role holders to roles the process designer needs to consider value addition and process costs. To maximise the value added by a given set of roles (and their embedded activity requirements) in general it is necessary to minimise various 'wastes', and where practical to reduce non-value adding activities carried out by assigned role holders.

TABLE 1
ROLE REQUIREMENTS SPECIFICATION

ID	Input	Activity	Competency required	Output	Elements of work	Host Role
D01-RR01	Pedestal fix jig	Fix pedestal with jig	Manual install	Pedestal fixed	Per pedestal	Preparation
D01-RR02		Setting up assembly machine	Manual setting up	Ass-machine ready	Depend on batch size	preparation
D01-RR03	Pedestal feet	sanding to satisfied part requirement	Manual sanding	Sanded pedestal feet	Depend on batch size	Sander
D01-RR04	Pedestal	sanding to satisfied part requirement	Manual sanding	Sanded pedestal	Depend on batch size	Sander
D01-RR05	Pedestal top	sanding to satisfied part requirement	Manual sanding	Sanded pedestal top	Depend on batch size	Sander
D01-RR06	Pedestal parts	Assembly parts	Assembly	Assembly pedestal parts	Depend on batch size	Assembler
D01-RR07	Assembled pedestal	Transport to table assembly	Manual movement	Delivered pedestal	Depend on batch size	Internal delivery

TABLE 2
RESOURCES POOL ELEMNTS AND ATTRIBUTE LIST

Pool name	Resources involved	Competency available	Capacity (products oriented)	Constraints (efficiency, cost)
D01-RP1	Staff 01	sand DL3	10/ hour	Motivation, skills, knowledge
		sand DL4	6/hour	
	Staff02	sand DL3	12/hour	Motivation, skills, knowledge
		Assembly DL3	2/hour	
D01-RP2	Staff 03	Assemble DL4	3/hour	Motivation, skills, knowledge
	Assembly Machine A	Assemble DL3, DL4	5/ hour	Breakdown percentage

TABLE 3
ROLE ASSIGNMENT AND RESOURCE ALLOCATION-SINGLE SCENARIO

Role Assignment id	Driven Role Requirement	Relational Resources Pool	Scenario	Assigned Resources
D01-RA01	D01-RR03	D01-RP1	8 DL3 table pedestal	Sander A
D01-RA02	D01-RR04	D01-RP1	2 DL3 table pedestal	Sander B
D01-RA03	D01-RR05	D01-RP1	2 DL3 table pedestal top	Sander B
D01-RA04	D01-RR06	D01-RP2	2 DL3 pedestal parts	Machine A

Such a requirement will be particularly explicit in companies adopting a Lean manufacturing policy. Hence it may prove effective for process designers to systematically consider value analysis when designing sets of roles and assigning role holders. In the DLTA area the roles 'Preparation' and 'Internal delivery' include non-direct value adding activities, such as collect components from the parts area, set up machines, jigs and tools and transport sub-assembly parts from station to station. These operation are necessary to complete table assembly tasks, however, they do not directly add value to products. Whereas with the other four DLTA role holders will directly impart value, e.g. by transforming components and assemblies, in terms of their size, shape, structure, composition, function, etc. This kind of analysis was observed to provide useful reference points during later stage role performance analysis, and can help to optimise the selected topology and occupancy of a role, role holder set.

Step 6: Causal Loop dynamic analysis

The previous modelling stages inform the design of a role, role holder set for a particular process segment, but thus far only static (non time dependent) analysis has been deployed. Only limited dynamic analysis work has been done by authors' colleagues. [2] Up to this point also the authors have deployed essentially static CIMOSA diagram templates and role attribute tabulations. However dynamic analysis and performance predictions about how a given role, role holder set can cope with different work patterns also requires use of modelling technologies that describe both causal and temporal impacts arising in any given process segment. Such dynamic variables are many in the real situation and may include changes in: work orders, staff shortage, machine breakdown, etc. Hence the present authors chose to deploy Casual Loop (CL) modelling to achieve qualitative analysis of role, role holder sets, designed via modelling stages 1 to 5. Fig 2 illustrates how a CL model can be created to understand how causal impacts propagate through complex dynamic production systems. The figure was divided into several parts. The first on the left side, is mainly concerned with customer related behaviour that impacts on product and works order requirements placed on the case company. The second part, at the bottom of the diagram, concerns conventional thinking about the process operation and financial implications arising from role related performance changes that impact on customer satisfaction. The third part is directly concerned with role based thinking and its propagated causal impacts. Causal effects arising from outside the targeted case company segment were also considered. The three star symbol is configured as 1) Scenarios 2) Problems 3) Solutions, that relate to three principle stages when using role based thinking to model, analyse and solve organisation design and change problems. With respect to the 'solution module' this diagram indicates outcomes from choosing different potential solutions and satisfying role requirements specifications via enhanced resource assignments or simplified requirements (through redesigning roles). Either can meet overall requirements but different outcomes result (in terms of process costs for instance).

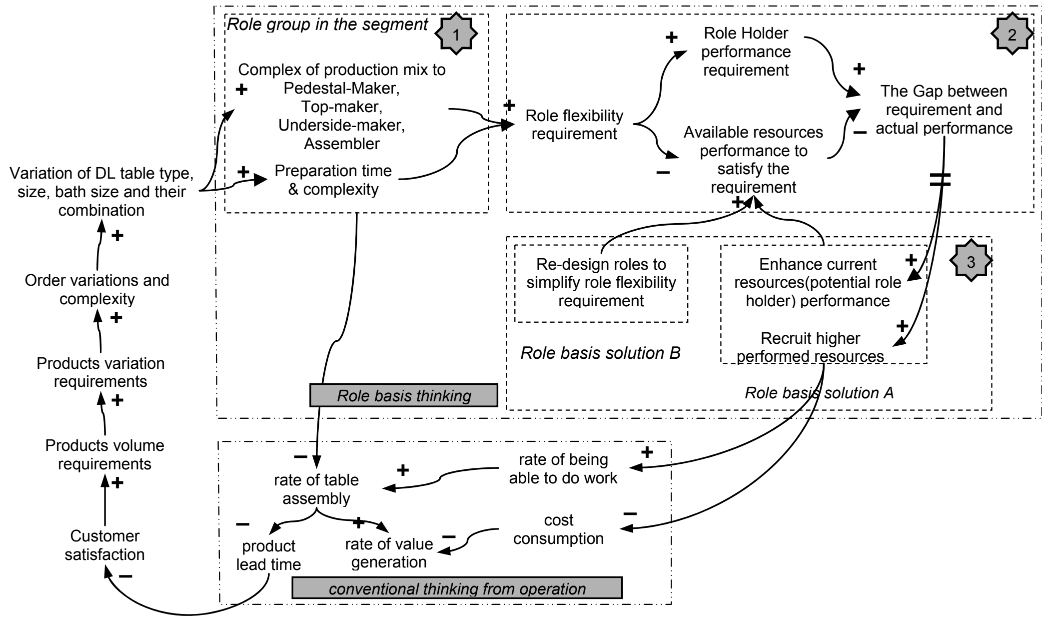


Fig. 2 Causal Loop diagram formatted example: Modelled to DLTA segment in case company

B Modelling Stages under development

Step 7: Enhanced dynamic modelling and analysis with software simulation tools

CL modelling helps understand likely outcomes from different role, role holder designs. It has also proven effective as a basis for specifying the purpose, scope and focus of simulation models that: (i) individually support resource system design and change decision making and (ii) collectively can replicate and predict holistic performances and behaviours of the case organisation. This naturally leads on to (a) the design of simulation models and simulation modelling experiments and (b) the ability to realise interoperation between simulation models.

Simulation experiments can quantify benefits and costs of different role, role holder configurations. Proprietary Simul8 software has been used to create multi-scenario dynamic models of the case company. This predicts outcomes as selected changes to process elements impact on each other Historical work pattern data about the case company, derived mainly from works orders information over a seven month time period, has been analysed. Similar product groupings have been observed to simplify and enable the input of work pattern data to the Simul8 models. This has allowed real DLTA process segment behaviours to be replicated with an acceptable level of precision, so as to validate the design of the simulation model.

Two further stages of modelling work remain. In the first additional stage, parameter changes are being made during simulation modelling experiments that reflect new role and role holder configurations. In the second additional stage, focus is on achieving interoperation between simulation models of ‘operational’, ‘tactical’, ‘strategic’ and ‘infrastructural’ process segments. The idea here is to develop reusable and computer executable organisational models that coherently support many kinds of decision making in manufacturing organisations. [3]

III ROLE BASED MODELLING INTEGRATION WITH DPU MODELLING CONCEPTS

The stepwise role-based modelling approach described herein is also being used in conjunction with a new approach to modelling multi-product flows. The authors have conceived so called ‘Dynamic Producer Unit’ (DPU) modelling concepts, that provide a coherent modelled abstraction of all possible kinds of work loaded resource system configuration, be that a person, a group of people, a machine or group of machines and people, IT systems or indeed business units and complete manufacturing enterprises. Details of DPU concepts and the static and dynamic models created so far will be presented in a sister paper. [4]

IV ILLUSTATION SUMMARY AND CONCLUSION

On an ongoing basis the new modelling approach is being used to improve the competitiveness of the case company; by better understanding staff and/or staff/machine combinations that act as role holders; by gaining new understandings about dependency relationships in terms of responsibilities, resources and products among different organizational configurations (i.e.

work stations, workshops, external stockists and suppliers); minimizing time loss and risks associated with investment in change (that previously had resulted in poor performance because of making ill advised change decisions). In a number of related modelling studies the authors have recommended (1) localized improvements to specific process segments of prime concern to the case organization and (2) recommended improved business and manufacturing policies that span multiple process segments based on role basis model analysis.

Through current model development and case study analysis, the role-based modelling approach was conceived as a means of developing and using coherent abstract descriptions of common reusable components (or building blocks) of manufacturing organizations. It was found that (1) role holder models could function individually to perform requirements of an assigned role and (2) where role interoperation is needed, role holders could function collectively through performing one or more higher level role composed of lower level roles.

It was necessary to explicitly define terms like: competency requirements, competency potential, and to link the use of these terms to terms used to describe DPUs. In the case organizations considered thus far, by modelling stereotypical DPUs as potential holders of roles, significant benefit has been observed. Although more extensive testing is required, the new approaches are founded on key modelling separations and decompositions within process network, role configuration and DPU models. Subsequent reintegration of concepts is achieved systematically via coherent use of enterprise, causal loop and simulation modelling techniques and tools. Further key separations related to structural aspects of these models facilitate both decoupling and flexible integration of ‘process’, ‘resource’ and ‘work pattern’ aspects. Therefore in theory at least, the modelling structures, concepts and techniques researched can usefully input to ontological developments related to complex organization design and change.

REFERENCE

[1] Chatha, K A and Weston, R H, 2005, Combined Enterprise & Simulation Modelling in Support of Process Engineering, *Int. J of Computer Integrated Manufacturing*, Vol., 18 No. 8, pp 652-670.

[2] Rahimifard A., Weston R.H. 2006 “The enhanced use of enterprise and simulation modelling techniques to support factory changeability” Accepted for publication in IJCIM

[3] Wagner, J.A., Hollenbeck, J.R. 1992, “Management of Organisational Behaviour”, Englewood Cliffs, N.J., Prentice Hall

[4] Weston,R.H., Zhen,M, Rahimifard, A., Ajaefobi, J., Ding, C., 2006. “Simulation Model Interoperability in Support of Complex Organisation Design and Change”, accepted for publication in ESM’2006

Proceedings of DET2009
6th International Conference on Digital Enterprise Technology
Hong Kong
14-16 December 2009

DEVELOPMENT OF NEW CONFIGURABLE PROCESS-RESOURCE MODELLING UNIT FOR DYNAMIC MANUFACTURING SYSTEM DESIGN

Chenghua Ding
Centre of Excellence in Customised Assembly
Loughborough University, Leicestershire UK
C.Ding@lboro.ac.uk

Richard Weston
Manufacturing System Integration Research
Institute Loughborough University, UK
R.H.Weston@lboro.ac.uk

ABSTRACT

This paper presents the development of a new modelling constructs enable human and technical resource system to be described coherently and explicitly as ‘configurable’, ‘re-usable’ ‘component’ of manufacturing enterprise, so as to support agile dynamic manufacturing process-resource system design and decision making. These components are referred to as ‘Dynamic Producer Units’ or DPUs. DPU characterization is designed to facilitate: (1) Graphical Representation (2) Explicit Specification and (3) Implementation Description of Resource systems. This enable the modelling of responsive production systems; where such systems comprise user defined configurations of process networks, resource systems and time dependent flows of units of work. The new modelling methods was then applied through a case study concentrate on engine assembly, illustrated how responsive production systems could be designed by using the method, followed by discussion of future development especially the capability of computer executable within simulation modelling environments.

KEYWORDS

Process-Resource System Design, Configurable Production System, Flexibility, Component

1. INTRODUCTION

Manufacturing organizations need to function as dynamic systems, such remain competitive during their lifetime. Therefore when it is necessary to realize organizational change on any significant scale, consultative decision making is needed to conceive and agree upon improved ways of working. Manufacturing Enterprises (MEs) must make optimisation concerning their process-resource system structure; product variety versus production complexity; manufacturing facilities, process and the entire logistical chain. The authors are conceiving and testing the application of more integrated models in support of various types of MEs decision making. One principle focus of the work is on combining the use of existing modelling approaches to externalize organizational process-resource system design and deployment typically vested to multiple decision makers. This paper will describe the new model approach development with its conceptual testing in a case study organization.

2. REQUIREMENTS FOR COMPLEX PRODUCTION SYSTEM

The functions of production system are achieved via both relatively enduring and short-lived structures such as project plans, product structures, work lists, process routes, workflow specifications, role descriptions. To complex system, significant benefit can be gained by developing and reusing separate models of (1) processes and (2) candidate resource systems to realize processes (Vernadat, 1996). It’s important to conceptualizes such a separation in MEs where processes and resource systems often have distinctive life time and change requirements. Formalize any change realization to ME processes and resource systems themselves require process as guided procedure and instruction (Weston, 1999). Process-oriented views of MEs can be used to potentially improve their current practice by changing human and technical resource systems, but could be only successful with deep understanding of what current production system required.

2.1 FUNCTIONAL REQUIREMENT

Functional capabilities of candidate resource systems can be deduced from knowledge about the various types and instances of process. One clear unifying need is for systems that structure and co-ordinate the way grouping people and technical resources to accomplish various types of tasks.

2.2 DECOMPOSITION REQUIREMENT

Rational basis is needed to decompose general ME requirements into classes of ME system, with defined specific requirements of decomposition and identification of system goal is not static problem. In addition, they are decision making to achieve system goals with timely dynamic change (Sackett and Fan, 1989).

2.3 INHERENT HANDLING MULTIPLE RESOURCE SYSTEM TYPES

It is impractical to suppose that a single, universal resource system could be designed to systemize all needed classes of manufacturing process types and instance. Multiple decomposed resource system types should be programmed to handle anticipated changes or reactively modified in response to unanticipated changes in business requirements and environmental conditions.

2.4 PROCESS AND RESOURCE SYSTEM INTEGRATION REQUIREMENT

ME resource systems should enable dependencies between concurrently executing threads of ME processes to be realized, underpinned and maintained. Within ME cases multiple resource system will need to interoperate to realize all needs. ME processes. If any given set of ME systems to be integrated are derived from a common system decomposition, in principle their interoperation should be more effectively and readily achieved.

2.5 ORGANIZATIONAL REQUIREMENT

All above complex requirements from functional, structural and integration would essentially ask ME process and resource system elements to be organized appropriately, and adjust organization accordingly when change incurs, so that process integration and system interoperation are appropriately enabled and do not overly constrain interworking in a specific ME by imposing inappropriate organizational boundary conditions

3. SUMMARY OF LITERATURE

The main literature has reviewed and analyzed to instruct this paper has covered the following four main aspects:

ME flexibility – Enabling manufacturing flexibility has been widely recognised as an essential strategy in current manufacturing industries and enterprises. It can facilitate various forms of change to processes and equipment within MEs (Olhader, 1989; Hill, 1995).

Enterprise Modelling (EM) – Can coherently represent MEs from different viewpoints and at alternative levels of abstraction. This can enable the development of well decoupled models of process segments and sub-systems and can facilitate model reuse in support of many types of change decision making (Vernadat, 1996).

Human system and role based modelling – The understandings of human system developed can enable the identification of suitable rules, responsibilities and authorities related to the assignment of 'jobs' and 'tasks'. Role based modelling methods linked to models of ME processes have been developed by research colleagues of the present author to explicitly identify 'change capable' requirements (Ajaefobi and Weston, 2005; 2006).

Component type architecture and modelling – have supported the application of flexible concepts. There are a variety of similar but not identical component technologies. It was stated formal components modelling concept has been developed (Boer et al, 2003; Gössler and Sifakis, 2005).

4. NEW APPROACH TO SYSTEMATIC COMPOSITION

4.1 PRELIMINARY MODELLING STAGES

The present authors and their colleagues at CECA[1] and MSI[2] used existing modelling approaches and tools, including Enterprise Modelling (EM), Role based Modelling (RM), Causal Loop Modelling (CLM) and Plant Simulation®, to coherently model multi-product realization systems, covered both static and dynamic, functional and behavioural aspects. The preliminary stages before the development of integrated new modelling approach

---

[1] CECA: Centre of Excellence in Customized Assembly, Loughborough University Leicestershire, UK

[2] MSI: Manufacturing System Integration Research Institute, Loughborough University Leicestershire, UK

was presented by present authors in pervious papers (Ding and Weston 2007; Ajaefobi et al, 2008). It can be summarized as following stages:

1) Context Modelling – EM techniques provide means of handling organizational complexity, decompose process networks into their process segments. Activity Diagrams of EM document and visualize associated flows of activity, material, information and control logic.
2) Role definition and configuration – Roles defined with their overlaid onto process segment (group of activities). The observed role specifications captured functional requirements of candidate role holders in a common format.
3) Assignment of resource to roles – It has been observed that any designed system of roles can only be evaluated meaningfully when resource have been assigned as role holders and loaded with actual work patterns.

These stages of modelling work are collectively presented in Figure 1.

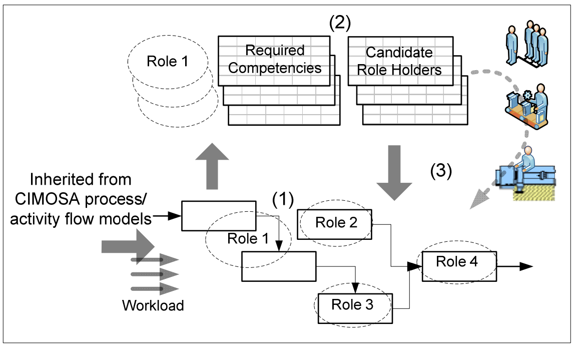


Figure 1 – Preliminary modelling stages

4.2 COMPONENTS MODELLING UNIT

Based on the previous modelling work, the new development towards integrated process oriented component concepts where the focus of study has been on developing and deploying the new modelling constructs to enable human, machine and IT resource systems to be described coherently and explicitly as 'reusable', 'change capable', 'components' within manufacturing enterprises. These components are referred to as 'Dynamic Producer Units' or DPUs.

DPU concept is to provide coherent abstract descriptions of common reusable building components of manufacturing organisations. Hence the component based model results could instruct decision makers in organisation how to achieve integrated and effective use of finite, valuable and constrained sets of resource systems, accordingly resource system changes can be made dynamically and continuously through the lifetime of those organisations. Consider typical manufacturing organisations, resource system components as building blocks comprise various distributed people, machines and computers. Common building blocks are configured into various system format through organisational structures and parametric data, so that they could function and behave as required (specified during the configuration) in a specific workplace and under specified set of workload conditions. Therefore to the overall abstraction of above characteristics, the DPU is defined as '*An organisational unit comprising human and technical resources that is a configurable, reusable and interoperable component of one or more complex organisations*'. In addition to the definition, some assumptions were made: (1) each DPU could function individually, as a holder of one or more assigned roles and (2) configurations of multiple DPUs will interoperate so as to function collectively as holders of one or more higher level (more abstract) roles (i.e. roles composed of lower level roles).

4.3 MODELLING ARCHITECTURE

When looking into the proposed architecture of DPU, its configuration with composition of human and technical resource system could be categorised into three aspects:

Functional aspect – expressed in terms of 'functional competencies', to specify what is expected to be capable or achieve, through explicit expression. For example competencies to process orders of type X, design products of type Y and assemble product Z.

Structural aspect – expressed in terms of organisation method to activity, information, control and material flows, how they are linked, how to assign roles and descriptions of roles interactions. Graphics and tabulation are the two primary methods used in this aspect.

Behavioural aspect – expressed its dynamic characters in terms of productivity characters i.e. performance levels (e.g. lead-times, rate of value addition and costs consumed), changeability characters (e.g. change capability and operational flexibility) and self characters i.e. relevant cultural and personality concerns (e.g. level of workforce motivation and influential cultural values).

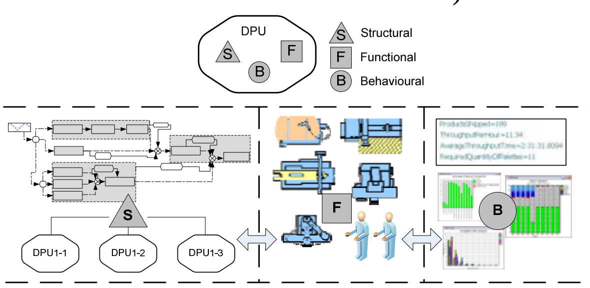


Figure 2 DPU modelling architecture

DPU's three aspect architecture are abstracted by three different symbols: Triangle – Structural, Rectangle – Functional and Circle – Behavioural, as shown in Figure 2. Each linking to modelling natures presented as some snapshots at the bottom of the diagram.

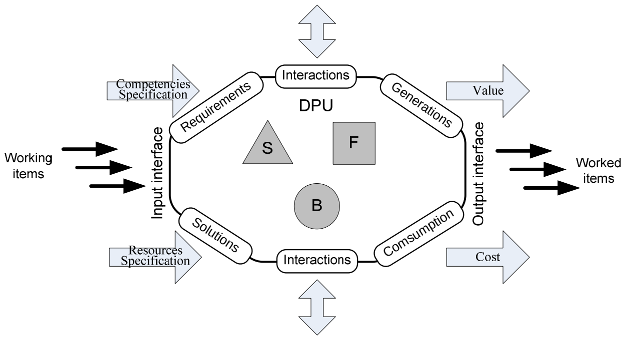


Figure 3. Integration view of Dynamic Producer

Figure 3 denotes DPU in an integrated view. Externally, DPUs can be considered as a black box component, which can process multiple work streams through specification of competencies and resources input, delivering with value and cost(via timely resource consumption). During its deployment, DPUs need to use finite resources to cope with predictable and unpredictable dynamics, with respect to required input work patterns; process logic; and assigned human and technical resources. Further more, DPU needs interact with other DPUs, all these external parameters pass through different input/output interface. Such 'black box' DPU with its classified interfaces for connection, is particularly useful for high abstract level model users whose primary focus is not on detailed modelling specification to each DPU, rather their linking, collaboration, coordination in terms of working items, resources, value as well as other multiple DPUs, thus their main focus could concentrate on supervising and managing DPU deployment within broad ME environment and their overall performance achievement.

4.4 COMPUTATIONAL CAPABILITY

In addition to the conceptual DPU's modelling approaches integration, DPU modelling should be capable to give computational presentation to ME system behaviour. It is required to establish a computational basis for modelling unitary DPUs in relation to work streams, it is also important to consider when dealing with multiple products work stream, the value of these parameters may change:

4.4.1 Work item type

Those physical, logical or information entities that require processing by a DPU. This could be raw material, parts or semi-finished product which needs processing. Alternatively it could be an input of a set of mechanical or electrical components in the case of assembly DPU.

4.4.2 Unit of work

This defines type(s) of unit operation that need to be performed on a particular work item type. One unit of work for DPU may include multiple operations or multiple physical items, however those operations or physical items should be processed as one batch over the period of time as required.

4.4.3 Work item input rate

This is defined as the input frequency of any given work item type to be processed by one or more DPUs. In reality work item types will depend on enterprise specific demand patterns, inventory levels, adopted production synchronisation policies, etc. It initially varies depending on the previous stage, which is independent. However, DPU's designed achievable work rate would instruct the processable work item rate to avoid significant bottle necks.

4.4.4 Quantity of work required

This is the sum of work units necessary to process a given work item type. Combined with the defined 'Unit of work' concept, this can identify the total required number of work to single given work item type.

4.4.5 Rate of processing

This represents the processing time required for a unit of work. This rate varies with respect to different work item type, so as to present variable rate specify to work item types.

4.4.6 (Achievable) DPU work rate

This is the total number of work items by type [or units of work (whichever is relevant)] that a particular DPU has potential to process in a unit of time, when disregard the possible delay, switch over, motivation, machine breakdown etc. Thus only the maximized target rate, yet give a guidance indicator.

4.4.7 Example of DPU computational parameters

Table 1 gives a simple example of above defined DPU computational parameter, help to understand the description of those parameter terminologies.

Table 1 DPU parameters terminology example

Parameter Term	Example at operational level
DPU	Drilling centre
Work item type	Part X
Work item input rate	50 pats/day
Unit of work	Drilling a standard hole; Drilling a large hole
Quantity of work required	1 std hole; 3 large holes
Rate of processing	Std hole – 2 minutes OR Large hole – 3 minutes
Achieveable work rate	48 part X / day 240 std holes / day OR 160 large holes / day

4.5 DPU'S COMPUTATIONAL EXPRESSION

Having above computational parameter set, computational feature of DPU can further be calculated through developing mathematical expression.

Essentially multiple work item arrivals, the factors induced to DPU is working item processing rate, ultimately depend on 1) the behavioural characteristics of their actual involved resource elements (people, machines & IT) and 2) configured structure, therefore to determine a DPU's potential 'capacity to do work'. The 'quantity of work required' to process specific work items will be different (and the processing of each work item may need more than one unit of work). With such 'rate of processing', once work items are input to a DPU, it assumed that total operation time based on single workflow stream can be calculated from the expression:

$$T_{1-n} = \sum_{w=1}^{w=n} \left(N_w \middle/ Rp_w \right) \qquad (1)$$

Where

T_{1-n}: total operation time for all number of 'n' type of different work items;

W_1 , $W_2 \ldots Wn$: All different work items types;

R_{pw1}, R_{pw2}, R_{pwn}: Rate of processing specify to each work item type;

N_{w1} , N_{w2} , $\ldots N_{wn}$: the quantity of work required for each item type during defined time(e.g. each shift, each working week etc.)

From a DPU configuration structure, multiple sub-DPUs with available resource could process work items concurrently. Based on having available resource assigning to DPUs, parallel processing would increase the DPU capability and reduce total operation time when same amount of work items arrive. Taking the same expression structure from above, assume the DPU structure has been configured with several parallel processing streams. The type aggregated in each collection could vary, which means the number of working item type in each collection might not necessary to be same. Interpret from above definition, here:

$$N_{all} = \sum_{i=1}^{i=m} N_i \qquad (2)$$

N_i: number of each work item type which share same standard processing time;

N_{all}: total different work items;

m: the number of parallel processing stream.

thus using same format, in each stream, the total operation time could be defined as:

$$T_{1-ni} = \sum_{w=1}^{w=ni} \left(N_w \middle/ Rp_w \right) \qquad (3)$$

$[W_{1,\ n1}]$, $[W_{2,\ n2}] \ldots [W_{m,\ nm}]$: the collection of specific work item types, each collection could be processed by one parallel stream, from 1,2, till m.

The total operation time for the DPU would be restrict by the stream operation which spend longest time to processing work items flow into it:

$$T_{1-n} = Max_{i=1}^{i=m} (T_{1-ni}) \qquad (4)$$

The above expression enable represent complex configuration with working item type and variable number go into DPU. Such time constraints raised the concern of how to balance the working load to each parallel stream (Sub-DPUs) to minimise their time difference, which would ask the structure configuration design put this in the mind, also, need capable for resource assigning to each sub-DPU flexible to move and re-allocated, to dynamically balance working.

5. CASE STUDY OF ENGINE ASSEMBLY

The application and testing of the new DPU modelling approach was taken into a diesel engine manufacturing company. However in view of time constraints on the authors' research thus far, in this paper the author only reports on conceptual modelling infrastructure.

The case study is conducted with powertrain division of a company designing and producing diesel engines for trucks and boats, here referred as DEA. DEA has established a mixed model type assembly strategy. Their current assembly systems run in both parallel and linear (serial) assembly steps. Most of the customizations (such as installation of special components and customised branding) takes place in the final assembly stage. Currently there are two high volume engine families and one low volume engine family share the same line. High volume engines' assembly go through both two parallel station streams; low volume engines always only go through same one.

5.1 MAIN RESOURCES FOR ASSEMBLY PROCESS

The main resources during assembly process are divided into three groups:

Line operators: They are distributed along work stations on each line. When engines arrive and stop at their working place, standard assembly work instructions are followed that are initiated by guidance signals sent from a ‘mainframe’ database via a networked information distribution system. These signals synchronize instructions and movement of the various stations.

Hand operated accessory tools: These are a set of tools available in side tool racks, located at a workstation and are used by operators to install small parts such as bolts, screws, company brand badges, etc.

Carrier AGVs: They are automated mobile trolleys that move the engine through the workstations. AGV stops at a designated working place, then rotate the engine with its hold-rotate mechanism to provide the operator with a optimal working angle to perform a task. There are several types of AGVs. More advanced AGVs provide precise rotation or lean angles, and lift engines to suitable working height from an ergonomic perspective where necessary. They also have a touch screen as an information board. While the basic AGVs don’t have a lean or lift capability, nor a built-in display screen information.

5.2 DPU CONCEPTUAL MODELLING TO FINAL ASSEMBLY PROCESS

The set of resource was defined as DPU named “Engine Assembly Unit”(EAU) with ‘*configurable capability to complete dynamic engine assembly operations as specific required*’. Figure 4 illustrates some examples of such DPUs distributed within final assembly area. They are grouped by different possible resource compositions.

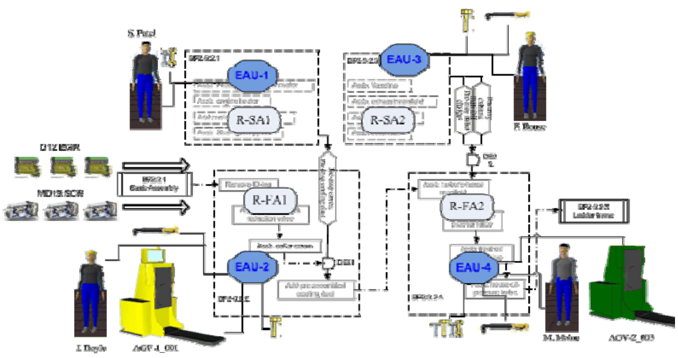


Figure 4 EAU Resource Group

5.3 RESOURCE ANALYSIS TO DPU CONFIGURABILITY

Carrier AGV, operators, operation instruction, hand tool kits and information display screen are common resource types used for assembly. To utilizing these different types of resource, they are analyzed in terms of their different characteristics.

5.3.1 Applicable competency variance

Each resource class has several type options, provide different capability and features, which could evaluated as their variable possessed competencies to fulfil requirement. Figure 5 listed the different options for the five resource classes could apply in final assembly process:

- Different Carrier AGVs with variable technical specification, thus hold variable functions.
- Different skill level Operators rely upon their knowledge and experience, could work with different capabilities and performances.
- Operation instruction could be provided by different ways, either on screen with very detail or simple colour differentiation. While surly they vary in terms of information semantic richness.
- Different hand tools functional differently, can deal with different parts and accessories regarding the working point shape, size, motion etc.
- Information display screen, as the most essential information resource solution, the screen could be integrated on top of advanced AGVs, overhead of the line, or networked pc along the line. They could provide some type of information, but have different convenience to access and read by operators.

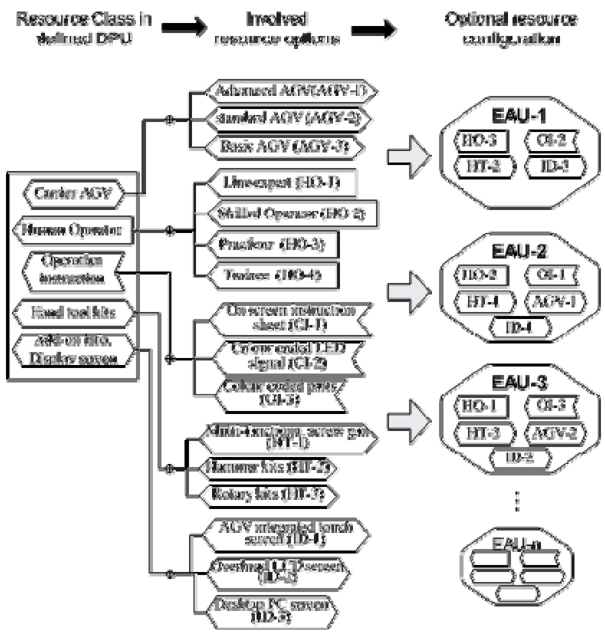


Figure 5 EAU optional resource configuration architecture

5.3.2 DPU's optional resources configuration

The above resource analysis indicates that different resource classes with variable options bring in different capability from available competencies. Concern TEM assembly process in reality, human/technical resources are structurally combined. Thus when different operators, AGVs, hand tools, information indicators options are grouped together, they could provide variable competencies through the configuration. DPUs composed by these resource groups could then take variable roles regard their required competency groups if match each other. As shown in figure 5, looking resources in the final assembly process:

1) The defined 'EAU' could include up to five resource classes;
2) All included resources options, their capability associated role required competencies were specified;
3) Hence different configuration of resource options could make them into multiple DPU instances as EAU-1, EAU-2 till EAU-n.

By this means, configuring these resources into different groups, they are designed to carry specific competency, and in further, they constitute candidate DPU instances.

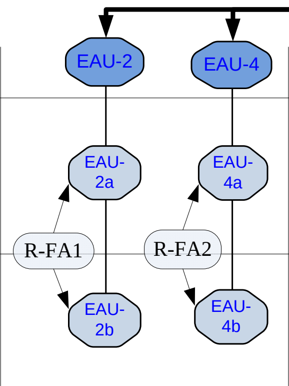
5.3.3 Potential improvement through resource re-assignment to DPU

Taking the method of above resource configuration, when the feature of two sub-line within final assembly, new solution to use different resource assignment policy can be compared. Associated with optional resource, Table 2 gave a comparison example of how new resource configuration to EAU instances. The result of comparison thus can support the necessary decision making for operation management to improve resource utilization.

6. CONCLUSION AND FUTURE DEVELOPMENT

DPUs are a modelling abstraction of elemental building blocks (or components) of an organisation that itself comprises human and technical resources (people, machines and/or computers). In this paper focus has been on representing functional structural and behavioural aspects of DPUs concept and architecture, as building blocks of responsive production systems. Lifecycle engineering of alternative configurations of DPUs requires methods that structure and inform human decision making about resource configurations by enabling behaviour modelling.

Table 2- the Caption should be placed above the table



	Operation feature comparison	Resource characteristics requirements comparison	DPU Resources assignment solutions
Sub-line A	• Higher volume • Less frequent change • Shorter step working time • Lower skill level requirements	• Quick transport carriers, easy access instruction • Standard tools, standard instruction display • Less skilled operators • More carriers and operators number	• AGV-1, • HO-2,HO-3, HO-4; • OI-1, OI-3; • HT-2, HT-3 • ID-1
Sub-line B	• Lower volume • More frequent change • Longer step working time • Higher skill level requirements	• Flexible change, detailed instruction • Flexible hand tools • Highly skilled operators • Less carriers and operators number	• AGV-2, • HO-1,HO-2; • OI-1,OI-2; • HT-1, HT-3 • ID-2, ID-3

It is assumed that typical behaviour modelling exercises need to be preceded by (a) role requirements definition and (b) candidate mappings of individual and collective DPU structures, competencies and characters onto the role requirements identified.

- Linking previous modelling stages with DPU development presented in this paper, DPU integrates a conceptual overview of a new process-oriented approach to achieving system composition from reusable systems components. It implicit principles as follows:
- Processes are decomposed into viable Roles that DPUs can realize;
- DPUs are flexible configurations of human and technical (machine + IT) resources that possess abilities to realize defined Roles;
- DPUs will be programmable resources, i.e. can possess local changeability enabling them to reach various states within their design envelope;
- DPUs will collectively be flexibly configured or recomposed via the imposition of flexible structures to bind some selected set of DPUs into higher level DPUs;

- DPUs can be attributed to one or many roles, hence their actual assignments to roles may need to be scheduled.

DPU, as new integrated modelling concepts, the development thus far restricts within paper based configuration. Itself still lack of complete computer executable from definition, structural configuration till resource assignment execution. The case study carried out also only restricted within quite narrow production system segment. The conceptual model result didn't get support by generating simulation model with quantitative analysis and measurement how different resource configuration options would impact production output and resource utilization. So further development to enhance overall computer executable capability would rely on some existing component based modelling software tools, to embed DPU's functional, structural and behavioural modelling capability into computerised environment

7. ACKNOWLEDGMENTS

The new modelling approach development has been exploited by the Loughborough University CECA team through creating multi-perspective, multi-level simulation models of production systems used by industrial clients from various industry sectors (http://www.ceca-uk.com/). Parallel PhD research activities in the MSI Research Institute have been contributed to ongoing development.

REFERENCES

Ajaefobi J.O., Wahid, B.M., Weston R.H., Rahimifard A., "Modelling Complex Systems in Support of Human Systems Design and Change Part 1: Applied to a case study SME", *accepted by IJCIM for publishing* 2008

Ajaefobi J.O., Weston R.H, "Human systems engineering instrumented by modelling techniques", *12th IFAC Symposium on Information Control Problems in Manufacturing*, Saint Etienne, France, 2006

Ajaefobi J.O., Weston R.H., "Modelling Human Systems in Support of Process Engineering", *Proceedings of the International Conference On Human Aspects in Production Management*, Karlsruhe, Germany, 2005, pp3 – 16

Boer F.S.D, Bonsangue, Graf M.S. and de Roever W.P., "Formal Methods for Components and Objects", Springer- Verlag, Berlin, 2003

Ding C.; Weston R.H., "Role Based Modelling Approach to Designing Multi-product Systems". *Industrial Electronics and Applications, 2007. ICIEA 2007. 2nd IEEE Conference*, 2007, p1706 – 1711

Gösslera G; Sifakisb J., "Composition for component-based modelling", *Science of Computer Programming* Vol 55 2005, p161–183

Hill T., "Manufacturing Strategy: Text and Cases", MacMillan, London, 1995

Olhager J., "Manufacturing flexibility and profitability", *International Journal of Production Economics* Vol 30-31 1993, pp67-78

Sackett P, Fan I., "The Control of a Flexible Manufacturing System by Short-term Goal Identification", *International Journal Of Advanced Manufacturing Technology*, vol.4, 1989, pp123-143

Vernadat F.B., "Enterprise Modelling and Integration: Principle and Applications", London, Chapman & Hall, 1996.

Weston R.H., "Manufacturing Business Systems Requirements & Current Practices", *Manufacturing Business System Notes, Loughborough University*, 1999