DEVELOPMENTS TO GRAPHICAL MODELLING METHODS AND THEIR APPLICATION IN MANUFACTURING SYSTEMS ANALYSIS AND DESIGN

Gary John Colquhoun

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ABSTRACT

Systems modelling methods have evolved out of the need to understand and analyse complex human/machine/object systems. This research aims to contribute to the use of static graphical modelling methods as a means of gaining insight, analysing, designing and developing strategies for change in manufacturing enterprise systems.

The research is introduced through a discussion of the factors underlying modelling in manufacturing enterprises. The success of IDEF methods in the US defence manufacturing industry has strongly influenced this work and their development is reviewed. Findings from a survey of published IDEF methods research are reported and an investigation of IDEF$_0$ modelling practice in the UK is accomplished using a survey of modelling practitioners. The surveys and a comparative analysis of a range of modelling methods provide a basis to contextualise IDEF$_0$ modelling and review the potential to expand its capability. Reference models for manufacturing systems are analysed and an IDEF$_0$ reference model case study is used to demonstrate their capacity to provide significant improvements in aspects of the modelling process. An investigation of systems architectures and frameworks provides a precursor to proposals to combine IDEF$_0$ and IDEF3 methods in the context of a manufacturing enterprise modelling framework.

A modelling approach is developed by combining the two methods in a novel composite IDEF0-3 method that has the capability to describe the behavioural characteristics of manufacturing systems. The model syntax is refined and tested and an IDEF0-3 methodology is developed. The new method is validated through a case study in a batch manufacturing company currently undergoing re-organisation to expand its manufacturing capability. IDEF0-3 is shown to be capable of capturing and representing the perceptions of domain experts, providing sufficient resolution for analysis and substantially influencing the design of an improved TO BE model. The research concludes that IDEF0-3 is able to represent features of systems hitherto not possible to describe using IDEF$_0$ or IDEF3 as individual methods, that it allows meaningful analysis and that it can effectively contribute to manufacturing enterprise systems analysis and design.

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NOMENCLATURE

ABLE PM	Automated Business Logic Engineering - Process Modelling
AFCAM	Air Force Computer Aided Manufacturing
AMTeC	Advanced Manufacturing Technology Centre
APEC	Asia-Pacific Economic Co-operation organisation
APT	Automatically Programmed Tool
BDF	Business Design Facility CASE tool (Texas Instruments)
BM	Behaviour Model (a sub-model of IDEF4)
BOM	Bill Of Material
BPR	Business Process Re-engineering
BPwin	IDEF$_{1X}$ modelling software tool (Logic Works Inc.)
BSD	British Steel Distribution
CAD	Computer Aided Design
CAM-I	Computer Aided Manufacturing - International
CAPP	Computer Aided Process Planning
CASE	Computer Aided Software Engineering
CATWOE	Customer, Actor, Transformation, World-view, Owner, Environment
CEME	Construction Earth Moving Equipment centre
CIM	Computer Integrated Manufacturing
CIM-OSA	CIM - Open Systems Architecture
CNC	Computer Numerical Control
CORE	The COntrolled Requirements Expression method
COSMO	Interactive Enterprise engineering and CASE software tool
CPA	Critical Path Analysis
CPN	Coloured Petri-Net
DACOM	D. Appleton Company
DFD	Data Flow Diagram
DM	Dynamic Model (a sub-model of IDEF4)
E/R	Entity Relationship (model)
EDC	Engineering Data Control
EPSRC-CDP	Engineering and Physical Sciences Research Council-Control Design and Production group
ERwin/ERX	IDEF$_{1X}$ modelling tool
ESPRIT	European Strategic Programme for Research and Development in Information Technology
FEDD	For Early Domestic Dissemination

FEO	For Exposition Only
FIPS	Federal Information Processing Standard
FMEA	Failure Mode Effect Analysis
GDP	Gross Domestic Product
GERTE	Graphical Evaluation and Review TEchnique
GRAI	Graphe à Résultats et Activités Interliés (Graphs with Results and Activities Interrelated).
HIPO	Hierarchical Input-Process-Output
HOS	Higher Order Software
ICAM	Integrated Computer Aided Manufacturing programme
ICOM	Input, Output, Control, Mechanism (in IDEF$_0$ diagrams)
IDEF	The I-CAM DEFinition techniques (as defined by the ICAM programme)
IDEF	Integration DEFinition methods (as defined by KBSI, i.e. post-IDEF$_2$ methods)
IDEF$_0$	The I-CAM DEFinition functional modelling method.
IDEF0-3	The Composite behavioural modelling method
IDEF0-TD	The IDEF$_0$ - Triple Diagonal technique
IDEF$_1$	The I-CAM DEFinition information modelling method
IDEF$_{1X}$	The I-CAM DEFinition IDEF$_1$ eXtended data modelling method
IDEF$_2$	The I-CAM DEFinition dynamics modelling method
IDEF3	Integration DEFinition - Process Description capture method
IDEF4	Integration DEFinition - Object oriented design modelling
IDEF5	Integration DEFinition - Ontology description capture methods
IDEF6	Integration DEFinition - Design rationale modelling
IDEF8	Integration DEFinition - User interface modelling
IDEF9	Integration DEFinition - Scenario-driven IS design
IDEF10	Integration DEFinition - Implementation architecture modelling
IDEF12	Integration DEFinition - Organisation modelling
IDEF13	Integration DEFinition - Three- schema mapping design
IDEF14	Integration DEFinition - Network design
IDEM	Integrated Design and Modelling methodology
IEEE	The Institute of Electrical and Electronics Engineers
IFEM	Integrated Framework for Enterprise Modelling
IICE	Information Integration for Concurrent Engineering programme
IISS	Integrated Information Support System
IMP	Integrated Manufacturing systems design Procedure
IS	Information System
ISO	International Standards Organisation
KBSI	Knowledge Based Systems Inc.

LDDT	Logical Database Design Technique
LOT	Lexical Object Types (from the Nijssen Information Analysis Method)
LUM-TM	Liverpool University Method for Tool Management
MAP	Manufacturing Automation Protocol
MOSES	Model Oriented Simultaneous Engineering System
NCMS	National Centre for Manufacturing Science
NET_TRANS	Net Translator
NIAM	Nijssen Information Analysis Method
NIST	National Institute of Standards and Technology
NOLOT	Non-Lexical Object Types (from NIAM)
OR	Operations Research
OMT	Object Method Technique
OOA/OOD	Object Oriented Analysis and Design technique
OSTN	Object State Transition Network (from IDEF3)
PERT	Programme Evaluation and Review Technique
PFN	Process Flow Network (from IDEF3)
ProSim	IDEF3 software tool (KBSI)
QC	Quality Control
RAM	Random Access Memory
SA	Structured Analysis
SE	Structured Engineering
SADT	Structured Analysis and Design Technique
SAINT	System Analysis of Integrated Networks of Tasks modelling method
SEE	Society for Enterprise Engineering
SIMCON/2	Simulation cell Controller
SM	Static model - a sub-model of IDEF4
SSADM	Structured System Analysis Design Methodology
SSM	Soft Systems Methodology - Checkland
TIF	Toronto Industrial Fabrications
UOB	Unit Of Behaviour (from IDEF3)
VSM	The Viable Systems Model
WIP	Work In Progress
WITNESS	A simulation software tool (AT&T ISTEL)
ZENO	A manufacturing cell name (at Scholl Consumer Products)

CHAPTER 1

INTRODUCTION

1.1 PREAMBLE

The work presented in this thesis grew from the early research of Baines (Baines and Betts, 1984, Hughes and Baines, 1985) and from work carried out by the Advanced Manufacturing Technology Centre[1] (AMTeC) on the use of IDEF methods in modelling manufacturing enterprises. These two threads were the foundation of an AMTeC supported project that used modelling methods to examine the role of Computer Aided Process Planning in a CIM environment (Colquhoun, 1988), findings from the work were subsequently published (Colquhoun, Gamble and Baines, 1989) and led to the line of research presented in this thesis.

This chapter discusses the global business environment facing UK manufacturing in the late 20th century and presents a case for the adoption of modelling methods as tools for manufacturing enterprise analysis, planning and management. The key concepts that underpin enterprise modelling are discussed and the $IDEF_0$ modelling method, that has substantially influenced the research, is introduced. The objectives and research methodology are defined and the chapter ends by reviewing the contribution to knowledge and validation of the work.

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[1] AMTeC was an arm of the Machine Tool Industries Research Association, Macclesfield, Cheshire, UK.

1.2 MANUFACTURING - A GLOBAL CONTEXT

Manufacturing industry is undergoing a period of fundamental change. National and political boundaries are no longer limits to company organisation, trade blocs working to pool manufacturing ability and protect markets are emerging to change the nature of industrial co-operation and competition. Global communication links are forming new economic patterns sensitive to industrial performance around the world The pace of new technologies and the rate at which new products enter the global marketplace are all forces that make the manufacturing future for industrialised nations less predictable and more changeable than at any previous period in the twentieth century.

For the UK and other industrialised economies manufacturing is a key to national prosperity, 'In the UK manufacturing contributes 22% of GDP, employs five million people (21% of the workforce), generates employment for a further five million' (Deasley, and Collins, 1994) and, in 1993, 82% of visible exports consisted of manufactured goods (HMSO, 1995). This is despite the period between 1980 and 1992 when high exchange rates and a world-wide recession forced the closure of many manufacturing enterprises accelerating the decline of the UK's industrial base and when Britain had its first manufacturing trade deficit since the Industrial Revolution (Elliott and Beavis, 1994). In the UK now (1995) there is some cause for optimism in manufacturing, modest growth, lower unemployment and low inflation. There is, however, still concern about the size of its manufacturing base, the loss of skills, the short term view taken by investors, the dependence on inward investment (40% of total inward investment coming into the EU has been taken by the UK, (Elliott, 1995)) and the future for foreign owned enterprises based on assembly plants. Initiatives such as the Manufacturing and Construction Alliance (a parliamentary lobby for manufacturing chaired by Nicholas Winterton MP) have failed to persuade Government, Banks, Pension funds or Venture Capitalists of the need to treat manufacturing differently and to finance renewal of manufacturing industry through investment in research and development. Small and medium manufacturing enterprises (SMMEs) are critical for the future of manufacturing, in the UK 99% of VAT registered manufacturing units are SMMEs employing 45% of the manufacturing workforce and producing 30% of total manufacturing output (Levy, 1993). International competitors such as Germany offer funding through a dedicated low interest, government supported bank for small enterprises and in Japan access to new technology and long term finance for small enterprises is supported by the 'Small and Medium Enterprise Law'.

In the USA public expenditure has supported military development and its defence establishment has been 'the largest single source of R&D funding in the world' (Samuels, 1994). The USA is still the foremost industrial nation in the world today however their decline through a contracting manufacturing base and competition in home and European markets from Japan and emerging Asian nations is recognised. They have responded to changing global markets in the formation, in 1989, of the Asia-Pacific Economic Co-operation organisation (APEC) an ominous sign for Europe and the fragile UK manufacturing recovery. 'By 2000, APEC will be larger than the G-7 industrialised countries and will dominate US trade' (Tran, 1993). A marginalisation of manufacturing in the UK and Europe will result from a failure to develop existing markets and penetrate emerging markets in the Pacific rim and Eastern Europe.

The situation of UK companies means it has never been more important for them to understand the way they work and to adapt and respond to competition using innovative manufacturing and organisation. For manufacturers without flexibility or the ability to adapt, the new world is a major threat. In July 1994 a UK government research initiative (The Innovative Manufacturing Initiative (IMI)) was launched in recognition of the importance of longer term research in manufacturing to the economic vitality of the UK. Process based manufacturing is the first industrial sector to be targeted and will receive £20M research funding over the next ten years. An aim of the initiative is that by 2005 the UK will be a world leader in the modelling and analysis of the global supply, distribution and marketing of process products and will be the recognised leader in business processes for the process industries (EPSRC, 1994). Global competition, in a world where developed countries are all capable of buying technology and skills, demands an ability to continually review an enterprise's operation for it to be able to maintain its position and gain advantage. Success may lie in the exploitation of a unique product or technology but for most manufacturers it is more likely to be gained from what Drucker (1991) describes as 'working smarter', that is a combination of technology, organisation, management, the control of information and an ability to continually adapt to new situations.

Most UK enterprises must meet the challenge of global competition with 'organisational structures that came of age in a different competitive environment' (Hammer, 1990) using existing plants, and cultures and often with less staff and with current practices that almost always constrain future development. Jones (1988) advocates that change should be a continuous process, 'management is not about preservation of the status quo, it is about maintaining the highest rate of change an organisation and the people can stand'. Gould and Dent (1993) propose that 'To be successful manufacturing companies will need a top down integration strategy covering all aspects of organisation, culture, people and business processes as well as the enabling technologies'. Change processes are likely to be complex, they may involve the whole enterprise and may challenge entrenched organisational structures, practices and culture. Understanding the constraints to change that critically effect system efficiency and effectiveness is essential to be able to organise the analysis and planning necessary before changes are made. Those involved in implementing change are faced with a range of problems, processes are interdependent, important operational details are hidden, information systems are complex and the consequences of decisions delayed. The initial task is one of reducing the size of the problem to expose important details and describing behaviour to such an extent that it is possible to predict the consequences of decisions. One strategy for the successful management of change for re-engineering manufacturing enterprises is to employ practical, accessible, proven approaches to modelling that systems engineers can use routinely for the analysis and design of complex established human/machine/object systems. This thesis addresses research that is required into the use of modelling methods as tools to implement such a strategy.

1.3 SYSTEMS CONCEPTS

Rational-analytical thinking and systems thinking are two approaches that have been applied to the study and analysis of manufacturing organisations. Rational-analytical thinking developed in science in the eighteenth century and, until the middle of the twentieth century, was the accepted philosophy underlying problem solving in both science and social sciences. It is an approach to problem solving based on three perspectives: (i) A reductionist view to deal with complexity, breaking down problems into smaller simpler elements to a level where the elements can be understood and the source of the problem exposed. (ii) A positivistic view that argues that all the information about a problem can be known and unambiguous. (iii) A deterministic view that argues that the operation of a system can be predicted if system parameters are known and if they can be measured to identify changes. The philosophy is widely and successfully applied in mechanical systems for example but is less suitable for the complex, dynamic human/machine/object systems that comprise manufacturing enterprises.

Alternatively, Systems thinking approaches take a holistic view of a problem where no detail can be studied without knowing its relevance to, or dependence on, the larger system in which it exists. In systems thinking the overall purpose of a system is considered critical for investigation and, in contrast to rational-analytical thinking, subjectivity is an acceptable aspect of the approach. A fundamental aspect of systems thinking is the concept of 'emergent properties', which are properties a system possesses at one level because it is structured in a certain way. The same properties may not be apparent in sub-systems at lower levels. The origins of Systems thinking lie in the roots of Western and Eastern culture. In 300 BC Plato discussed systems of government and the need for a common purpose to unite the efforts of all the elements of a system. The philosophies of Kant and Hegel in the nineteenth century introduced phenomenology and 'inquiring systems' laying the foundation for the 'learning organisation'. However recognition of the importance of Systems concepts to deal with complexity in engineering, social science and management are relatively recent. In 1956 the biologist Ludwig von Bertalanffy (Bertalanffy, 1956) published his General Systems Theory and predicted that 'the concept of a 'system' is to become a fulcrum in modern scientific thought' Miller (1978) defines the General Systems Theory as a 'set of related definitions, assumptions and propositions which deal with reality as an integrated hierarchy of organisations of matter and energy.' Bertalanffy's work advocated the need to study a system as a entity and to open interactions for examination in contrast to the then contemporary approach 'to isolate phenomena in narrowly confined contexts' the rational analytical approach.

In describing the, then new, systems approach to scientific thought Ackoff (1959) propounded 'these research pursuits and many others are being interwoven into a co-operative research effort involving an ever widening spectrum of scientific and engineering disciplines. We are participating in what is the most comprehensive effort to attain a synthesis of scientific knowledge yet made'. In the same year Emery and Trist (1959) recognised that 'The analysis of the characteristics of enterprises as systems would appear to have strategic significance for furthering our understanding of a great number of specific industrial problems' and that 'the more we know about these systems the more we are able to identify what is relevant to a particular problem and to detect problems that tend to be missed by the conventional framework of problem analysis.' Bertalanffy (1962) saw the importance of systems thinking for manufacturing and proposed that 'entities whose components are most heterogeneous - men, machines, buildings, monetary and other values, inflow of raw material, outflow of product and many other items can successfully be submitted to systems analysis' Problem solving using systems thinking has evolved into diverse streams, Beer's organisational cybernetics approach (Beer, 1979), Checkland's soft systems thinking (Checkland, 1981) and the Systems Analysis movement for example, in different spheres but sharing common concepts and terminology. The word 'system' is now commonly used to describe a wide variety of organised collections of things, functions, or people. A filing system, a penal system, a control system for example all reflect the Oxford Dictionary definition of a system as a: 'complex whole, set of connected things or parts, organised body of material or immaterial things.'

1.3.1 Manufacturing systems

The focus of this work is on manufacturing enterprise systems which comprise of elements i.e. humans, equipment, machines, buildings, objects or material (which can be described by a noun or noun phrase) related and organised as processes to interact with each other and their environment with the objective of manufacturing products to satisfy consumer demands.

The concepts of manufacturing systems described by Hitomi in 1990 as 'integrated manufacturing unifying material flow (manufacturing processes) and information flow (production management)' are expanded in his exhaustive review of their development in 1994 (Hitomi, 1994). He proposes that manufacturing systems are based on three aspects (i) structure - a unified assembly of workers, production facilities and material handling, (ii) transformation - material flow and the conversion of raw material to products, (iii) procedure - the management cycle, planning, implementation and control. For those involved, the need to understand, design and develop such systems has given rise to research aimed at providing suitable methods and tools to deal with their often complex and ill-defined nature.

1.3.2 System complexity and modelling

Measures of system complexity are difficult to establish, Klir (1985) argues that there has been 'virtually no sufficiently comprehensive study that is oriented to capturing its general characterisation (i.e. measures of complexity)'. The Oxford English dictionary describes complexity as 'hard to unravel' and Webster's English dictionary as 'marked by an involvement of many parts, aspects or notions, and necessitating earnest study or examination to understand or cope with'. System complexity is more generally described by Flood and Carson, (1988) and others as a relative term involving (i) a number of elements, (ii) a number of relationships between elements and (iii) a perception or viewpoint. Given that a measure of complexity involves a perception of a system it must also implicitly involve the ability of an observer to understand the system. Klir (1985) concludes that 'complexity is in the eyes of the observer' and cites Ashby's (1973) incisive definition of a measure of systems complexity as 'the quantity of information required to describe the system'. Baines (1984) considered models to assess the complexity of the production control function in a manufacturing system, stressing that three properties are of primary importance: (i) The model must provide managers with an easy to use scientific approach for assessment. (ii) It must be able to deal with an extremely variable data input and (iii) it must be possible to compare the output with a relative complexity scale.

A manufacturing enterprise system contains a large range of diverse elements: material, parts, humans, data, documents, machines, processes etc. and the number of possible relationships between elements is a function of that range. Judged from the perspective of designing or re-designing they are undoubtedly complex systems. Modelling using diagrams has been used to visualise systems and to aid understanding by simplifying and describing system elements and the relationships between elements. Models can be static or dynamic and be represented physically, mathematically or graphically.

This research is concerned with static graphical models that are characterised by the following:

- They are used as a means of describing complexity for investigation or problem solving.
- They can be decomposed to show different levels of detail.
- They can be used to describe a system from many perspectives.
- They are produced with a definition of context that establishes the boundary and scope of the system under investigation.
- They cannot be all embracing and will have a viewpoint that will emphasise some aspects of reality at the expense of others.

In this research a model is considered to be a static graphical description using a formal documented syntax constructed from a given viewpoint for a given purpose.

Various approaches have been used to model manufacturing enterprise systems using diagrams, the impetus to use models derives from a general recognition that they can provide relatively low cost, verifiable descriptions of complex enterprise systems to provide a basis for system analysis, improvement and design. A survey (Colquhoun et al., 1993) has shown that Information System (IS) software analysis and design methodologies and Requirements Definition approaches are often the basis of modelling methods however the exhaustive detail required by IS approaches is often not necessary to the same extent in enterprise modelling 'it is at the broader functional levels that there is the greatest potential for improvement' (Shunk et al., 1986). Modelling methods in manufacturing enterprises have received added impetus in the 1990's with the emergence of Business Process Re-engineering (BPR) as an acknowledged area of activity utilising modelling extensively (Jennison, 1994).

A thread of enterprise modelling evolution began in 1957 as part of the development of the Automatically Programmed Tool (APT) symbolic programming language (Kief and Walters, 1992) at the Massachusetts Institute of Technology in 1957. Ross (1994) claims that the concept of graphical Structured Analysis (SA), the 'box notation', later to become the basis of the Structured Analysis and Design Technique (SADT) was first used in the project. The SA approach was subsequently developed by the US Air Force and Boeing to become SADT (Ross and Schoman, 1977) and finally evolved into the $IDEF_0$ and $IDEF_1$ functional and data modelling methods (US Air Force, 1981a, b) in 1981. IDEF modelling methods have substantially influenced the research presented in this thesis.

1.4 $IDEF_0$ FUNCTIONAL MODELLING

$IDEF_0$ is a functional modelling method that uses graphical and text conventions to describe functions or activities and their relationships in terms of information, objects, material and resources. An $IDEF_0$ model consists of a series of diagrams and associated text describing a system. Diagrams are numbered to indicate their relative position in a structured hierarchy, upper levels of the hierarchy are general descriptions that become more detailed as the hierarchy expands (see figure 1.1).

The method uses principles established for software development, those of Abstraction, Modularity, and Hiding. Abstraction allows the grouping of common properties of a system, Modularity (or decomposition) allows the division of component parts of a system and the definition of relations between parts and the concept of Hiding allows the display or examination of only the level of detail of interest.

In practice this means an IDEF$_0$ model can provide a means of representing the decomposition of a system (consisting of men, machines, material, products etc.) into easily understood, related elements using a series of diagrams and text to the level of detail required by a user. Ross (1977a) advocates the use of IDEF$_0$ as a structured modelling method for manufacturing systems in his proposal 'IDEF$_0$ greatly increases both the quality and quantity of understanding that can be effectively and precisely communicated well beyond the limitations inherently imposed by the imbedded natural or formal language used to address the chosen subject matter'.

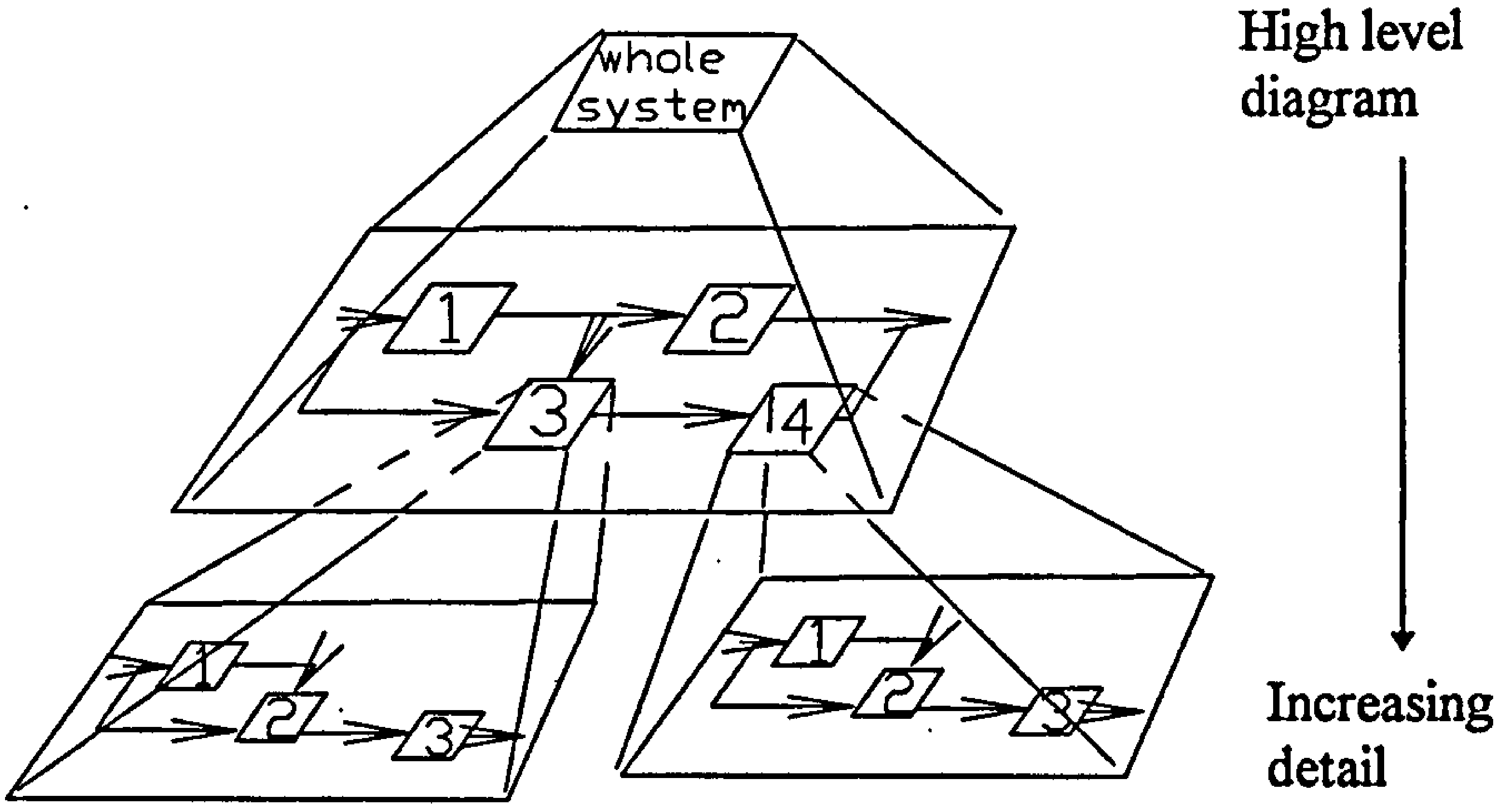

Figure 1.1 Hierarchical decomposition - ICAM's architecture for manufacturing

(Source - Wisnosky, 1979)

1.5 RESEARCH OBJECTIVES

This research is concerned with enterprise modelling as a means of managing complexity that provides a systemic approach to present a whole picture and one that is not specifically focused on information engineering.

The aim of this research work is to further the use of IDEF modelling methods as a means of gaining insight, designing or improving performance in manufacturing enterprise systems. The following objectives are being pursued to achieve that aim:

- To advance the understanding and use of modelling methods in the context of manufacturing enterprises.
- To research potential areas for the improvement and synthesis of IDEF modelling methods within a manufacturing enterprise framework.
- To test and validate improved modelling methods.

1.6 RESEARCH METHODOLOGY

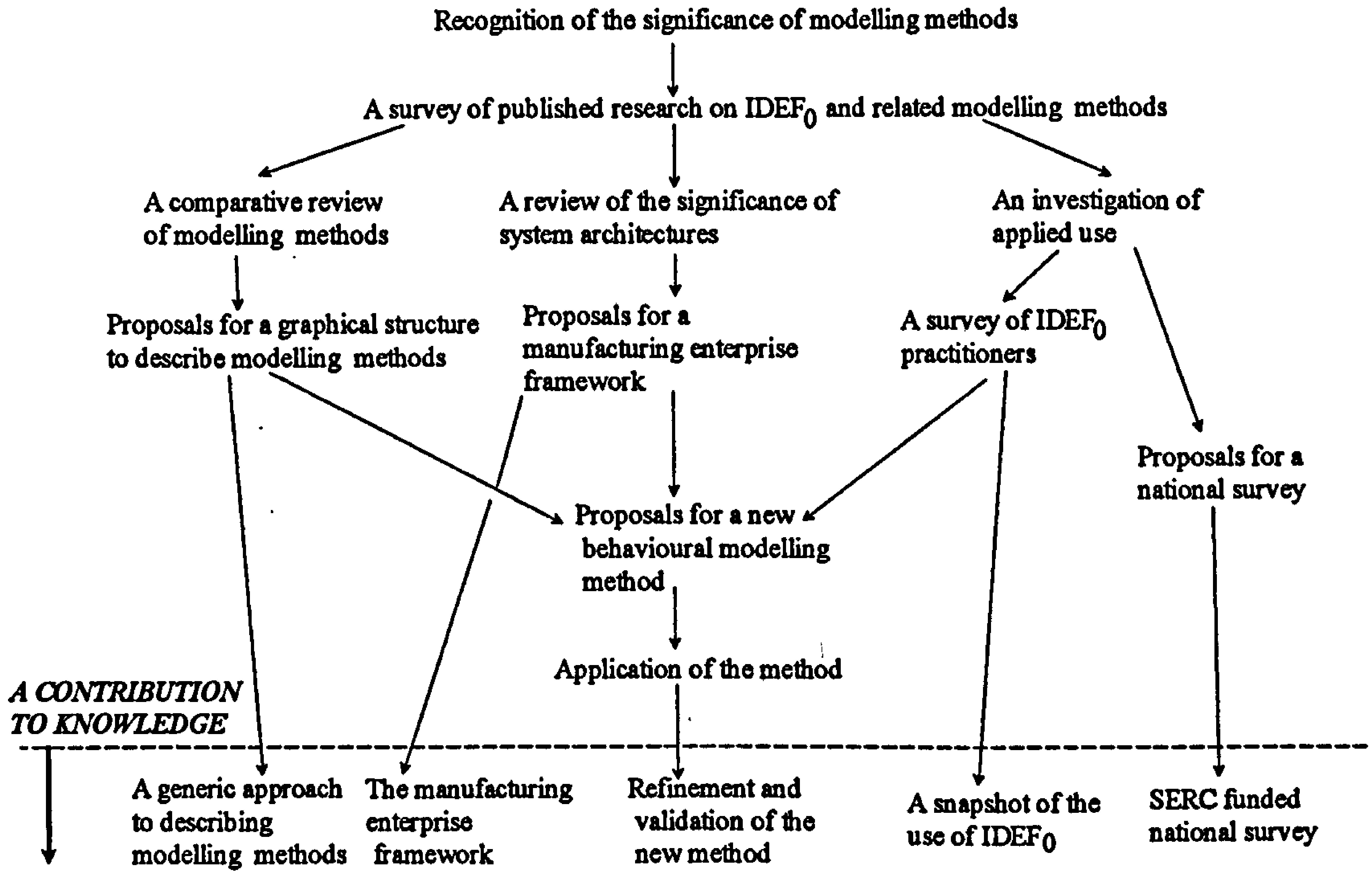

Figure 1.2 The structure of the research methodology

The structure of the research methodology employed is shown in figure 1.2. The initial survey of published work identified the lack of a coherent, comprehensive body of knowledge related to the use of $IDEF_0$ or other comparable modelling methods used in manufacturing systems in the UK and led to three avenues of investigation:

(i) A comparative review of the modelling methods that have been identified at the survey stage as those that have the potential to contribute to modelling in manufacturing enterprises. From this work came proposals to enhance the scope of $IDEF_0$ functional modelling to include aspects of system behaviour.

(ii) The role of system architectures and the need to develop an approach that clearly identifies the role of modelling methods specifically in the context of manufacturing enterprises.

iii) An investigation of the use of $IDEF_0$ and other modelling methods in manufacturing enterprises.

As a result of subsequent research a comparative analysis of modelling methods and a survey of the use of IDEF methods in the UK was carried out. A manufacturing enterprise framework was proposed and aspects of two modelling methods, $IDEF_0$ and IDEF3, were integrated to develop a new modelling approach. The new approach was refined in a manufacturing situation and a methodology to support the new approach was proposed. Finally a case study site was used to refine and validate the proposals.

1.7 CONTRIBUTION TO KNOWLEDGE

The contribution to knowledge arising from the research is in eight related areas:

1. A comparative analysis of modelling methods has been provided.
2. An $IDEF_0$ reference model for manufacturing has been proposed and validated
3. A survey of $IDEF_0$ practitioners has been carried out to provide a picture of the way the method is used in the UK.

4. The first published UK application of the use of the IDEF3 method in manufacturing has been provided.
5. A manufacturing enterprise modelling framework has been developed.
6. A meta-model to describe the structure of modelling methods has been developed.
7. A new composite behavioural modelling method has been developed.

1.8 VALIDATION OF THE RESEARCH

As a means of validating the research IDEF$_0$, IDEF3 and IDEF0-3 modelling has been carried out in six manufacturing companies:

- Lucas Aerospace, Shaftsmoor Lane, Birmingham.
- Scholl Consumer Product, Derby.
- Cannon Industries, Wolverhampton.
- British Steel Distribution, Leeds
- British Steel Automotive Centre, Wolverhampton
- ABB Nürnberg, Nürnberg, Germany

Seventeen papers (listed in appendix 1) dealing with aspects of this research have been produced, four have been published in international journals, one in a UK journal, one in a German journal, two at international conferences, six in UK conferences and one in a book. One further international journal paper has been accepted by referees and is awaiting a publication date and one UK conference paper is awaiting referees reports. In addition five papers on related topics have been published during the research.

Throughout the work supporting studies were pursued in the areas relevant to the main body of research and ten conferences in the area of manufacturing systems were attended over the period of the research.

In an initial phase of the research published literature on manufacturing modelling, primarily IDEF$_0$ related, was analysed, as was the use and application of modelling methods in general. A key finding was the absence of information relating to the way that modelling is used by

UK manufacturing enterprises to manage change. The evidence for this finding was used to pursue a research grant to fund an investigation of 'Best practice modelling methods in manufacturing enterprises'. A grant of £120K was awarded by the Engineering and Physical Sciences Research Council - Control Design and Production group (EPSRC-CDP) in October 1994 to identify and develop 'Best Practice' modelling methods in manufacturing (EPSRC-CDP grant Reference GR/K39400) and the research (not reported in this thesis) commenced in April 1995. The research announcement is shown in appendix 5.

In 1993 the IDEF3 method was recognised as having the potential to contribute to this research. As a result the author approached the US vendors of the IDEF3 tool to support the work and subsequently obtained a grant of $5840. The letter of agreement is shown in appendix 6.

During the course of the research the author has acted as a reviewer for one book (Wu, 1994) and as referee for two papers in the area of systems and IDEF modelling for the International Journal of Computer Integrated Manufacturing.

CHAPTER 2

THE IDEF METHODS

2.1 INTRODUCTION

This chapter provides a historical perspective of the IDEF methods developed under the ICAM programme. Those IDEF methods pertinent to this research are introduced and the latest generation of IDEF methods developed by Knowledge Based Systems Inc. are briefly reviewed.

To augment this chapter appendix 3 provides a review of the syntax and semantics of all the relevant IDEF methods together with a discussion of their role and a review of the software tools available to support IDEF modelling.

2.2 A REVIEW OF THE ICAM PROGRAMME

The United States Air Force initiated a master plan in the early 1970s as a long term strategy to control and co-ordinate aerospace manufacturing. The work was carried out by the US Air Force Materials Laboratory as the Air Force Computer Aided Manufacturing (AFCAM) project (US Air Force, 1974). AFCAM was established as the first step in a strategy to support military and space research manufacturing and technology growth into the next century.

The subsequent development of the initiative was the Integrated Computer Aided Manufacturing (ICAM) programme (Le Clair, 1982). In 1978 the ICAM programme was formalised with the objective of realising the benefits of integrating the sub-systems of manufacturing and extending the level of technology available to aerospace manufacturers. The perceived need nationally being to establish the long term supremacy of the American aerospace industry and to transfer the knowledge gained to other domestic manufacturing industries.

Wisnosky (1979), manager of the ICAM project, describes the manufacturing systems integration concepts adopted by the ICAM program as a structure of inter-communicating elements or functions in the form of a hierarchy, in ICAM terms 'An Architecture for Manufacturing' that he represented as figure 1.1.

In figure 1.1 each truncated pyramid represents a level of detail on the top face and a decomposition into smaller levels of detail on the bottom face. For instance the 'whole system' is composed of sub-functions 1, 2, 3 and 4. Functions 1, 2, 3 and 4 have their own sub-functions, in this way the 'architecture' can extend to any level of detail. The hierarchy consists of 'Executive control' at the top levels followed by 'Management control', 'Technical support', 'Process control' and 'Direct manufacturing' at subsequent levels. The diagram reproduced in figure 1.1 is now commonly used to represent the concept of hierarchical decomposition and many authors have used it to explain the principles of the $IDEF_0$ method (Hughes and Maull, 1985a, Banerjee and Al-Maliki, 1988, Wu, 1994).

An interesting development of this description of ICAM Architecture is the description used in a later US Air Force (1981a) report 'ICAM Architecture'. Here the ICAM Architecture is described as a 'definition of manufacturing' consisting of three models: A functional model the 'blueprint', an information model the 'dictionary' and a dynamic model the 'scenario'.

The concept takes account of different approaches to manufacturing in 'factory views' of the architecture that can represent how individual plants carry out manufacture. Together with a 'composite view' of the architecture to represent an 'industry wide aggregation of several factory views'. This concept is used consistently in post-1980 ICAM publications for instance in the $IDEF_0$ Architects Manual (Ross et al., 1980) ICAM architecture is defined from a functional perspective as: 'blueprints, drawings and specifications that constitute a formal definition of manufacturing - a model which is a logically consistent and demonstrably accurate representation of the functions of manufacturing and the relationships between those functions' The composite view is described as representing, current practice for the production of a single, new, major aerospace product, such as an aeroplane,' 'emphasising the essential function, information and material flow necessary'.

The work carried out in the ICAM project was sponsored by the US Air Force primarily for the aerospace industry Jones (1979), an ICAM program manager, explained: 'the ICAM program needed a factory that was like most targeted aerospace factories for setting scope and for integrating ICAM sub-systems'. Funding prevented the physical building of a factory so an architecture of manufacturing using models of specific factories was produced and those factory views were then merged into a single composite view of manufacturing. The composite model was reviewed by an industrial panel with the result that 'it gave us confidence that the architecture of manufacturing represents manufacturing in general and not aerospace manufacturing only' (Jones, 1979). The model was released into the public domain in 1980 (CAM-I).

An essential element of the ICAM approach was the drive to 'establish structured methods and tools for applying computer technology to manufacturing and to demonstrate ICAM technology for transition to industry' (US Air Force, 1981a). In order to meet the objectives of identifying common functions, information requirements and usage across the aerospace community three modelling approaches were identified. After 'a review of over fifty systems modelling techniques' (Mayer, 1979) the Functional model, the Information model and the User Interface (dynamics) model were considered essential to support the decision making process required for integrated system development. The Structured Analysis and Design Technique (SADT) was selected for functional modelling as a first step.

2.3 A HISTORICAL PERSPECTIVE OF THE IDEF METHODS

2.3.1 A review of the development of $IDEF_0$

The concepts underlying SADT stem from Ross (1977a, b) and his Structured Analysis thinking in the development of Automatically Programmed Tools (APT) machine tool programming language and Hori's (1972) 'Human-directed activity cell model' with philosophical foundations in Ackoff's 'Scientific Method' (1962).

The 'box notation', later to become the basis of SADT, was first used by Ross in developing APT at the Massachusetts Institute of Technology in the late 1950s. The concept of 'hierarchical decomposition' was also recognised by Ross in the early 1960s but the two fundamental elements were not formally linked until the emergence of Ross's 'structured analysis' in 1969. Ross's seminal papers (Ross, 1977a, Ross, 1977b, Ross and Schoman, 1977) describe the foundation of Structured Analysis and SADT thinking.

SADT was developed jointly by Boeing Inc. and the company Ross and Schoman founded, SofTech Inc., and was funded by the AFCAM project. In an account of the development of SADT Ross (1985) explains that: 'SADT broke new ground in the areas of problem analysis, requirements definition and functional specification because it allowed rigorous expression of high level ideas that had previously seemed too nebulous to treat technically'.

The technique SADT^{TM} was commercially available from SofTech by 1975, early reports of its use and potential are given by Combelic (1978) and Ross and Schoman (1979). In the first phase of the ICAM project from 1976/78 the US Air Force continued to use SADT^{TM} under licence however as Brovoco (1991) explains 'ICAM part 2 came up for bid and the Air Force did not want to continue buying SADT^{TM} licences'. In addition they wanted to improve the method.

SofTech Inc. agreed to develop a public domain version of SADT incorporating the changes required by the ICAM project (the inclusion of function lists (node index), Information matrices (Data dictionary), AS IS and TO BE concepts, Factory Views, Composite and Generic models and the deletion of data modelling) in order to win the ICAM part 2 contract and in October 1978 Ross, Feldman and Mayer began the revision of SADT (Mayer, 1993a). Wisnosky and Ross used the acronym IDEF (The I-CAM DEFinition technique) for the revised method, Wisnosky (1979) explains 'With it (ICAM part 2) has also come an integrated system defining both vocabulary and language, called IDEF, to facilitate inter-communication and the description of manufacturing operations. The resultant common terminology will allow future software deliverables to be mutually compatible and easily integrated into ICAM-established technology'.

The new method was termed the IDEF$_0$ Function model to differentiate it from other aspects of the ICAM part 2 project that included the development of IDEF$_1$ an Information model and IDEF$_2$ a Dynamics model. In parallel with these developments Boeing Inc. were given the task of designing AUTOIDEF$_0$, a software tool for IDEF$_0$.

The IDEF$_0$ method was approved for public release (in the USA) in February 1980 by Wisnosky the ICAM project leader. The IDEF$_0$ 'Architects Manual' (SofTech Inc., 1980) was published in February 1980. The more widely used manual for IDEF$_0$ was released into the public domain by the US Air Force through the Wright Aeronautical Laboratories in 1981 (US Air Force, 1981a). The IDEF$_0$ method is now supported by a range of software tools (discussed in detail in appendix 3 section A3.3) and has an established record of successful use particularly in the USA. In May 1992 The Institute of Electrical and Electronics Engineers (IEEE) accredited IDEF$_0$ and released an IEEE/IDEF$_0$ standard in

February 1995. In 1992 the National Institute of Standards and Technology (NIST) authorised a programme to establish IDEF$_0$ as a Federal Information Processing Standard (FIPS) for formal release in April 1995. Sudnick (1993) notes that an objective is to obtain international (ISO) acceptance.

In the UK, the first recorded use of IDEF$_0$ was by Crossley, Davies, and Richardson (1978, 1979) in Progress Reports to the Air Force Office of Scientific Research in the USA. These two reports formed the first two deliverables of an ICAM contract the 'Preliminary Design of a Job Shop Control System' that was undertaken by the University of Salford Industrial Centre. It was 1984 before references to the method began to appear in UK research publications and a survey carried out by Colquhoun and Baines (1993a) in 1992/3 revealed over fifty UK and European publications relating to IDEF$_0$.

2.3.2 The development of associated IDEF methods

The IDEF methods $_0$, $_1$ and $_2$ were envisaged as an integrated 'Architecture' for manufacturing and SofTech were given the responsibility for the 'Integration of ICAM modules and the orderly transition of ICAM modules into ICAM systems' in effect they were responsible for documentation of the ICAM modelling methods. Their final report on ICAM architecture was published by the US Air Force in 1981 (US Air Force, 1981d).

ICAM's information model, IDEF$_1$, was developed by the Hughes Aircraft Corporation (US Air Force, 1981b) and IDEF$_2$, the dynamics model, was developed by Higher Order Software (HOS) Inc. and finally by Prisker and Associates (US Air Force, 1981c). Both were approved for publication in 1981 along with IDEF$_0$ however they were subject to For Early Domestic Dissemination (FEDD) control and export of the documents was considered a violation of US Traffic-in-Arms regulations. The control was in force until 1982 for IDEF$_0$ and 1983 for IDEF$_1$ and $_2$. In discussing the diversity of sub-contractors to the ICAM project Brovoco (1991) notes 'Is it any wonder why $IDEF_{0,1}$ and $_2$ are not totally integrated. In fact the $IDEF_1$ and $IDEF_2$ developers were never required to be $IDEF_0$ experts'.

In 1983 an Integrated Information Support System (IISS) project was initiated under the ICAM program focused on the 'capture, management and use of a single semantic definition of the data resource referred to as a Conceptual Schema'. The project carried out by D. Appleton Company (DACOM) developed and extended the Logical database Design Technique (LDDT) and the $IDEF_1$ method and released it as IDEF1eXtended in 1986 (US Air Force, 1986).

A review of commercial modelling tools supporting the IDEF methods has been carried out as a precursor to the survey detailed in section 3.5 and is presented in appendix 3 section A3.3. It is not the intention, in this research, to compare the use of the various tools but to establish the extent of computer support for IDEF methods as part of the picture of the use of $IDEF_0$ and its relationship with other modelling methods developed in depth in chapter 4.

In the USA a focal point for the discussion and development of IDEF methods has been the IDEF Users Group (now re-named the Society for Enterprise Engineering (SEE), (Preston, 1995). Research connected with IDEF methods seems largely concentrated on those universities with funding from US defence industry contracts notably the Texas A&M University. Interest in the IDEF methods generally appears to be industry driven and is in direct contrast to the UK where the interest appears to be academic driven. A review of eleven USA IDEF User Group conferences from 1991 to 1995 revealed that eight universities presented papers and (in late 1995) the last three conferences had only six university delegates. All other attendees being industry or government based.

IDEF methods and new IDEF initiatives are now under the control of the Logistics Research Division of the Air Force Armstrong Laboratory through their Information Integration for Concurrent Engineering (IICE) programme. In May 1992 the programme released an interim report (Mayer et al., 1992a) describing IDEF3, a Process Description capture method. The method was developed in conjunction with Knowledge Based Systems Inc. (KBSI) who are the Air Force contractor responsible for the continued development and maintenance of IDEF systems and software. In the KBSI IDEF methods the identifying number (3, 4, 5 etc.) is used in standard script to distinguish it from the ICAM derived methods which use subscript numbers.

KBSI declare that 'the IDEF acronym has been re-cast as the name referring to an integrated family of Integration DEFinition methods' (Mayer et al., 1992a). Their involvement has led to significant developments extending the range of IDEF methods to encompass object oriented design (IDEF4), ontology description capture methods (IDEF5) and design rationale modelling (IDEF6).

2.4 THE LATEST GENERATION OF IDEF METHODS

This section briefly introduces the range of IDEF methods currently under development by KBSI who are now the US Air Force contractor responsible for the continued development and maintenance of IDEF methods.

The IDEF5 Ontology description capture method

Ontology is the study of *what there is,* described by Menzel et al. (1992) as an 'activity at work across the full range of human inquiry prompted by humanity's persistent effort to understand the world in which it exists and which it helped to shape'. He uses an example of ontology in the world of sub-atomic physics 'to develop a taxonomy of the most basic kinds of objects that exist in the natural world; electrons, protons, muons and their fellows'. Perakath (1995) describes an ontology as 'a precise definition of the terminology in a domain'.

IDEF5 is an ontology description capture method with theoretical foundations in set-theoretic semantics and first-order modal logic (Menzel et al., 1992). It is designed to capture and describe the basic entities that populate a manufacturing system such as personnel, machines, material etc.. The method involves;

- Providing an inventory of the kinds of objects that exist in a domain according to the best sources of information regarding the domain, such as a domain expert or established theory.
- For each kind of object, providing a description of the properties common to all and only instances of that kind
- providing an inventory of the associations that exist within a given domain between (and within) kinds of objects.

The method is seen as a means of providing a structured language that can be interpreted unambiguously, that can remove ambiguities in terminology and that will ultimately be amenable to automated reasoning. No formal links with other IDEF methods are proposed but the method has the potential to provide a common pool of information from which other methods can extract.

The IDEF6 Design rationale capture method

The IDEF6 method is a means to acquire and represent the rationale behind the design of Information Systems to answer the question *why?* a particular decision, strategy or feature was adopted or an assumption made'. The method is in the concept stage and is seen as a 'series of adjuncts to other modelling tools rather than being a stand alone method' (Mayer et al., 1992c).

Future IDEF methods:

The IDEF methods under consideration in 1995 (Perakath, 1995) are:
IDEF8 User interface modelling

IDEF9	Scenario-driven IS design
IDEF10	Implementation architecture modelling
IDEF12	Organisation modelling
IDEF13	Three-schema mapping design
IDEF14	Network design.

CHAPTER 3

PUBLISHED IDEF$_0$ AND IDEF3 RESEARCH

3.1 INTRODUCTION

This chapter reports the findings from research into published literature relating to IDEF$_0$ and IDEF3. The research followed four specific lines of inquiry: (i) To expose how researchers perceive the use and application of the methods in the context of manufacturing systems. (ii) To establish how use of the methods has been evaluated. (iii) To investigate proposals to modify the methods. (iv) To analyse how the methods have been used in a wide range of applications. The rationale was to provide a greater understanding of the use of modelling methods in the context of manufacturing enterprises, to investigate potential improvements to existing methods and to investigate the potential to develop the use of modelling for manufacturing applications.

Four broad categories of published research provide a framework for examination of the methods, they are: (i) Descriptions and reviews of the basic principles of IDEF$_0$. (ii) Performance evaluations of IDEF$_0$ and comparisons with other methods. (iii) Proposed enhancements of the IDEF$_0$ method. (iv) Applications of the IDEF$_0$ method.

The research established that, in contrast to the IDEF$_0$ method, there is a dearth of published information related to the IDEF3 method, as a result research findings are presented as a general review in section 3.4.

An initial literature review was carried out in the first stage of the research and published in 1993 (Colquhoun et al., 1993a). Kusiak et al. (1994) acknowledged that the review revealed 'several issues that had received little attention in the literature'. It focused on the application of IDEF$_0$ in manufacturing systems and gave Hitomi (1994), in citing the review, an opportunity to reinforce his definition of manufacturing systems engineering as 'integrated manufacturing unifying material flow (manufacturing processes) and Information flow (production management)'. A key finding from this stage of the research was that there were few published industrial applications of the use of the IDEF$_0$ method. To identify and access industrial users of the method the leading UK IDEF$_0$ software Tool vendor[1] was approached to support an investigation of the use and application of the Design/IDEF Tool, the findings are detailed in section 3.5.

3.2 STANDARD REFERENCE SOURCES

Section 2.3 discussed the role of SADT as the precursor of IDEF$_0$ and Marca and McGowan (1987) have provided a key publication for the study of SADT activity modelling. It contains a complete account of the concepts, method and author/reader cycle methodology together with applications. Interestingly they do not include the data modelling aspects of SADT which by the mid-80's had not been widely adopted and had been overshadowed by other data modelling methods based on DeMarco's (1979) Data Flow Diagram (DFD) approach. Little has been published on SADT data modelling however Ross (1985) provides an account of the basics and in 1994 he still advocates the advantages of SADT 'Dual' activity and data modelling functionality (Ross, 1994).

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[1] IDEFine Ltd., Crowthorne, UK. (Formerly MicroMatch Ltd.).

Three basic sources of reference are available for the study of $IDEF_0$; the US Air force $IDEF_0$ report (US Air Force, 1981a), the Architects Manual ICAM Definition Method - $IDEF_0$ (Ross et al., 1980) and the recently published $IDEF_0$ Function Modelling (Mayer, 1993a). They have a similar format and provide a detailed description of the method; the rules, syntax, diagram and model format, text presentation as well as model validation, document control procedures, interview techniques and guides to understanding and using activity diagrams.

Mayer's approach in '$IDEF_0$ Function Modelling', although rigorous in describing modelling syntax and semantics, is less formal in terms of describing the author reader/cycle preferring to call it teamwork discipline. His 'Guide to creating $IDEF_0$ diagrams' also provides a practical guide to good practice in diagramming methods. The application oriented approach used throughout the book suggests that use of the method has been refined from experience since the previous manual was produced in 1981. Hill (1995) has published a guide to the application of $IDEF_0$ which provides a detailed review of the method concentrating on practical application rather than methodology.

3.3 A STATE OF THE ART REVIEW OF $IDEF_0$

This ongoing literature review that followed the initial literature review in 1993 (Colquhoun, et al., 1993a) has re-enforced the finding that published work relating to $IDEF_0$ continues to fall into one of four broad categories albeit with different emphasis:

1. Papers that deal with descriptions and reviews of the basic principles of the method.
2. Performance evaluations, or comparisons with other methods.
3. Proposals for enhancements of the method.
4. Specific applications of the method.

3.3.1 Category 1: Descriptions and reviews of basic principles

Several manufacturing systems textbooks now provide outline descriptions of the IDEF$_0$ method. After describing the principles of the method Wu (1992), for example, uses the method as means of presenting his ideas on material and information flow in manufacturing systems. Similarly Ranky (1992) describes the method and uses IDEF$_0$ diagrams extensively to present ideas. Bauer et al., (1994) briefly introduce SADT and use a structured set of diagrams to describe shop floor material and information flow. Waldner (1992) also introduces SADT as a methodology for CIM implementation. Mitchell (1991) introduces IDEF$_0$ and uses IDEF$_0$ diagrams to describe a 'System-Environment Simulation' approach. In contrast Rembold et al. (1993) use IDEF$_0$ diagrams to describe manufacturing operations without explaining the principles of the method.

Mackulak, (1984) provides a detailed review of I-CAM and the role of IDEF$_0$ and goes on to explain the principles of the method. His description includes an example of a node glossary, an aspect of modelling often overlooked in simple reviews of the method. Harrington (1985) was an early advocate of IDEF$_0$ who proposed it to help understand the complexity of manufacturing process. He describes the principles of the method and uses the analogy of IDEF$_0$ providing a two dimensional map of manufacturing that allows the human mind to deal with specific elements whilst retaining overall relationships. His model is based on an environment diagram (A-1) 'Conduct a manufacturing enterprise' with examples of decomposition down to the level of an A36 diagram. He also suggests two other applications for the method, the first is the use of a generic model of manufacturing to evaluate or establish deficiencies in an organisation and the second is the use of IDEF$_0$ models as a means of planning the integration of manufacturing functions. He concludes with the claim that 'One of ICAM's greatest contributions to the science of manufacturing will prove to be the development and use of the structural [sic] analysis methodology called IDEF'. The complete 'Conduct a manufacturing enterprise' model is presented in his book on the subject of understanding the manufacturing process (Harrington, 1984) the model has been subject of much interest by other authors Graves et al. (1989), for example, use Harrington's diagrams as a context for their proposals for a methodology for CAPP. Early interest in $IDEF_0$ in the UK is characterised by Hughes and Maull (1985b) who proposed $IDEF_0$ as a means of designing CIM system architectures.

Other papers that provide brief descriptions of the principles of the method include Goldman and Cullinane (1987), Yeomans (1987a), Parnaby (1988), Baines and Colquhoun (1990), Sarkis and Lin (1994) and Deng et al. (1990).

3.3.2 Category 2: Performance evaluations and comparisons

The bulk of published work is in this category reflecting the early investigative interest generated by $IDEF_0$ after its release into the public domain. Comparisons of various 'competing' methods have been used to investigate their role in systems development and the extent of their capability.

Buchel et al. (1984) carried out a detailed comparison of 'Known methods used in the design of production management systems' comparing four structured methods, $IDEF_0$, SSADM, S.E. (Structured Engineering), and GRAI. The criteria used for comparison being their ability to handle complex systems, their ability to describe a system, formal aspects of the methods and computerisation of the method. In concluding, the authors describe the GRAI model as a methodology for structuring a specific application field (production management systems) and strongly advocate its use proposing that GRAI 'represents an integration of three different viewpoints' 'the Physical system and its associated material flow, a hierarchical model of the Decision system and the Information system'. $IDEF_0$ is seen by the authors as 'almost exclusively concerned with functional requirements'.

Industrial applications of the GRAI method have not been widely reported and published examples of its use are largely in French companies for example; SNECMA, SNPE Toulouse and SMG Cededur Pechiney (AUGRAI, 1987). In the UK, Ho and Ridgeway (1994) describe an application in the design of cellular manufacturing and Ridgeway and Downey (1991) and Ridgeway (1992) have proposed other applications for the GRAI methodology.

Maji and Stevenson (1988) discuss formal approaches to the development of information system specifications. The paper focuses on a comparison of $IDEF_0$ and the Structured System Analysis Design Methodology (SSADM) (Longworth and Nicholls 1987), the author proposes that $IDEF_0$ and the Data Flow Diagram (DFD) of SSADM have similar basic principles but that in a DFD the source and destination of data is shown, whereas in $IDEF_0$ it is difficult to understand this aspect of the model. The author's criticism can be countered by the use of a node index (Colquhoun et al., 1989) however. The author sees $IDEF_0$ and SSADM as two of many approaches that include the GRAI method (Pun et al., 1985, Doumeingts, 1985), the Soft Systems Methodology (Checkland, 1981) and SADT. He concludes that the methodologies may be suitable for the development of information system specification but that further research work is required in various areas of the methodologies. A brief comparison of the same methods, GRAI, SSADM and $IDEF_0$ is also provided by Wyatt and Al-Maliki (1990).

Roboam et al. (1989) however advocate the need for an integrated methodology for the analysis of production systems claiming that no single methodology exists for physical, decisional and informational aspects of systems. The authors select $IDEF_0$ as a complementary method to GRAI (Doumeingts, 1984) and Merise (Rochfeld and Tardieu, 1983). They propose that $IDEF_0$ can provide a functional model, defining the elements of the physical system and the flows of information and objects between them. Whereas the GRAI and Merise methods are capable of analysing and designing the management decision system. Roboam and Pun (1989) have surveyed and classified manufacturing system design methodologies. Their work draws no definite conclusions regarding the role of $IDEF_0$ but re-enforces the view that it is not possible to use the methodology for the analysis and design of both the physical and decisional sub-systems. Wood and Johnson (1989), compare $IDEF_0$ and SSADM and also conclude that no single method offers the complete answer for manufacturing systems analysis.

Using an experimental method based on users, Yadav et al. (1988) carried out a comparison of DFDs and $IDEF_0$ in terms of requirements definition. Four criteria for comparison are used: syntactic, semantic, communicating ability and usability. The authors report that the groups of analysts involved in the study had confidence levels (in their own $IDEF_0$ models) of 82.5 % in syntactic correctness and completeness and 72.5% confidence in their semantic accuracy and analysts using $IDEF_0$ had higher confidence levels in their models than those using DFDs. The authors propose that the work is inconclusive and that it failed to establish which method produces a better result. They conclude that, although the DFD method is easier to learn and use, further work is required to establish which method produces a better model.

An assessment of all the IDEF methods was carried out by Godwin et al. (1989) using a methodology designed to assess $IDEF_0$ as a 'descriptive tool'. The work concludes that : 'It is certainly one of the main strengths of the method that, although possible, it is very difficult to produce an $IDEF_0$ model which is correct (in $IDEF_0$ terms) but inaccurate as a system description'. A complementary study by the same authors (Godwin et al., 1988) evaluates the $IDEF_0$ as a 'sub-model' of a complete IDEF model consisting of functional, information and dynamic sub- models. This is one of the few publications that provides a detailed discussion and an example of the integration of the first three IDEF methods, reviewing consistency across the sub-models, and assessing the strengths and weaknesses of a combined model.

Ming Wang and Smith (1988) contrast the Soft Systems Methodology with computer based $IDEF_0$ analysis and propose that the two approaches compliment each other. The authors emphasise the ill-structured 'soft' nature of manufacturing and the need for those developing information systems to start any analysis at a conceptual level. The ability of computer based $IDEF_0$ to enhance the quality and consistency of diagrams and models and improve system modelling productivity is recognised. In contrasting the two methods the authors see $IDEF_0$ as technique orientated in contrast to the 'sophisticated and mature' Soft Systems approach which requires experimental analysis and high intellectual input. The authors advocate incorporation of the Soft Systems approach into existing IDEF$_0$ software to combine the two approaches.

Maull (1986) evaluated the contribution IDEF$_0$ can make to the analysis and design of Computer Integrated Manufacturing Systems. His review examines application of the method in a number of manufacturing situations and concludes that his research demonstrates the usefulness of the method as a 'simple and effective communication tool'. His research also highlights some criticisms of IDEF$_0$ in its ability to describe certain characteristics of systems such as time, dependency, data-entity relationships and reliability requirements. In addition, along with other authors, he advocates software tools to simplify the model building process.

Other relevant evaluations and comparisons of the method have been carried out by Rzevski and Maji (1988) and Maji and Stevenson (1988).

3.3.3 Category 3: Proposed enhancements of the method

Much published research has been focused on modifying the method to overcome perceived failings, to extend its capability or to integrate it into methodologies that utilise other modelling methods. This aspect of IDEF$_0$ research was evident before the method was mature and before IDEF$_0$ computer tools were widely available. Over the last five years however the number of publications concerned with enhancing the method has increased. This section has been split into two areas; proposals to modify the IDEF$_0$ method and proposals to combine IDEF$_0$ into other methodologies.

(i) Proposals to modify the IDEF$_0$ method

Shunk et al. (1986) proposed a modification to the basic model format to overcome what they saw as a major drawback of the IDEF$_0$ model in that 'the large amount of data generated defies the sorting and assimilation efforts of many system developers, the user may not, therefore see a particular process as part of a larger CIM system'. As an alternative they propose a Triple Diagonal technique (IDEF0-TD) based on information, control and material flow that, it is claimed, provides a bottom up facility for model development. The method also identifies feedback information by modifying the diagram format to use colours and different line-types to distinguish classes of ICOM.

Mandel (1990) describes the method as a means of 'graphical process description' using a model of printed circuit board manufacture. In his description of the capabilities of $IDEF_0$ he recognises that it is capable of representing a process activity and the information and materials involved in the process (what is happening) and proposes that the method is not focused on organisational structure (who is doing it), however he later clarifies the role of the 'mechanism' as an indication of 'who' is carrying out the process. Three shortcomings of the method are cited: The amount of information contained in a diagram can cause clutter, that the methodology lacks the ability to relate an interface item with its originating activity directly and that the methodology lacks clarity in defining hierarchical and interface relationships. He proposes 'ports' with text descriptions to identify sources and destinations of information crossing the boundary of a diagram together with a modified format to enhance diagram clarity.

Mujtaba (1992, 1994) proposes the use of different ICOM arrow line-types to differentiate between passive physical objects, command information and data. Other authors have proposed changes to ICOM arrows Marran et al. (1989) for example use four different line-types to show material flow, command flow, resources and information flow.

Feller and Rucker (1990) propose extensions to $IDEF_0$ to 'allow additional classes of knowledge useful to a communication analysis to be represented'. The authors propose a modified (eight sided) activity box to explicitly identify feedback information, controls and triggers in order to incorporate the concept of process activation or 'firing' using Petri-Net principles. Niel et al. (1992) propose an extension to SADT in a Failure Mode Effect

Analysis (FMEA) (O'Connor, 1991) application using 'Entries' to represent Inputs and Controls and using activities to indicate a sequence of events. Kusiak et al. (1994) propose an approach that 'violates the basic premise of $IDEF_0$ modelling' using a model containing 27 activities and representing them on a single level diagram as a sequenced process graph.

Ang and Gay (1993) use $IDEF_0$ as the basis of a modelling method for project risk assessment they propose modifications to model syntax, annotations to diagrams and diagram layout changes to describe system characteristics such as the probability of activities occurring, the duplication of tasks, and activity activation.

The use of computer supported $IDEF_0$ diagram production was considered an essential enhancement to the method before such tools were widely available. The principles behind the first $IDEF_0$ software tool developed by Boeing for ICAM part 2 are described by Smith et al. (1980). Hartrum et al. (1988) describes 'SA tool' a Sun workstation based graphic editor system with the enhancement of a data dictionary. Gamble (1988) developed a prototype $IDEF_0$ tool interestingly using $IDEF_0$ to model his software before coding.

(ii) Proposals to combine $IDEF_0$ with other methods

Bachert et al. (1983) proposed incorporating $IDEF_0$ with the 'System Analysis of Integrated Networks of Tasks' (SAINT) simulation system. In their proposal $IDEF_0$ was used to model 'Tasks' as $IDEF_0$ functions each Task then became the subject of a dynamic simulation. An interesting variation on the use of IDEF mechanisms was their concept of using algorithms as mechanisms. Research linking $IDEF_0$ and SAINT is also described by Stockenberg (1986).

Wang and Fulton (1994) used $IDEF_0$ as part of an object-oriented approach to information system design. The approach incorporates DFDs and Entity relationship models where 'the DFDs and $IDEF_0$ diagrams are compared frequently to find any discrepancies in the models'. Snyder et al. (1991) combine $IDEF_0$ with 'Concept maps' and 'Storyboards' to overcome a weakness the authors claim $IDEF_0$ has 'for modelling extremely complex and dynamic environments where boundaries are fluid and the task priorities, conditions and interrelationships are continuously changing'.

For ESPRIT project 2439 (ROCOCO) Los et al. (1992) used IDEF$_0$ in conjunction with NIAM (Nijssen and Halpin, 1989) data modelling and the GRAI method (Doumeingts, 1985) in order to model 'operation, data and control' in a single methodology. In their methodology an IDEF$_0$ model was linked to a higher level GRAI model using the data flows of a NIAM model. Their approach is in contrast to Zgorzelski and Zgorzelska (1993) who also advocate the integration of NIAM and IDEF$_0$ their 'NIDEF' methodology which adds graphical symbols from NIAM to IDEF$_0$ diagrams. Their justification for this approach is not to improve IDEF$_0$ but to replace NIAMs functional modelling feature which they consider 'significantly weaker than SADT or IDEF$_0$'.

The 'IFEM' methodology proposed by Malhotra and Jayaraman (1992) is one of the few publications that proposes integration of IDEF methods. In their approach ICOMs in an IDEF$_0$ model become entities in an IDEF$_{1X}$ model and the IDEF$_0$ model is used as a dynamic model by 'extending it to model the temporal interactions between activities'. An example of a 'dynamics description script' for an activity is used to demonstrate the extension from a functional model to a dynamic model.

In an exposition of ESPRIT project 688 Jorysz and Vernadat (1990a) give an account of the role of IDEF$_0$ principles in the requirements definition phase of the CIM Open System architecture (CIM-OSA). The authors maintain that CIM-OSA 'goes far beyond previous modelling tools and CIM system methodologies' and claim that: 'CIM-OSA produces a processable model of the CIM system as opposed to SADT-based methods or to IDEF$_0$ which only produce static or incomplete descriptive models of system requirements lacking dynamics modelling, precise information modelling and technical implementation issues'.

Other methodologies have been proposed using IDEF$_0$ as a functional modelling element include: LUM-TM (Kehoe et al., 1991), IDEM (Wang et al., 1993), SIMCON/2 (Siggaard and Bilberg, 1992), IMP (O'Sullivan and Browne, 1993), 'The Five Step Method' (Page and Saunders, 1993). MOSES (Molina et al., 1995).

3.3.4 Category 4: Applications of the method

Papers in this category demonstrate the diversity of applications in manufacturing. Ross (1985) in a general review of the use of IDEF$_0$ claims that 'Thousands of people from hundreds of organisations working on more than one hundred major projects use the methodology not only for the technical work of system definition and design, but for project management and integration as well. The ICAM Program Office has cited IDEF as recipient of a Top-of-the-Line Manufacturing Technology Success Story award. The IDEF methodologies are taught in several universities.'

Komanduri et al. (1985) selected IDEF$_0$ as a suitable methodology for determining machine tool system requirements in a high speed/high-throughput machining application. The work uses a viewpoint diagram A0, node tree and provides a discussion of the use of the model down to level A22433. Bowden and Browne (1991) use a model based on an A1 diagram 'Design the Production Environment' to examine information integration in the design of manufacturing facilities. The model is decomposed to levels A113, A123 and A133 and the information flow described by the diagrams forms the basis of the authors analysis of activities involved.

Several applications of IDEF$_0$ in the field of quality assurance are available. Stephans and Fox (1987) presented a method for assessing quality systems that, the authors claim, 'should provide a complete picture of requirements resources procedures, people, actions and interactions resulting from the IDEF$_0$ technique forcing a systematic thorough evaluation'. Tannock and Maull (1988) propose a strategy for the development of quality systems in CIM using IDEF$_0$ and Maylor and Butler (1991) propose IDEF$_0$ as a suitable tool to model an existing quality system and as a means of obtaining maximum benefit from new system implementation. Barton (1994) provides a design for a reliability testing system for microwave devices using an '$IDEF_0$ representation of the testing process, which is easier for the database novice to understand and implement than the usual data flow or entity-relationship diagrams'.

Harrison et al. (1988) propose $IDEF_0$ as a way of establishing the functional specification for CIM sub systems, the work is based on an application at NCR (Manufacturing) Ltd Dundee. The activity diagrams are decomposed to level A42 describing the PCB manufacturing system. They see the method providing an insight into system behaviour and forming a functional CIM integration specification. In a similar application Banerjee and Al-Maliki (1988) propose a method for applying the IDEF methods to design a flexible manufacturing system. They reinforce the view of others that no single method can provide a means of developing system specifications but by exploiting the merits of several methods an enhanced modelling methodology can be developed. The application is illustrated with relevant $IDEF_0$ diagrams and the links between functional and information models is explained. Pandya et al. (1990) also use $IDEF_0$ as a method to model the functional aspects of a flexible manufacturing system and identify information which is then used to build an $IDEF_{1X}$ model of information requirements at cell level. Using $IDEF_0$ models in CIM applications to describe information flow and subsequently build data models is also advocated by Chadha et al. (1990, 1994) who use the $IDEF_0$ and DFD models to provide a functional description of mechanical handling and Extended Entity Relationship (EER) diagrams to build a data model based on the information defined in $IDEF_0$ diagrams.

3.4 A REVIEW OF PUBLISHED IDEF3 RESEARCH

The key reference work for IDEF3 is the IDEF3 Process description capture method report (Mayer et al., 1992a), a commercial version of the report is also available (Mayer, 1993b). The report is a description of the semantics, syntax, scenario concepts and the methodology associated with the method. Unlike $IDEF_0$, public release of the IDEF3 method was followed immediately by a software tool[2] and a review of the method is provided in the software system users guide (KBSI, 1994).

In an early account of IDEF3 by Mayer (1990a) the semantics of the method are explained and a prototype of the IDEF3 software tool (later to become ProSim, marketed by KBSI) is described. In reviewing use of the method Huff et al. (1991b) claim that IDEF3 process descriptions are simple enough to be read and maintained by 'everyone in the organisation'. The thrust of their research is the dynamic representation of IDEF3 descriptions using Petri net models. The authors provide examples of the conversion of an Object State Transition Network (OSTN) and a Process Flow Network (PFN) to a Petri net. For example the logic described by a PFN asynchronous 'AND' junction before a process is converted semantically into a Petri net 'Place' (representing a situation that, if conditions are met, the process is ready to take place). It is proposed that using the approach 'the Petri net models can be used to verify the performance of a process'. Cullinane and Mayer (1992) propose the use of IDEF$_0$ and IDEF3 to improve the control of warehouse operations. IDEF$_0$ is used to identify activities involved in operation of the system activity descriptions which are then combined with control charts to track performance. IDEF3 diagrams are used to establish methods for bringing the system under control, the authors claim that 'IDEF3 has proven to be an excellent method for describing an ordered sequence of activities as they should be performed' and that an analyst can 'walk through the IDEF3 description seeking a reason for out of control points, offering explanations and proposing potential solutions'. The authors treat the diagrams as separate entities and offer no formal syntactical links between IDEF$_0$, IDEF3 and control charts. Benjamin et al. (1992) propose a knowledge based simulation architecture in which an IDEF3 Tool provides the system description aspect of simulation. Their architecture is the concept behind 'KBSI's evolving Integration Platform' that is designed to provide an operating environment allowing different tools and systems to communicate exchange data and share functionality. The example given by the authors is of a simulation that could extract current scheduling data from a factory information system to use as input to a simulation with an IDEF3 model and elaboration documents to hold the system description.

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[2] ProSim and ProCap, Automated Process Modelling, (KBSI, College Station, Texas).

One aspect of KBSI's research aimed at interfacing IDEF3 and simulation systems is the ProSim/WITNESS simulation link currently marketed in the UK by AT&T ISTEL[3] and described in 'Generate your WITNESS simulation models automatically with ProSim' (AT&T ISTEL, 1995).

Cesarone and Dobrzeniecki (1992) describe research funded by the US Defence logistics agency where IDEF3 models have been used to investigate the 'complex value-added chain of sub-contractors' used in the manufacture of military aircraft by Lockheed. The authors describe the IDEF3 method as a 'transition network' that can be used to provide critical path analysis and activity based costing. Their approach involves the use of $IDEF_0$, $IDEF_{1X}$ and IDEF3 as discrete methods however the potential for integration is not discussed. Benjamin et al. (1994) claim that $IDEF_0$ and IDEF3 play complementary roles as support tools for BPR. IDEF3 is claimed to be a 'suitable vehicle for quantitative analysis' whereas the 'more abstract representational apparatus (sic) provided in $IDEF_0$' is claimed to be a 'powerful tool for conceptual design and analysis activities'. To summarise the key contrast between the two methods $IDEF_0$ is described as a method that focuses on *what* happens in an organisation and IDEF3 can describe *how things work.*

IDEF3 is also considered a key tool to support BPR by Gregory (1994) who advocates its use in a twelve step methodology supported at each stage by a combination of $IDEF_0$, $IDEF_{1X}$ and IDEF3. Huff et al. (1991a) proposes a modified version of IDEF3 for BPR to 'simplify its use for novice modellers and uninitiated process owners (sic)'. The modification involves removing synchronous/asynchronous identifiers associated with junction symbols. In a South African defence industry application Goosen (1994) explains the use of IDEF3 to document logistics procedures and uses 'the repair of components in SAAF repair facilities' as an example. A single diagram together with a text specification is used to define the logical sequence of processes necessary to carry out 'component repairs'. A modified elaboration document based on a table listing the sequence of processes (UOBs) with the staff responsible and the next step in the sequence for each process is also shown. Much of the research associated with the application of IDEF3 is concerned with process 'metrics', using the diagrams as a means of describing and analysing quantitative information about the

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[3] AT&T ISTEL Ltd. (Redditch, Worcestershire, UK).

subject under review. The description of a cost benefit analysis application by Benjamin et al. (1993) is an example where they propose an approach to estimate the cost of processes using PFNs where 'the cost of a series of UOBs is simply the costs of the individual UOBs but processes after exclusive OR fan out junctions require the use of probabilities to establish average, optimistic and pessimistic process costs. The approach involves building an IDEF3 process description, establishing process costs and 'rolling (a sequence of processes) up to a more abstract, less detailed IDEF_0 activity'.

3.5 A SURVEY OF IDEF_0 PRACTITIONERS

An important finding from the analysis of published research, carried out from 1990 to mid 1994 involving over one hundred and fifty publications, was that there were few examples of industrial applications of IDEF_0 modelling. The majority of the publications being wholly or partially academic based. In response to the finding the major UK software tool vendor[4] was approached and agreed to support an analysis of his UK customer database. The initiative was designed to give an insight into a group of IDEF_0 users and also to investigate the value of carrying out a wide ranging survey with a larger target population involving a larger range of modelling methods. The findings from this survey were presented to the EPSRC Workshop on Structured Methods and Tools in November 1995 and the response of the workshop to the issues raised is reported by Little (1995).

3.5.1 Questionnaire design

The design of the questionnaire drew on the work of Oppenheim (1970) and Crimp (1981), it considered the topics to be included and omitted and a depth of investigation that attempted to balance deterring respondents with capturing useful information. A blank modelling methods questionnaire is shown in Appendix 8, 'tick boxes' were used to maximise returns and the questionnaire was restricted to a single sided A4 card with a

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[4] MicroMatch Ltd. - At the time (late 1994) the only UK vendor actively promoting IDEF_0 software tools.

Business Reply label on the reverse. The questionnaire was included in a commercial mail-shot carried out by MicroMatch Ltd. Twenty three responses were received which represents approximately 20% of the questionnaires sent to the one hundred and eighteen Design/IDEF users in the UK.

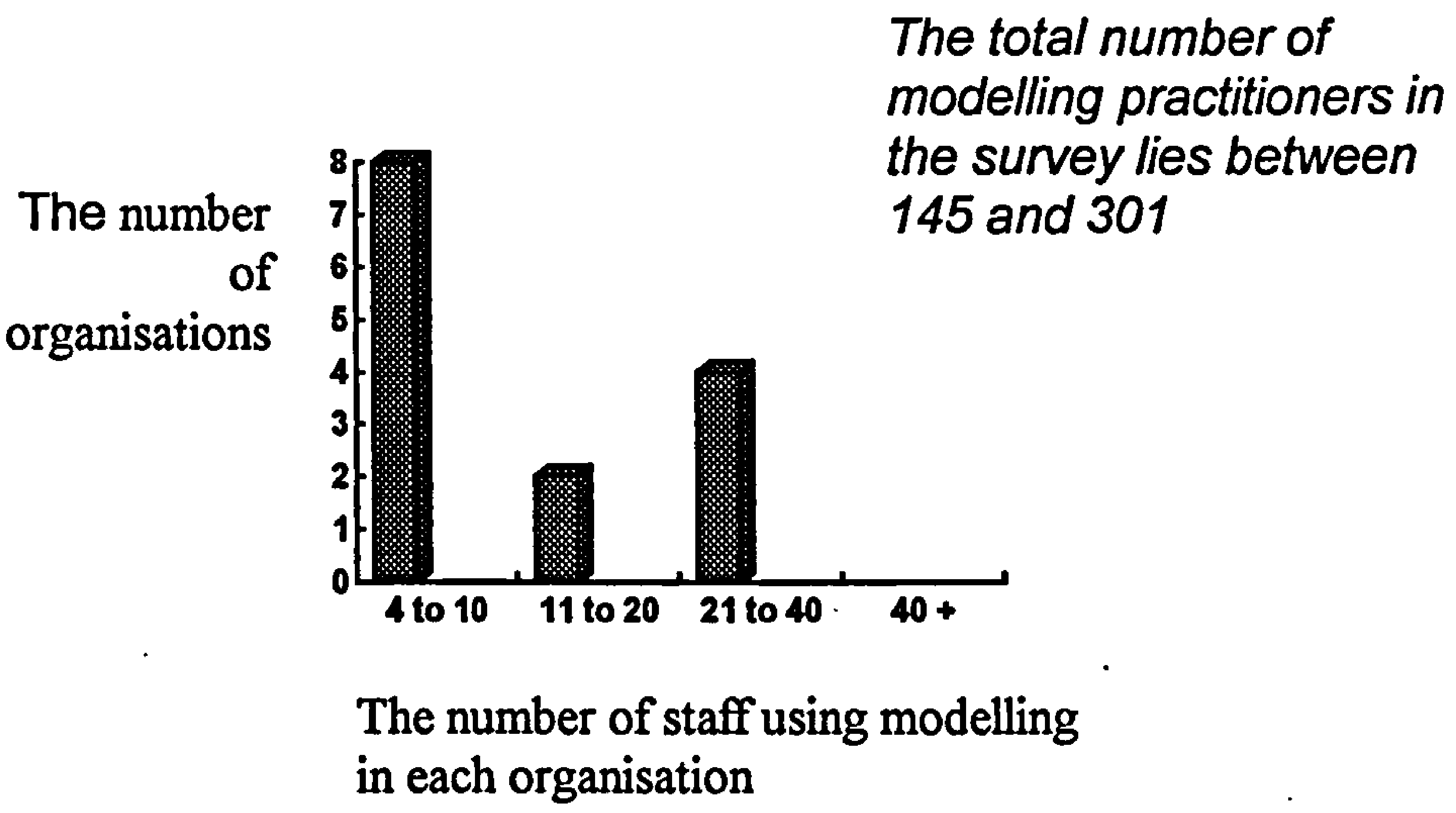
Seventeen questions were used, *Open* questions (1,3,4,6,8) together with *Classification* questions, (2 and 5) *Rating* questions (16, 17) and *closed* questions (11, 13). The use of *Open ended* questions was restricted to investigating the nature of the models used (questions 7, 9, 10, 12, 14, 15). In this case the potentially wide range of responses precluded the tick box approach.

Five aspects of $IDEF_0$ use were addressed: (i) the type of organisation using $IDEF_0$ modelling, (ii) the modelling practitioners within the organisation, (iii) the application areas for modelling methods (iv) the nature of the $IDEF_0$ models used and (v) a users view of $IDEF_0$.

3.5.2 Results of the survey

Principal activity	*Number of respondents*	*% of respondents*
University	6	26
Defence	3	13
Banking, financial, Business services	4	17.5
Manufacturing (various)	3	13
Government department	2	8.5
Computer services	2	8.5
Software & systems consultancy	2	8.5
Retail distribution	1	4.5

Table 3.1 Principal activities against number of respondents.



The total number of modelling practitioners in the survey lies between 145 and 301

Figure 3.1 The number of staff using modelling and number of organisations

Primary job functions of respondents	*Number of respondents*	*% of respondents*
Business analysis	8	34.5
Consultancy	5	21.5
Research	5	21.5
Teaching	2	8.5
Technical/customer support	1	4.5
Computer systems development	1	4.5
Manufacturing operations	1	4.5

Table 3.2 Primary job functions against numbers of respondents

	Requirements Capture	Process Redesign	Info. system Design	Organisational Change	Research	Others
IDEF$_0$	12	16	12	6	5	
IDEF$_1$			2		1	
IDEF$_{1x}$	1		1		1	
IDEF3	1	2	1	2	1	
CORE						
GRAI	1	1	1	1	1	
SADT	2	2	3		2	
SSADM	3	1	1			
Statecharts	3	1	3			
Petri Nets					1	
Checkland	1	1	1	2		
DFD	9	6	9	1	3	
Simulation	2	6		3	1	
Others:						
Information Engineering methodology	1	1	1			
Flowcharts	1	1	1	1		

Table 3.3 A Modelling method/Application matrix

Subject of last model	*Size (no of diagrams)*
Medium scale capacity analysis	16
Combined risk/business model	200
Defence equipment acquisition & support	28+
Customer services	7
Manufacturing system	50
Product data management system	15
New business processing	7
IS staff training and development function	25
No title	47
Structural steelwork	30
Software development project	10
Clinical trials data capture and reporting	5
Banking	150
Central quality processes	6
Utility-customer billing	16
Order fulfilment process	40
Engineering process	100
Chemical process development	10
Information technology	50
Aircraft maintenance costs	8

Table 3.4 The subject and size of IDEF$_0$ models

Primary job functions	*Why IDEF$_0$ was selected as a modelling tool*
Business analysis	Internationally recognised, Good at functional analysis, Recommended, Abstraction and Control flow, Found to be the most useful for our purpose at the time, Looked useful
Consultancy	Widely used in industry in BPR programmes, Hierarchical decomposition, Rigour, Robustness of methodology, Previous favourable experience, Fit for purpose
Research	Familiar, Ease of use, Industry standard, Requirement of STEP, Simple to use , Ideal communication tool
Teaching	Popular, ICOM roles, Splits and Joins
Technical/customer support	Recommended + successful trial
Computer systems development	Suited to business processes
Manufacturing operations	Recommended by consultants

Table 3.5 The relationship between primary job function and the reasons for selecting IDEF$_0$.

The benefits of using $IDEF_0$	Low	Medium	High	Excellent
Ease of modelling	2	2	12	5
Analytical capability		7	6	7
Usefulness of finished model	1	3	14	3

Table 3.6 A graded user view of the benefits of some aspects of $IDEF_0$ modelling

The benefits of using Design /IDEF	Low	Medium	High	Excellent
Quality of graphics	1	6	9	3
Ease of use	1	7	9	2
Glossary support	5	6	6	1
Parent/child linkage		2	12	4

Table 3.7 A graded user view of the benefits of some aspects of using the Design/IDEF tool

3.5.3 An analysis of survey results

(i) The Type of organisation using $IDEF_0$ modelling.

Table 3.1 shows that over 50% of the respondents were in the university, defence or banking, finance and business sectors. The six universities and one practitioner in banking, financial and business services have research or teaching as a primary job function. Three responses were received from the manufacturing sector. The responses to (ii) and (iii) however indicate, that although few manufacturing companies appear to be using modelling directly, modelling is being carried out in manufacturing companies through business analysis or consultancy.

(ii) Modelling practitioners within the organisation.

Table 3.2 and figure 3.2 indicate that the survey responses were from a modelling population of between 145 and 301 practitioners or users. Over 55% of respondents cite Business analysis or consultancy as their job functions and only one respondent is directly involved in manufacturing operations.

(iii) The application areas for a range of modelling methods.

The responses to question 8 give an indication of the application areas for IDEF$_0$ models and are collated in a modelling method/application matrix shown in table 3.3. Numbers in cells represent the number of practitioners using a particular modelling method, for a particular application area. Cells with five or more occurrences are shown in bold. All respondents use IDEF$_0$ in at least one application area. For information system design and requirements capture DFDs are used widely in addition to IDEF$_0$. Interestingly process redesign is the most widely applied area for IDEF$_0$ with information system design and requirements capture almost equally important. In contrast for DFDs the ranking is reversed, information system design and requirements capture are more widely used application areas than process redesign.

The range of software tools used by practitioners in addition to the DesignIDEF (IDEF$_0$) tool includes:

- ABC Flowcharter -Flowcharts
- VISIO -Windows graphics
- LOTUS -Spreadsheet
- ERWIN/ERX -IDEF$_0$ & IDEF$_{1X}$ tool
- IThink -BPR tool
- RADitor -BPR tool
- System Architect -Case tool
- Bachman analyst -Case tool
- Exellerator -Case tool
- PROSIM -IDEF3 tool

(iv) The nature of the $IDEF_0$ models used.

Over 90% of respondents used both AS-IS and TO-BE models and in terms of the type of models used the responses to question 9 and 10 provide a snapshot of the specific subject and size of models last completed (late 1994) by practitioners. Responses are collated in Table 3.4 and the subjects of the models are given verbatim. Of the models tabulated 50% used 30 diagrams or less and only three respondents produced models having 100 or more diagrams. Six respondents used ten or less diagrams for their model. In 91% of cases the models were used by staff in addition to the model builder inside the organisation. Of the model descriptions cited over 30% are manufacturing related and the two largest models described (in terms of number of diagrams) are for business and banking.

(v) a users view of the $IDEF_0$ method.

Question 12 is an open ended question designed to indicate the reasons behind the selection of $IDEF_0$ as a modelling method. A review of the responses related to the primary job functions of respondents is given in table 3.5. It was notable that not all returned questionnaires included a response to this question and the open ended approach produced a range of responses that included methodological reasons for adopting the method, management reasons and reasons based on general perceptions. The major users of $IDEF_0$ in Business analysis, Consultancy and Research show a consensus in citing, 'Internationally recognised', 'Widely used in industry' and 'Industry standard' as reasons for adopting the method. To establish an understanding of how users perceive the use of IDEF three questions were selected: to indicate if the method was easy to use, to establish a view on its analytical capabilities and to assess the usefulness of finished models. Table 3.6 is a matrix summarising the responses, numbers in cells represent the number of occurrences of the cell being selected by respondents. Ease of use and usefulness of finished models is rated highly. Analytical capability is however not rated as highly. Users rating of the Design/IDEF tool is high albeit with some negative rating of its Glossary support.

A speculative snapshot of IDEF modelling in the UK manufacturing, based on the limited number of responses to the survey, indicates that a modelling practitioner is a consultant. He/she uses other modelling methods in addition to $IDEF_0$, most likely DFDs or Simulation and other modelling software tools are used. Models are likely to comprise of less than 30 diagrams and are used by other members of staff in his/her organisation. The Design/IDEF tool is highly regarded and $IDEF_0$ was selected because it was considered to be a standard method.

In terms of the objectives of this research the survey has contributed to understanding the use of modelling methods particularly $IDEF_0$ in manufacturing. It provides a strong indication that manufacturing companies themselves are not using $IDEF_0$ widely and re-enforces the findings discussed in section 3.6, that a significant use of $IDEF_0$ in the UK is through Universities and research. The survey results have made the major contribution to the design of a larger national survey of manufacturing enterprises in the UK (Small, Baines and Colquhoun, 1996) that seeks to investigate other modelling methods in use and to provide an insight into those enterprises who have not considered or have rejected the use of modelling generally. The larger survey is not reported in this thesis.

3.6 CONCLUSIONS

When the initial state of the art review of $IDEF_0$ was carried out (Colquhoun et al., 1993) a majority of publications were concerned with category 2 - performance evaluations or comparisons. There is evidence now that the emphasis of publications has changed, a majority of later publications are in categories 3 - proposals for enhancements and 4 - specific applications of the method. This reflects the maturity of the method, that its use is established and well understood and that research is focusing on perceived weaknesses, development and on applied use of the method.

The basic concepts are now well recognised as evidenced in both the amount of related published work and in the general use of the method to represent the concepts of manufacturing systems. In those publications providing descriptions and reviews of the basic method, most introduce the method and its potential applications and restrict descriptions to activity diagram construction. Few authors deal with the broader aspects of the method such as model structure, author-reader cycle and the interview methodology.

The majority of reported work has taken place in the USA as a result of the impetus provided by the US Air Force. In discussing its use in the USA Stephans and Fox (1987) report that 'the method is used primarily to review government contracts and there is relatively little data concerning its application outside the defence or government environment', the claim is supported by this review. Few complete $IDEF_0$ models are in the public domain however a comprehensive analysis of aerospace manufacturing has been provided by CAM-I (1980) in their model 'Get and use aerospace product'. Use of the four categories in this analysis has revealed that applications of the method are the least well documented and that few detailed applications of $IDEF_0$ have been reported by UK enterprises. The survey in section 3.5 indicates that the method is being used more widely than the literature survey would suggest though the evidence of the survey re-enforces the argument that non-academic *manufacturing* applications in the UK are very limited. The emphasis is on a largely academic/research approach to the subject and could be an indication that the rich picture that an $IDEF_0$ model can provide may be in conflict with the confidential nature of industrially based models.

Early researchers raised the problem of a lack of computer tools to support the method for example in 1983 Yadav (1983), using SADT, found that 'for large and complex systems the lack of automation makes an SADT model vulnerable to inconsistency and incompatibility' Other authors refer to the large number of diagrams and amount of documentation required for an $IDEF_0$ model and see the tedious nature of diagram production as a drawback to its use. The proliferation of $IDEF_0$ computer tools in the 1990's has largely overcome the problems of diagram production and model administration.

However the building of an $IDEF_0$ model of a manufacturing system can be a difficult process demanding a great deal of time and care, manufacturing systems are truly complex with many formal and informal relationships occurring between sub-systems and their representation tests any modelling method. Wu (1992, p.330) observes that 'actual operations are likely to be "greased" by informal systems that often provide methods of overcoming short-term problems and occasionally allow an unworkable operating procedure to work and so it is essential they are considered in the analysis'. There is a consensus that $IDEF_0$ is powerful enough to stand up to modelling both formal and informal functional relationships and that experienced practitioners of the method can provide useful and largely accurate models. Few authors are wholly critical of the method and most support the basic tenet that the method provides a means of understanding the complex interaction of men, machines and information, and a means of communicating that understanding to others. It is evident however that most authors agree no one method can model the functional, information, dynamic and decision aspects of systems. It is therefore surprising that the interface between $IDEF_0$ and other IDEF methods have not been widely discussed. Goldman and Cullinane (1987) identify a need for a linking methodology to develop $IDEF_1$ models from $IDEF_0$ models and some other authors have discussed IDEF method integration (Godwin et al., 1988, Schneider, 1994)

Amongst the criticisms of the method Shunk et al. (1986) claims that 'diagrams often go unused' and Harrison et al. (1988) claims that the effort in diagram production involves a significant amount of work. Busby and Williams (1993) claim that '$IDEF_0$ cannot represent in any profound way the manner in which people take decisions'. Goldman and Cullinane (1987) also suggest that limitations of the method are related to the lack of decision rules for model decomposition and the lack of an explicit link between information flows and claim that decomposition is frequently misunderstood by users. The most frequently cited shortcoming of the method is the lack of a 'time' dimension to describe activities.

$IDEF_0$ has been designed to model manufacturing and no other modelling method claims to provide the same functional analysis capability, it is accessible, in the public domain and has strong software tool support with a large body of knowledge and a proven capability in the US defence manufacturing arena.

CHAPTER 4

A COMPARATIVE ANALYSIS OF MANUFACTURING ENTERPRISE SYSTEMS ANALYSIS AND DESIGN METHODS

4.1 INTRODUCTION

This chapter reports on an analysis of methods used to model manufacturing enterprises. It focuses on methods that predominantly use models based on diagrams and sets of diagrams representing various aspects of manufacturing enterprises. The descriptive methods, diagram syntax and model structure used in graphical presentation are also analysed.

The analysis re-enforces a generally accepted view (Jones et al., 1991, Roboam and Pun, 1989) that no single method can be used to model the full complexity of a manufacturing enterprise. The methodologies that underlie the various methods were also reviewed. Shortcomings derived from analysing the capability of each method provide a basis for recommending how aspects of several approaches could be integrated to provide a hybrid approach robust enough to model a broader range of manufacturing enterprise characteristics than has previously been the case.

This chapter extends the work published by Colquhoun and Baines (1993b).

4.2 CONTEXT FOR A COMPARATIVE ANALYSIS

Definitions:

Modelling method - A manual or computer prepared graphical and text description based on a formal documented syntax such as IDEF$_0$ or other structured approaches.

Methodology - A method or collection of methods or computer tools whose use is governed by a procedure superimposed on the method or collection.

Tool - (as in CASE tool) a software system designed to support the application of a modelling method or methodology.

Widely recognised *formal*[1] graphical modelling methods for the representation of concepts, design proposals and the transfer of information are routinely used disciplines such as architecture, engineering design and software engineering. In the emerging discipline of manufacturing systems design and analysis, engineers are dealing with complex system characteristics that range from human constraints to material flow. In this environment a clear consensus on the application of the many formal modelling methods that have been proposed has yet to emerge. A general commitment to the use and standardisation of formal methods however is evident in the scale of research initiatives such as CIM-OSA, launched in 1984 involving twenty one companies from seven European countries (Jorysz, and Vernadat, 1990a, b, Klittich, 1990, Klittich, 1995) and the US Air Force Information Integration for Concurrent Engineering (IICE) program (Painter, 1992) that has led to the development of the IDEF3 to IDEF14 family of methods.

Modelling methods used in manufacturing systems design and analysis are an aspect of problem-solving that have diverse roots in Operations Research, Software Design and General Systems Research, three broad areas that pre-date the emergence of manufacturing systems engineering as a recognised discipline. Modelling methods can combine both quantitative and descriptive aspects of a situation and can be either static or dynamic and can describe an existing situation or conceptualise future situations. There

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[1] 'Formal' refers to the a standardised set of rules and constructs for graphical presentation.

are no distinct categories of modelling methods for manufacturing systems however the two broad domains of 'Hard' and 'Soft' systems approaches (Wu, 1994, Cavaleri and Obloj, 1993, Boardman, 1990) have become accepted.

Hard systems approaches are based on rational decision making to solve problems that are well defined and that can be largely described quantitatively and hence solved mathematically. Wilson (1984) proposes four categories for mathematical analytical modelling, *steady state* and *dynamic* (modelling over time) each of which can be either *deterministic*, an algorithmic approach that assumes all the relevant system parameters are known, or *non deterministic* demanding the use of statistics that assume a range of values can describe a particular situation. The goal of hard systems approaches is to identify alternative solutions to a problem which can subsequently be evaluated against some criteria such as risk, costs or benefits.

In contrast soft systems approaches are proposed to deal with ill-structured problems without well defined objectives or a commonly agreed problem definition and with incomplete or few quantitative measures of performance or behaviour. Real world problems that Boardman (1990) argues 'are more complex than hard systems methodology admits' because they involve, or have arisen because of, the different perceptions of those involved. The contrast to hard systems approaches is re-enforced by soft system goals that are 'more concerned with the orchestration of debate centred on perceived problematical situations' (Checkland, 1989). In a soft systems approach there are no permanent optimised solutions to a problem situation but the tenet that a continuous series of improvements are possible.

Hard systems approaches for manufacturing enterprise systems assume that all necessary information will be available and that problem solutions will be implemented as predicted by a mathematical model using constraints to meet certain criteria. The approach is in conflict with many aspects of manufacturing enterprises which are subject to the control of humans and can be dynamic, uncertain, and in some conditions chaotic. It is at a tactical level that hard systems methods tend to be applied 'because many operational goals have been refined by the time they reach this level and can thus be more readily measured' (Cavaleri and Obloj, 1993).

Figure 4.1 is an overview of a range of systems modelling approaches in the context of 'hard' and 'soft' approaches. The spectrum of modelling approaches positions a representative selection of methods that have been proposed for modelling aspects of the manufacturing domain.

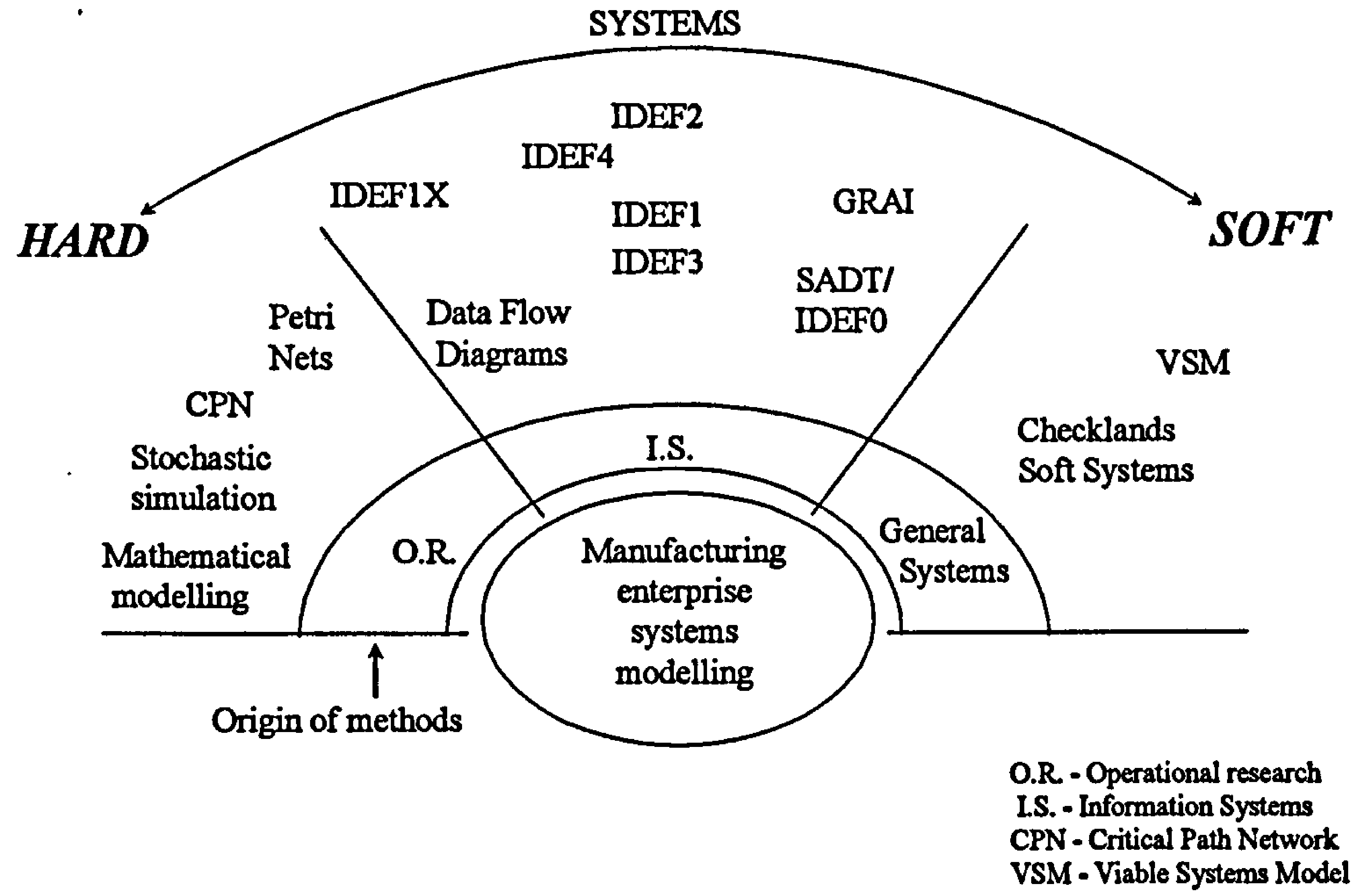

Figure 4.1 The modelling methods spectrum

The IDEF methods have substantially influenced this research and have provided a reference point (rather than a benchmark) for a review of some of the modelling approaches referred to in the modelling methods spectrum of figure 4.1

4.3 SOFT SYSTEMS MODELLING METHODS

Soft systems modelling methods rely on viewing systems through the perceptions of participants in the systems. The approach acknowledges that there may be no single well defined problem in a complex dynamic system and that it is only by exposing, discussing and refining understanding of a system that improvements can be made. Two clearly 'soft' methodologies have been applied in manufacturing enterprise modelling, the Checkland

Soft Systems Methodology (discussed in appendix 4.1) and the Viable Systems Model (VSM) (discussed in appendix 4.2).

VSM has been described as a theory of organisation, and Espejo (1989a) advocates the approach as a 'paradigm for problem solving' and a tool 'to diagnose the effectiveness of an organisations structure'. It is certainly more than an analysis methodology and shares some structural characteristics with the Checkland approach. The directed modelling methodology in terms of the systems; (operating core, control and co-ordinating mechanism, internal information systems, external information systems and policy making) has parallels with the CATWOE of Checkland. VSM uses the principle of 'recursion' to examine aspects of a system in greater detail and in a structured manner that reflects the decomposition approach of hierarchical modelling methods.

The essence of the method does not lie in graphical representation but in the use of the model to guide the intellect of the analyst in dealing with a problem. The potential difficulty of routine application in manufacturing enterprises lies in the intellectual rigour necessary to apply VSM concepts.

The structured diagramming of 'harder' approaches demands more sophisticated symbols and representations in order to be able to map the problem to the model. Whereas the VSM and Checkand tend toward mapping the problem to the concept. Anderton (1989) draws an interestingly similar contrast from a different viewpoint between 'harder' approaches of systems engineers and the 'softer' VSM and Checkland SSM highlighting the rationale behind the, apparently, casual sketch approach used to present soft system models.

'They (Beer and Checkland) insist their freehand drafts are reproduced unchanged with the slightly wiggly lines retained. They prefer cloud shapes to boxes. Intuitively they feel that something of the richness of their propositions, of the organic origins of what they seek to represent, is lost by a conversion into perfect grids, squares and other geometric artefacts.'

The GRAI (Graphe à Résultats et Activités Interliés) methodology has been influenced by IS and general systems approaches and is at the 'softer' end of the modelling spectrum. The method lies in the same area of the modelling spectrum (shown in figure 4.1) as IDEF$_0$. It is focused on representing real aspects of a manufacturing system but can represent concepts and can deal with subjectivity in its graphical representation. A review of the methodology is presented in appendix 4.3.

4.4 INFORMATION SYSTEM MODELLING METHODS

Modelling methods associated with data modelling and software design lie in the centre of the modelling methods spectrum. These modelling methods have had a major influence on the development of manufacturing enterprise modelling in both proving the value of modelling and in the development of methods and methodologies.

The emphasis of diagramming methods such as data flow diagrams and data model diagrams has been to provide a concise description of an existing or a proposed system in order to build software to run or to support the system. The rationale behind the development of such methods has been to ensure fault free design, to eliminate data redundancy, to minimise software development time and to render large computerisation projects manageable. Rationalisation or redesign of the system structure was an outcome of the application of computers rather than an end in itself. The recent rise of Business Process Re-engineering (BPR) which according to Gutkowski (1994) 'was a provocative concept only a few years ago' and the development of Computer Aided Systems Engineering (CASE) tools used for the automation of structured methodologies (Britton and Doake, 1993) has shifted the emphasis to focus on re-organisation of systems before designing and implementing computer systems.

In contrast, the primary focus of manufacturing enterprise systems modelling from its beginnings in Operational Research in the 1940's has been problem solving or system change to improve performance. Some of the accepted principles of modelling methods have however been developed from software design methods such as 'Top Down' programming from the early 1970's and structured design and structured analysis (Yourdon and Constantine, 1978, Yourdon, 1989, DeMarco, 1979). Cavaleri and Obloj (1993) see

Systems Analysis (in the context of Information Systems) as an approach that integrates quantitative aspects of systems with organisation theory and that it 'acknowledges that systems are often pluralistic in that they contain many decision makers with diverse and often competing values'. Re-enforcing the argument that information system modelling has characteristics of both hard and soft systems approaches.

An analysis of the range of graphical modelling methods in the information system domain exposed the following broad categories:

(i) those used to model *data* from a logical viewpoint.
(ii) those used to model *processes* (or activities) and the flow of data between them.
(iii) those used to model the *structure* of software.

(i) In this category a variety of similar graphical notations have been used to represent entity-relationship concepts based on relational theory proposed by Chen (1976), Codd (1970) and others. The entity-relationship (E-R) modelling used in the IDEF_{1X} method is an example. In basic form Entities (represented by rectangles in figure 4.2) are 'things' or collections of 'things' which have a relationship with each other (represented by the joining line and a verb phrase written along the line).

The cardinality of the relationship is described by symbols on the joining line, in figure 4.4 the entity-relationship diagram represents a situation where a *customer* (the entity customer has attached data such as name , address etc.) can *place* many *orders* (similarly, the entity order has attached data such as order number, quantity, description etc.). From a normalised entity-relationship diagram (or schema) the tables and table structure of a relational database can be established.

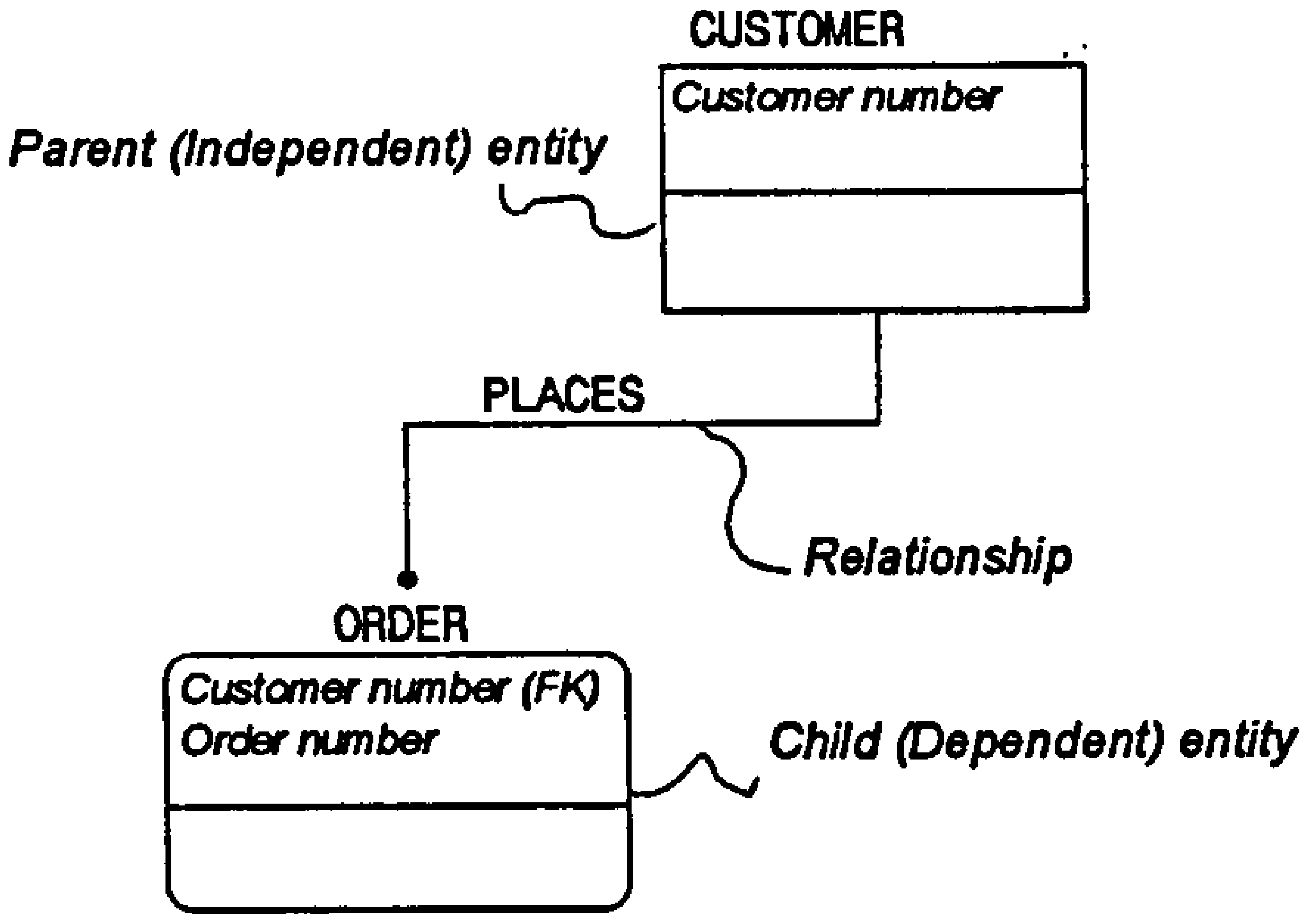

Figure 4.2 An IDEF$_{1X}$ representation of an entity-relationship

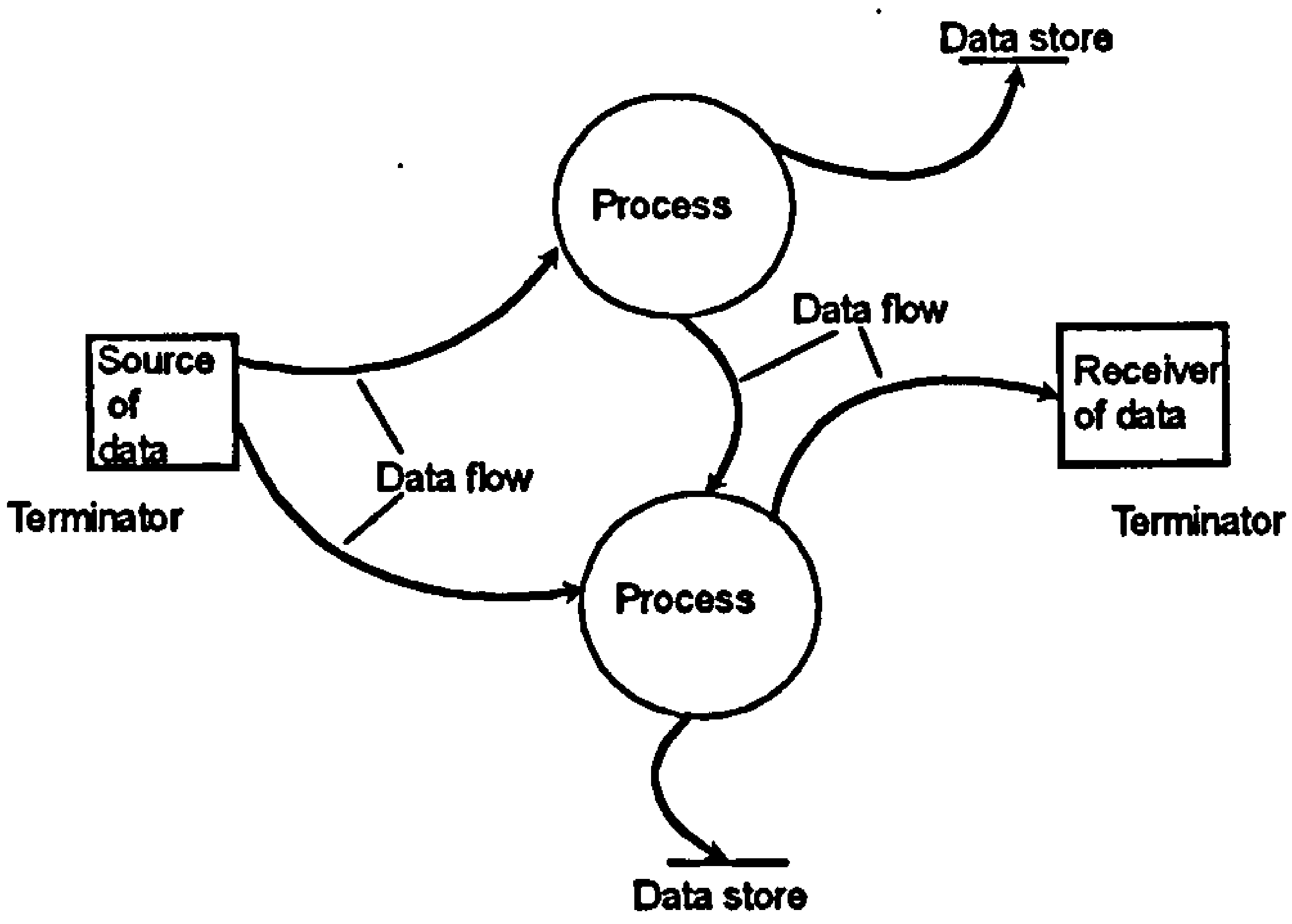

Figure 4.3 The elements of a DeMarco Data Flow Diagram (DFD)

(ii) Various diagramming notations have been proposed to represent the flow of data in a software system and are largely based on DeMarco's (1978) data flow diagramming method. A Data Flow Diagram (DFD) depicts processes and the flow of data between processes as a graphical network to identify the requirements of software systems. Figure 4.3 is an example of a data flow diagram using DeMarco's graphical symbols.

A DFD has four graphical elements: (1) *Processes* - a process involves data transformation (for example, using arithmetic or logic operations) and is represented by circles or round cornered rectangles with a concise description of the process inside. (2) *Data flows* are arrows tracing the path and direction of data flow from process to process. (3) *Data stores* or files are represented by horizontal lines with the name of the data store written above. The direction of arrows entering or leaving a store indicates a 'read' or 'write' operation. (4) *Terminators* are squares indicate the originator or receiver of data and are shown on the periphery of a diagram.

Other DFD approaches include Gane and Sarson (1977) and the Structured Systems Analysis and Design Methodology (SSADM) Longworth and Nicholls (1987). Figure 4.4 shows the DFD notation from SSADM the core elements are the same as DeMarco but different symbols are used. Data Flow Diagrams can be used to model high level and lower level, detailed views of a system, what takes place in a higher level 'process' box can be exploded into a lower level diagram, the decomposition of diagrams is termed 'levelling'.

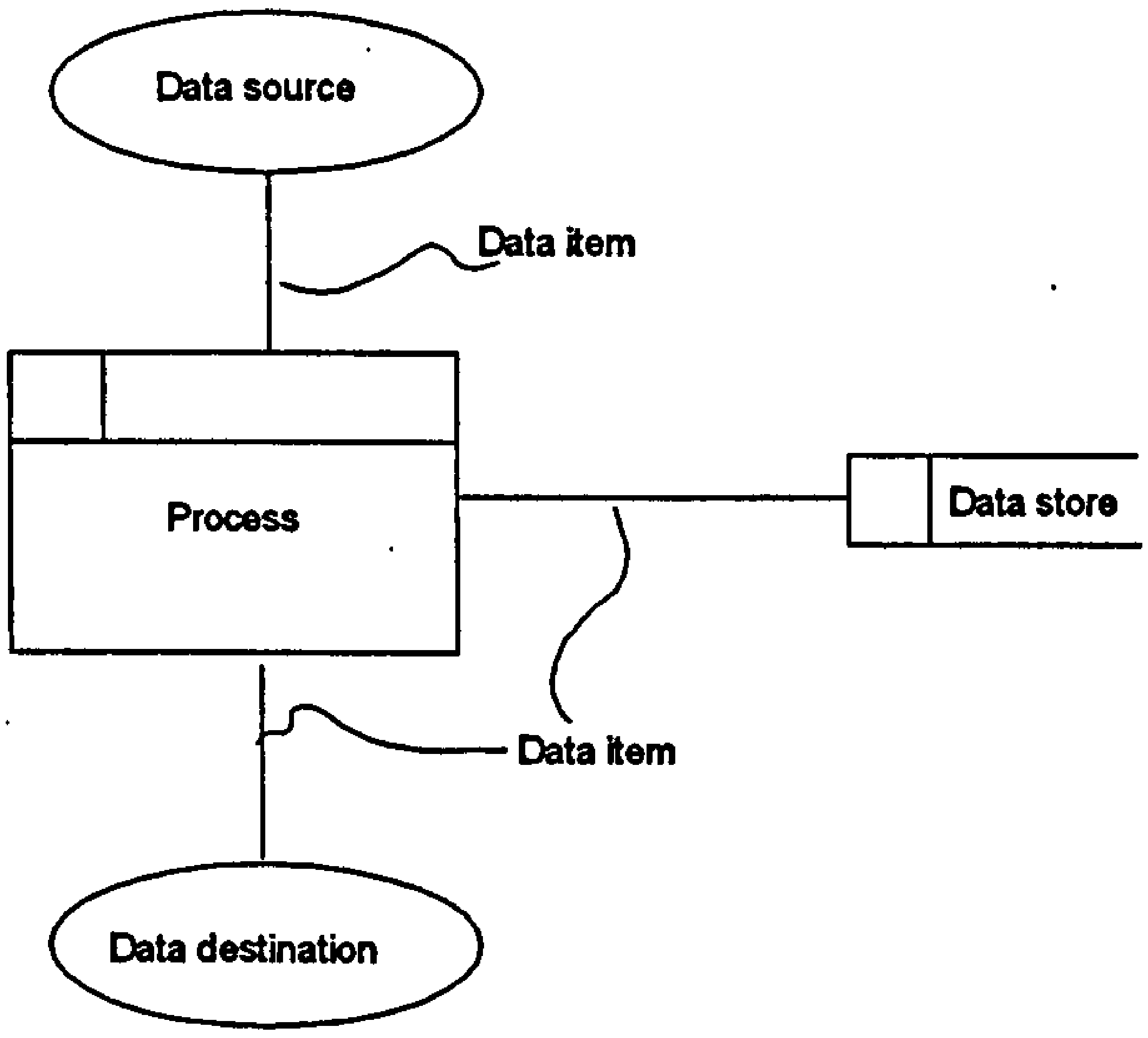

Figure 4.4 The graphical elements of an SSADM Data Flow Diagram

Some authors have proposed modifications to the DFD; Ward (1986) claims that DFD models have not provided a comprehensive way to represent timing, control and data transformation and proposes extensions to model structure to overcome the problem. To use DFDs in manufacturing MacIntosh (1993) proposes a structured integration of DFDs and GRAI grids. He uses DFDs to describe information flow and builds a GRAI grid for 'to act as a summary' for each Data Flow Diagram and provide a picture of the decisions governing information flow.

(iii) Early approaches to modelling program structure were based on flowcharts but the lack of functional decomposition and the emphasis on detailed logical flow meant they were of less use as program size and complexity increased. Nassi-Shneiderman (Nassi and Schneiderman, 1973) diagrams attempt to overcome the disadvantages of conventional flow charts using a nesting syntax which is claimed to be easily transferable to structured program code. Warnier-Orr diagrams (Warnier, 1981) use a hierarchical text list that shows the logical relationships between processes (*processes* in this case being routines or sub-routines in a program). Michael Jackson diagrams and Hierarchical Input-Process-Output (HIPO) diagrams (Martin and McClure, 1985) have also been proposed as graphical methods to model program structure.

The three categories discussed: modelling *data* from a logical viewpoint, modelling *processes* (or activities) and the flow of data between them and modelling the *structure* of software are steps in complete methodologies for software development. Three such IS derived methodologies have been widely discussed in the context of modelling for manufacturing systems:

- The Structured Systems Analysis and Design Methodology (SSADM) (see appendix 4.4).
- The Nijssen Information Analysis Method (NIAM) (see appendix 4.5).
- The COntrolled Requirements Expression (CORE) method (see appendix 4.6).

Over the last decade a wide range of support tools have been developed. Computer Aided Software Engineering (CASE) tools has become the generic term for such systems. Somerville (1992) proposes that there are several hundred commercially available systems.

The scope of CASE tools for software development includes system specification, design, implementation and validation and their functionality can include: modelling and simulation, language processing, method support, prototyping, document preparation, project control.

4.5 'IS' MODELLING METHODS IN THE CONTEXT OF MANUFACTURING SYSTEMS

A range of IS modelling approaches have been proposed to model manufacturing enterprise systems and in many cases have been compared to $IDEF_0$ (Chapter 3 section 3.3.2 discusses comparisons with $IDEF_0$ in detail). This section discusses specific IS modelling approaches, which, the research to date has established, have the greatest potential to contribute to modelling in manufacturing.

DFDs are amongst the most popular modelling methods used in manufacturing systems applications. The modelling principles of DFDs are very close to $IDEF_0$ and DeMarco (1979) argues that 'an SADT diagram is a slight variation' of a DFD. A complete DFD model involves decomposition of a single top level diagram called the 'context diagram' which defines the scope of the model. Just as in SADT and $IDEF_0$, rules based on 'balancing' parent and child diagrams provide structured decomposition of higher level diagrams.

In contrast to a DFD an $IDEF_0$ model diagram is constrained by a more rigorous set of rules however the concepts and model building process of DFDs are analogous to those of $IDEF_0$. Two key differences between the methods are the specific data flow focus of a DFD and the identification of 'Controls' in $IDEF_0$. The arrow structure of $IDEF_0$ is also designed to represent objects in addition to data or information. Used as originally intended a DFD is a 'harder' approach than $IDEF_0$ conceived to define software requirements accurately and as such would not be intended to describe concepts or provide a subjective description of a situation.

The focus of data flow diagrams on *processes* has lead to its application in manufacturing enterprise systems modelling. For manufacturing, DFD graphical representation has no advantage over $IDEF_0$, it cannot describe any additional characteristics of a manufacturing enterprise and $IDEF_0$ provides a much richer description. I would suggest that the simplicity and lack of rigour in diagram format has had some influence on its adoption. Little training is necessary to understand a DFD (despite the intellectual effort necessary to build models) only four symbols are used, no constraints are imposed over diagram format and the diagrams can be understood intuitively. One important lesson to be learnt from the DeMarco DFD approach is that modelling method complexity must be kept to a minimum. However the approach generally does not attempt to describe the time processes take or the logic of process sequence or the conditions that govern process sequences.

CORE has been specifically designed for modelling in manufacturing applications. Using CORE a process sequence can be described however alternative sequences (or branches) are limited to two formal constructs; 'mutual exclusion' and 'indeterminate order of actions'. On the other hand CORE has the ability to describe five different types of action iteration conditions. The focus of the method is on the description of data in relation to actions rather than on the relationship between actions. A CORE model involving the six types of diagram with sophisticated model syntax and Node notes is an exhaustive means of exposing detail data requirements in a complex 'one of a kind' manufacturing environment. A characteristic of both CORE and NIAM is the ability of the methods to describe types of data. In thread diagrams CORE can describe ; event data, data containing information and control data and distinguishes between 'critical' and 'non-critical' data. NIAM makes the distinction between objects and data about objects.

4.6 'HARD' SYSTEMS MODELLING METHODS

Hard system modelling methods rely on a reductionist approach, breaking down problem situations into clearly definable packages where all the parameters relevant to a problem are known and where statistical methods or algorithms can be applied to predict future events or solve problems Cavaleri and Obloj (1993) claim that OR lies at the core of hard systems approaches and that the critical foundation of hard systems is 'a well defined problem'. 'Hard' graphical methods have been used to model various aspects of manufacturing enterprises. Sauter and Judd (1990) argue that as manufacturing systems are man made machines (sic) 'they cannot be described by differential or difference equations, but rather they generate events which must be controlled and that such systems have been termed Discrete Event Dynamic Systems (DEDS)'. This review does not consider mathematical models such as Markov chains, queuing theory or inventory models.

The three important 'hard' modelling methods in the context of this work are discussed in appendix 4.7, 4.8 and 4.9, they are; Discrete Event Simulation, Petri nets and Critical Path Analysis (CPA).

4.7 GRAPHICAL REPRESENTATION

Most of the methods analysed have been proposed by practitioners as suitable for modelling man, machine, material and information systems in a manufacturing context. Some of the methods are, in the broadest sense, methodologies. The analysis has however concentrated on the graphical or textual descriptive aspects of the methodologies or methods. They have widely differing applications however the analysis has revealed that they share some fundamental common characteristics:

They all use a graphical descriptive language having a formal syntax and use symbols to represent attributes or characteristics of a system and the relationships between symbols, text descriptions and numbering systems are used in conjunction to form a complete model.

The scale or area of their respective diagrams, line length or symbol size do not have any descriptive significance.

The relative position of symbols is used to describe some system attribute.

Arrows or lines are used to describe the relationships between symbols in terms of sequence or flow.

The principle of abstraction (information 'hiding') is used to expose different levels of detail and the application of abstraction over several diagrams is the basis of a complete model.

Text is used as an additional means of system description, some methods use formal rules to constrain the nature of text within models. Checkland (1981) for instance suggests that the root definition of the Checkland soft systems model should be in the form of 'a structured set of verbs in the imperative mood'. In $IDEF_0$ an activity is described by a 'concise active verb phrase' (Ross et al., 1980).

Recognition of these common characteristics has provided a framework for the structured comparative analysis discussed in section 4.8.

4.8 A STRUCTURED COMPARATIVE ANALYSIS

A structured analysis of the characteristics of a representative range of methods in the context of manufacturing enterprises is presented in this section. The methods have been examined in chapters 2, 3, 4 and appendix 4 and selected because they have been used to model aspects of manufacturing systems. To provide a structure for the analysis it has been necessary to identify modelling parameters that would be useful when attempting to represent a wide range of manufacturing systems features. In total 14 modelling parameters have been identified and presented in a comparative table (table 4.1 a, b, c) that describes characteristics associated with each method considered. The table also highlights, in italics, the graphical symbols or representation adopted by the method to describe the states or characteristics of a system.

Following is an explanation of the modelling parameters used in Table 4.1 (a, b, c).

1. **Model state**: Three states have been identified:

- An 'AS IS' model represents a situation as it exists in practice, defined in company specific terminology.
- 'Generic' describes a model that represents the generally accepted or intrinsic activities that exist within a defined process or system and will represent all occurrences of those activities (Colquhoun and Baines, 1991).
- 'Planning' describes a model that can be used to express a design or to conceive or propose a future state of a system (an 'TO BE' state).

2. **Basic elements**: Are the aspects of a system that provide the focus of a method and basis of the diagrams produced. The symbols used to represent these *basic elements* are the key elements of a model diagram.

3. **Link between basic elements**: This modelling parameter refers to those aspects of a system that relate basic elements (parameter 2) and are shown diagramatically as symbols that link basic element symbols.

4. **Nature of the link between basic elements**: In most cases the nature of the link between the basic elements will be physical such as material, information or data. However they could also be linked by concepts, for example by a 'decision to proceed' or 'design ideas'.

5. **Basic element dependency**: Two conditions have been considered either the basic elements will be *non-conditional* in which case the method is not capable of modelling the conditions for a basic element to occur, proceed or exist. Whereas a *conditional* relationship is one where the method is capable of modelling the conditions for a basic element to occur.

6. **Basic element time span**: A method's ability to model the time span of basic elements or between basic elements, two states have been considered; (i) 'intrinsic' means that time is an essential element of the method and is represented using graphics or text

and (ii) 'not represented' means that the time span of basic elements is not considered in the modelling method.

7. **Nature of time span**: This is closely related to parameter 6 and considers whether the model can support deterministic and/or stochastic times.

8. **Representation of concurrent elements**: This simply considers whether the method can model basic elements or linking elements that occur concurrently.

9. **Representation of dependent elements**: Similarly this parameter considers whether the method can model any dependency or sequence of basic elements or linking elements.

10. **Representation of resource requirements**: Is the ability to describe the associated resources (in terms of people, machines finance etc.) necessary for carry out basic or linking elements.

11. **Representation of model hierarchy**: This refers to the ability to provide a structured hierarchy of diagrams.

12. **Supporting information:** This considers the formal rules associated with text descriptions necessary to support the basic diagramming method.

13. **Model validation**: This considers the formal means of model validation associated with a method.

14. **Complete model context**: This relates the ability to establish the model in a wider context.

	MODELLING PARAMETERS	IDEF$_0$	IDEF3 PFN	GRAI	BASIC PETRI NET	CPA PERT	CHECKLAND SOFT SYSTEMS	CORE Thread diagrams	DFD
1	MODEL STATE	'AS IS.' PLANNED. GENERIC.	'AS IS'. PLANNED.	'AS IS' . PLANNED. GENERIC.	'AS IS'. PLANNED. GENERIC.	PLANNED. GENERIC.	'AS IS'. PLANNED.	'AS IS' PLANNED	'AS IS'. PLANNED. GENERIC.
2	BASIC ELEMENT	ACTIVITY *RECTANGLE & VERB PHRASE.*	UNIT OF BEHAVIOUR *RECTANGLE & VERB PHRASE.*	DECISION MAKING ACTIVITY CENTRE *GRAI GRID & INFINITIVE VERB*	EVENT *RECTANGLE OR BAR & LABEL*	EVENT *CIRCLE & LABEL*	ACTIVITY *BUBBLE AND VERB PHRASE*	'ACTION' *TABULAR ENTRY VERB PHRASE*	DATA FLOW *ARROW & LABEL.*
3	LINK BETWEEN BASIC ELEMENTS	INPUTS. OUTPUTS. CONTROLS. MECHANISMS. *ARROWS & NOUN DESCRIPTION*	PROCESS SEQUENCE LOGIC *ARROWS JUNCTIONS LABELS*	DECISIONS, IMPORTANT INFORMATION *BROAD ARROW, ARROWS & LABEL.*	CONDITIONS FOR EVENTS. LOGIC. *CIRCLE, ARROW & LABEL*	EVENT SEQUENCE *ARROW & LABEL*	LOGICAL DEPENDENCY INFORMATION *ARROW, BROAD ARROW. & LABEL*	ACTION SEQUENCE. LOGIC, DATA. CONTROL. MECHANISM. *ARROW, LINETYPES & LABEL*	PROCESSES. FILES. DATA STORES. *CIRCLE.* *BAR* *RECTANGLE & LABEL.*
4	NATURE OF LINK BETWEEN BASIC ELEMENTS	PHYSICAL. CONCEPTUAL.	PHYSICAL	PHYSICAL. CONCEPTUAL.	PHYSICAL	CONCEPTUAL.	PHYSICAL. CONCEPTUAL.	PHYSICAL	PHYSICAL
5	BASIC ELEMENT DEPENDENCY	NON - CONDITIONAL	CONDITIONAL *LOGIC(ARROWS)*	NON - CONDITIONAL	CONDITIONAL *LOGIC-(ARROWS) TOKENS -(DOT)*	CONDITIONAL *LOGIC - (ARROWS)*	NON - CONDITIONAL	CONDITIONAL *LOGIC-(LINETYPES) LABELS*	CONDITIONAL *PROCEDURAL ANNOTATION.*
6	BASIC ELEMENT TIME SPAN	NOT REPRESENTED	INTRINSIC *TEXT (ELABORATION DOCUMENT)*	INTRINSIC *GRID HIERARCHY*	NOT REPRESENTED.	INTRINSIC *LABEL*	NOT REPRESENTED	NOT REPRESENTED	NOT REPRESENTED

Table 4.1a A comparative analysis of modelling method characteristics (adapted from Colquhoun and Baines, 1993b)

	MODELLING PARAMETERS	IDEF$_0$	IDEF3 PFN	GRAI	BASIC PETRI NET	CPA PERT	CHECKLAND SOFT SYSTEMS	CORE Thread diagrams	DFD
7	NATURE OF TIME SPAN	NOT REPRESENTED	DETERMINISTIC	DETERMINISTIC	NOT REPRESENTED	DETERMINISTIC. PROBABILISTIC.	NOT REPRESENTED	NOT REPRESENTED	NOT REPRESENTED
8	REPRESENTATION OF CONCURRENT ELEMENTS	NOT INTRINSIC	INTRINSIC *LOGIC-(ARROWS) JUNCTIONS*	INTRINSIC *GRID HIERARCHY*	INTRINSIC *LOGIC-(ARROWS) TOKENS-(DOTS)*	INTRINSIC *ARROWS*	NOT INTRINSIC	INTRINSIC *ACTION BOX RELATIVE POSITION*	NOT INTRINSIC
9	REPRESENTATION OF SEQUENTIAL ELEMENTS	NOT INTRINSIC	INTRINSIC *ARROWS. RELATIVE POSITION*	INTRINSIC *GRID HIERARCHY*	INTRINSIC *ARROWS*	INTRINSIC *ARROWS. RELATIVE POSITION*	NOT INTRINSIC	INTRINSIC *ARROWS. RELATIVE POSITION*	NOT INTRINSIC.
10	REPRESENTATION OF RESOURCE REQUIREMENTS	INTRINSIC *MECHANISM-(ARROWS)*	INTRINSIC *ELABORATION DOCUMENT*	INTRINSIC *GRAI NET*	NOT INTRINSIC	INTRINSIC *RESOURCE DIAGRAM*	INTRINSIC. *'ACTORS'*	INTRINSIC *MECHANISM-(ARROWS)*	NOT INTRINSIC

Table 4.1b A comparative analysis of modelling method characteristics

	MODELLING PARAMETERS	IDEF$_0$	IDEF3 PFN	GRAI	BASIC PETRI NET	CPA PERT	CHECKLAND	CORE Thread diagrams	DFD
11	REPRESENTATION OF MODEL HIERARCHY	INTRINSIC *DECOMPOSITION. NODE INDEX.*	INTRINSIC *DECOMPOSITION. UOB NUMBERS*	INTRINSIC *DETAIL GRID GRAINET*	NOT REPRESENTED	INTRINSIC *DECOMPOSITION EVENT NUMBERING*	NOT REPRESENTED	INTRINSIC. *DECOMPOSITION. VIEWPOINT REF. NO.*	INTRINSIC. *DECOMPOSITION. PROCESS NUMBER*
12	SUPPORTING INFORMATION	INTRINSIC. *DATA DICTIONARY PAGE PAIR*	INTRINSIC *ELABORATION DOCUMENTS. 'POOLS'*	NON FORMAL	NON FORMAL	NON FORMAL.	NON FORMAL.	INTRINSIC. *DATA NODE NOTES ACTION NODE NOTES*	INTRINSIC. *DATA DICTIONARY*
13	MODEL VALIDATION	INTRINSIC. *AUTHOR/READER CYCLE. SYNTAX RULES.*	INTRINSIC. *AUTHOR/READER CYCLE.*	INTRINSIC. *RULES OF COHERENCE.*	INTRINSIC. *FIRING TRANSITIONS LOGIC STRUCTURE*	INTRINSIC. *CALCULATION OF SLACK. LOGIC STRUCTURE.*	NON FORMAL.	INTRINSIC. *SYNTAX RULES*	INTRINSIC. *BALANCING*
14	MODEL CONTEXT	INTRINSIC. *ENVIRONMENT, CONTEXT AND VIEWPOINT DIAGRAMS.*	INTRINSIC *SCENARIO*	INTRINSIC. *GLOBAL GRID*	NOT INTRINSIC.	NOT INTRINSIC.	INTRINSIC. *'WORLDVIEW' ENVIRONMENTAL CONSTRAINTS*	INTRINSIC. *VIEWPOINT STRUCTURE DIAGRAM*	INTRINSIC. *CONTEXT BOUNDARY.*

Table 4.1c A comparative analysis of modelling method characteristics

Table 4.1 provides a structured comparison of the graphical syntax employed in the methods. The range of methods reviewed have widely differing approaches to representing aspects of manufacturing systems and all have been designed to model manufacturing systems from different perspectives. However all, with the exception of DFDs, have a form of 'transformation' event or activity as the basic element of a diagram. In all methods the basic elements are linked diagramatically by some other characteristic of a system, in the case of DFDs the 'transformation' is the linking element. Labelled arrows and boxes are commonly used graphical symbols. Most of the methods reviewed support the diagrams with a methodology that includes validation and a means of describing a context for models and in some cases a formalised procedure for presenting supporting information is used.

The comparison indicates that for $IDEF_0$ modelling parameter 6 and 7 are not represented and 8 and 9 are not intrinsic. Parameters 6 and 7 relate to the ability to model 'time' and 8 and 9 relate to the ability to describe aspects of a sequence of activities. Parameter 5 indicates that $IDEF_0$ is not capable of modelling the conditions for a basic element (activities) to occur, proceed or exist. Three methods, IDEF3, GRAI and CPA, however are able to represent aspects of parameters 5,6,7,8, and 9 but of the three only IDEF3 has a similar 'basic element' modelling parameter to $IDEF_0$.

4.9 CONCLUSIONS

All the modelling methods are specific and focused on some aspect of a system. They all omit non-essential details and concentrate on some parts of reality at the expense of others according to the aims and viewpoint of the analyst. In a complex manufacturing enterprise a single modelling method may not be sufficiently broad to capture the complexity and a series of modelling approaches may be necessary however none of the methods considered in the comparative analysis claim any syntactical or methodological links with other methods.

Arguably $IDEF_0$ has been the most favoured approach to provide static graphical models of manufacturing systems. (A recent study in UK manufacturing reported by Baines, Small and Colquhoun (1996) supports the claim but also reveals that DFDs are almost as widely used.)

The comparative analysis re-enforces the argument that IDEF$_0$ provides a modelling ability over a broad range of manufacturing enterprise characteristics. It also revealed some limitations of IDEF$_0$ when modelling fairly common situations in manufacturing systems such as;

- the absence of a facility to model time
- the lack of a facility to model the ordering of activities (sequence or logic)
- conditional relationship between activities

There have been several attempts to improve IDEF$_0$ using diagramming methods where the fundamental concepts have been retained yet extended to make them more amenable to modelling systems in manufacturing enterprises. Mandel (1990), for example, proposes the use of 'ports' on IDEF$_0$ diagrams to overcome the problem of identifying the sources and destinations of arrows crossing a diagram boundary together with a modified diagram format. Shunk et al., (1986) propose the Triple Diagonal Technique (IDEF$_0$-TD) using a modified IDEF$_0$ diagram structure to help distinguish between information, control and material flow (other proposals to modify the basic IDEF$_0$ method are discussed in section 3.3.3). There is no evidence that these modified IDEF$_0$ methods have been widely adopted, supporting the case adopted in this research for combining or integrating established methods to expand modelling capability rather than modifying robust well understood principles.

It could not be argued that the other methods reviewed in this paper do not have their own special advantages when they are applied to the modelling applications for which they were designed. Some of the methods reviewed are not structured analysis tools in the strict sense of the term but they do exhibit many individual modelling characteristics that if used in a structured framework could have mainstream applications in modelling systems in manufacturing enterprises.

The modelling characteristics that are candidates to be incorporated into any new approach are a representation of basic element dependency, the ability to describe time and a facility to model the logic of activities. This means that an enhanced IDEF$_0$ method or a combination of methods could have the additional capability to model concurrent and simultaneous activities, the state of constraint dependency and the time span of activities or linking activities using a commonly accepted set of diagramming symbols comprising of rectangles, arrows, tokens, etc..

The analysis informs an approach taken to develop a new method using IDEF$_0$ as a starting point and adding to it, some of the modelling characteristics identified in the reviewed methods that would have a strong application in modelling manufacturing systems. In any new method it would also be useful to adopt the same diagramming symbols (those highlighted in italics in table 4.1 a, b, c) from the source methods because their use is already understood by analysts and engineers and this will help to increase the acceptability and widespread use of any improved method. The methodology proposed in chapter 6 takes this approach by correlating IDEF$_0$ and IDEF3 PFNs to provide modelling capability in a larger range of modelling parameters than IDEF$_0$ and IDEF3 models alone.

CHAPTER 5

REFERENCE STRUCTURES FOR MANUFACTURING ENTERPRISE MODELLING

5.1 INTRODUCTION

This chapter introduces the concepts of reference models and system architectures for manufacturing enterprise modelling. The use of a generic model of process planning is explained and discussed in the context of reference models for manufacturing. This aspect of the research is based on the work published by Colquhoun et al. (1989), Colquhoun and Baines (1991), Baines and Colquhoun (1991). A proposal for a manufacturing enterprise modelling framework is explained and its potential as a frame of reference as part of an enterprise modelling methodology is discussed.

5.2 MANUFACTURING SYSTEMS ARCHITECTURES

Computer Integrated Manufacturing (CIM) is a manufacturing paradigm, largely developed through the 1980's. It has come to mean the control and execution of all phases of manufacturing from the concept phase through product design and manufacturing planning to manufacture using computers as the means of integration. It was recognised in the early stages of CIM evolution that a major impediment to progress was compatibility and data transmission between the many rapidly developing software systems. Computer Aided Design (CAD) and machine tool control systems for example were developed by different vendors to become 'islands of automation', effective as stand alone systems but difficult or inefficient to integrate. One response of research bodies was to fund efforts to overcome integration problems to enable vendors to design CIM systems within a common framework. Early examples include the European ESPRIT phase I-CIM project (Yeomans, 1987b) which provided flowcharts and text descriptions of the generic activities that comprise the machining sector of manufacturing. It is claimed to provide 'a European CIM architecture against which IT vendors could fashion CIM products'. Subsequently much of the ESPRIT phase II research was aimed at developing open-systems CIM architecture and communications to support multi-vendor environments.

In the USA the ICAM architecture (discussed in section 2.2) was taking a hierarchical architecture approach to do the same thing. The development of the ISO Manufacturing Automation Protocol (MAP) grew from a proposal (International Organisation for Standards, 1986) to 'create a multi-dimensional, open ended reference architecture and provide a basis for long-range planning and standardisation through the identification of interfaces and their characteristics, electrical, mechanical, man-machine, information, procedural language, etc.' Large manufacturing system vendors have also proposed CIM architectures (IBM, 1987) as frameworks to develop computer based manufacturing.

The scope of the proposed architectures were limited, in the case of ISO to 'discrete parts manufacture'. The ESPRIT CIM project was specifically aimed at mechanical engineering and machining operations 'because there are more manufacturing organisations within Europe involved in machining operations than any other single type of manufacturing and machining represents the largest market for CIM system vendors' (Yeomans, 1987b). GRAI is restricted to a 'production management system' according to Doumeingts and Breuil (1987). A common thread to the architectures is that they use graphical models to represent the various functions or aspects of manufacturing.

Subsequently many 'architectures' have been proposed (Jorysz and Vernadat 1990a, Klittich 1990, Davis and Jones 1989, Graefe and Thomson 1989, Scheer 1992, Weston 1995, Los et al., 1992) for manufacturing enterprise applications. There is little consistency in the approaches employed and the concepts used and the distinction between architectures, reference models, methodologies and modelling frameworks is blurred. It can be seen that as architectures have developed they have become more complicated in attempting to represent the breadth of manufacturing enterprise complexity.

5.2.1 CIM-OSA

The ESPRIT CIM Open System Architecture (CIM-OSA) is an example of a complex all embracing approach to manufacturing system architecture. The CIM-OSA is 'an open systems architecture that defines an integrated methodology to support all phases of a CIM system life cycle from requirements specification, through system design, implementation, operation and maintenance. Using a set of modelling methods a manufacturing enterprise can create a precise model of its own CIM requirements' (Jorysz and Vernadat, 1990a). The CIM-OSA architectural framework (or cube) is shown in figure 5.1. The diagram shows the CIM-OSA model generation process in the X axis of the cube, starting with a generic model using previously defined models (partial views) through to particular models of the subject under investigation. The model derivation process in the vertical axis of the cube uses a conventional structured approach for software development. From requirements definition through design specification to implementation description. The remaining axis of the cube bounds total enterprise modelling through four views; function, information, resource and organisation. CIM-OSA provides modelling constructs 'that take into account well-accepted ideas and principles such as SADT, IDEF and Chen's entity-relationship model' (Jorysz and Vernadat, 1990a). The focus of CIM-OSA is to use modelling methods to iteratively progress through each cell in the cube. To provide implementation models of function, information, resource and organisation, each processable by an integrating infrastructure (Jorysz and Vernadat, 1990b) that can be used to control the operation of a CIM system.

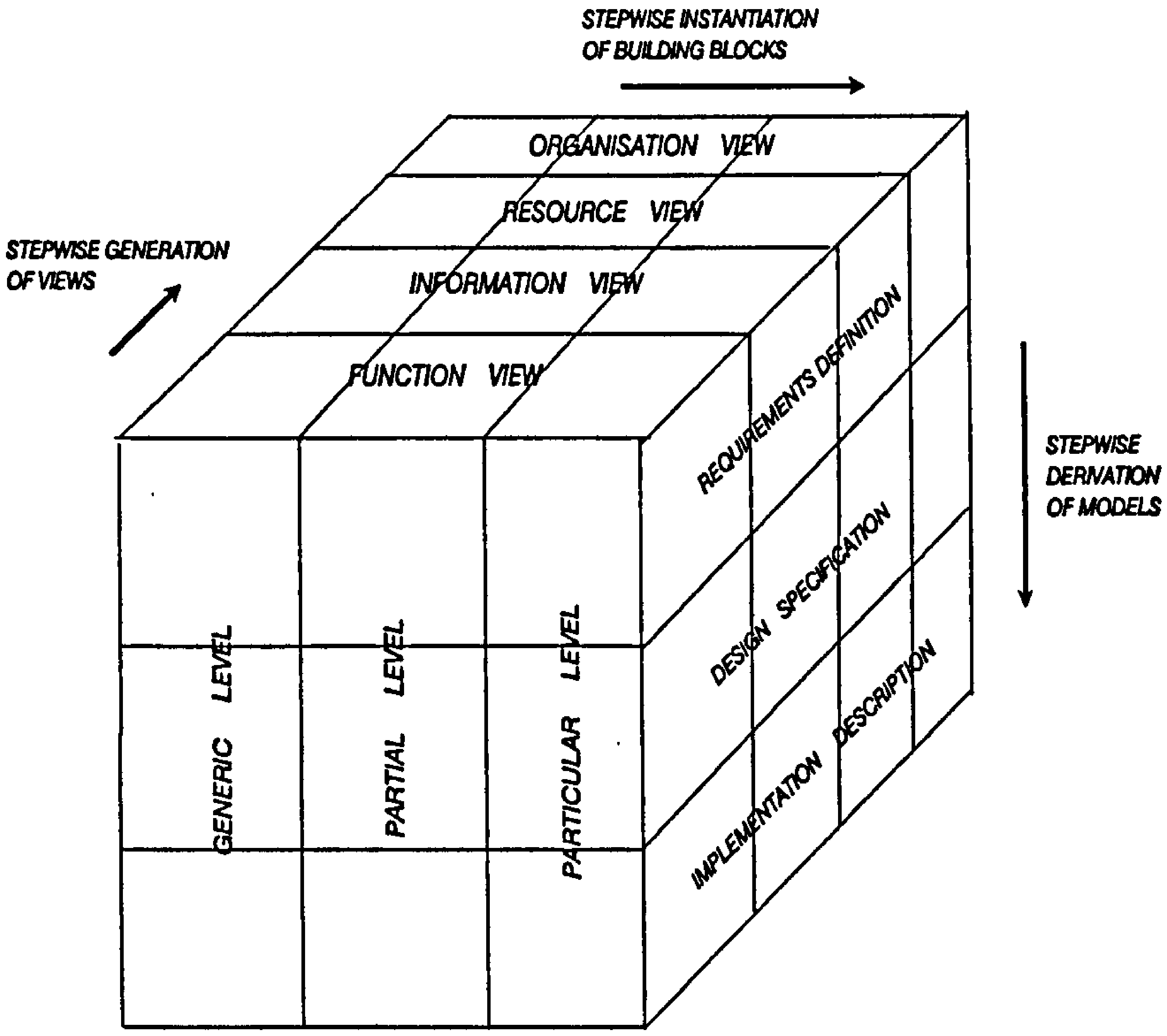

Figure 5.1 The CIM-OSA architectural framework (adapted from Jorysz and Vernadat, 1990a)

Two features are evident in the context of this research:

- That the complexity of the architecture and the scale of a complete modelling application (a simplistic view is that 36 integrated modelling initiatives are necessary to populate all the cells) reflects the exhaustive requirements of *software* or IS system design for an enterprise system life-cycle. CIM-OSA is seen by its creators as 'a formal reference base available in the public domain' and that 'further exploitation must now be conducted under private initiatives' (Klittich, 1995).

- Despite the development of software engineering tools such as those proposed by Aguiare and Weston (1994) the complete architecture and methodology, in its present stage of development, is of limited use for routine manufacturing enterprise modelling.

The notable difference between the earlier ESPRIT 'manufacturing architecture' approach and the CIM-OSA approach is the shift from a *reference model* of manufacturing defining functional organisation and interfaces to a ***modelling architecture and incorporated methodology*** applicable in any manufacturing sphere with the constraints related to analysis of an enterprise being only function, information, resource and organisation views. The generic concept of the framework has the disadvantage that its use in routine manufacturing applications is more obscure than the reference model approach. It requires a depth of understanding on both the purpose of the architecture and of the range of modelling methods used and in practical terms is likely to demand significant staff and computing resources. The reference model is more immediately accessible and arguably does not require the same intellectual skills to apply, however many reference models are likely to be required to provide a sufficiently broad reference base for manufacturing.

5.2.2 The Zachman framework

The Information System framework was proposed by Zachman (1987), who developed his 'methods and tools' framework for the information systems community. It can be used to define the role of existing and future modelling methods in terms of overlaps, gaps and the potential for integration. Zachman's original framework proposal is shown in figure 5.2. It is intended as a set of information architectures rather than an architecture in itself. Each cell in the framework is an 'architectural representation' that can be provided by one modelling method or an integrated group of modelling tools or methods. The framework shown in figure 5.2 is specifically focused on software and system design, it has been adopted by the IDEF User Group and developed to become a framework for enterprise system design (shown in figure 5.3), still with a strong IS influence but using 'types of description' in six columns that identify modelling approaches to address the interrogatives; what, how, where, who, when and why.

Despite the different concepts behind CIM-OSA and the Zachman framework there are some common strands. The interrogative axis of the framework (in figure 5.3) defining What, How, Where, etc. can be compared to the 'Z' axis of the CIM-OSA cube (in figure 5.1) that discriminates between Function, Information, Resource and Organisation. Similarly the perspective axis of the framework can be compared to the 'Y' axis of the cube discriminating between Requirements, Design and Implementation.

The fundamental difference between the two approaches is that CIM-OSA is a prescriptive software life-cycle methodology i.e. an architecture for system development in itself whereas the Zachman framework is a reference, aid or guide to IS systems thinking.

The framework approach offers considerable advantages for this research, it can provide a context or structure to relate and position various modelling methods. It offers some of the generality of architectures such as CIM-OSA but without intending to be a methodology in itself. A single framework is not sufficient to provide a context for all modelling situations, so like a reference model, a range of frameworks, albeit limited in number, could be necessary to provide a comprehensive base for modelling method applications.

Some proposals have been made to extend Zachman's original IS framework concept. Bruce (1992) suggests a framework for manual systems and points out that 'extending the (framework) concepts to consider other types of systems other than information systems is useful'. The IDEF User Group (1992) suggest 'non-information' system frameworks such as 'material systems' as potential extensions and O'Sullivan and Brown

(1993) have proposed a modified framework as the basis of a classification of system design methodologies.

Different perspectives

Different types of descriptions

	DATA DESCRIPTION	PROCESS DESCRIPTION	NETWORK DESCRIPTION
SCOPE DESCRIPTION (Ballpark view)	List of Entities important to the business.	List of processes the business performs	List of locations in which the business operates
MODEL OF THE BUSINESS (Owners view)	Entity/Relationship diagram	Functional flow diagram	Logistics network
MODEL OF THE INFORMATION SYSTEM (Designers view)	Data model e.g. entity/data relationship	Data flow diagram	Distributed system architecture e.g. Node function (processor, storage, etc.) Line characteristics
TECHNOLOGY MODEL (Builders view)	Data design e.g. Segment/row Pointer/key	Structure chart e.g. Computer function, screen or device formats	System architecture e.g. Node hardware/System software, Line specification
DETAILED DESCRIPTION	Data base description e.g. Fields/addresses	Program e.g. Language statements	Network architecture e.g. addresses, link protocols
ACTUAL SYSTEM	Data	Function	Communications

Figure 5.2 The Zachman framework (Adapted from Zachman 1987)

To advance the understanding and use of modelling methods the framework proposed in section 5.4 provides the context for the application of modelling methods in manufacturing enterprises. A framework specifically focused on manufacturing enterprise modelling does not require the user to consider architectural concepts and has the potential to simplify the selection and routine application of modelling methods. It provides a pragmatic compromise between the complexity of architectural approaches and the resource and investment necessary to develop a broad range of reference models.

	WHAT	HOW	WHERE	WHO	WHEN	WHY
SCOPE OF BUSINESS	List of *Things* important to the business.	List of processes the business performs	List of locations in which the business operates	List of organisations/agents important to the business	List of events significant to the business	List of business goals Critical success factors
BUSINESS MODEL	Entity/Relationship diagram	Process flow diagram	Logistics network	Organisational charts e.g. organisational units/work product	Master schedule	Business plan
SYSTEM MODEL	Data model e.g. Data entity/data relationship	Data flow diagram	Distributed system architecture e.g. Node function (processor, storage, etc.) Line characteristics	Human interface architecture e.g. role and deliverable	Processing structure e.g. processing cycle	Knowledge architecture e.g. criterion and options for decisions
TECHNOLOGY MODEL	Data design e.g. Segment/row Pointer/key	Structure chart e.g. Computer function, screen or device formats	System architecture e.g. Node hardware/System software, Line specification	Human/Technology interface e.g. User/job	Control structure e.g. execution times/component cycles	Knowledge design e.g. conditions and actions
DETAILED DESCRIPTION	Data definition e.g. Fields/addresses	Program e.g. Language statements	Network architecture e.g. addresses, link protocols	Security architecture e.g. users identity, transactions	Timing definition e.g. machine cycles	Knowledge definition e.g. ends and means
EXECUTABLE SYSTEM	Data	Function	Network	Organisation	Schedule	Strategy

Figure 5.3 The Zachman framework adopted by the IDEF User Group
(adapted from IDEF User group, 1992)

5.3 REFERENCE MODELS FOR MANUFACTURING SYSTEMS

Central to the early phase of this research was the contention that reference models could provide a routine tool to manage changes to organisational structure, to provide a means to implement changes in manufacturing systems or to design new systems. In order to test the use and suitability of such an approach a reference (generic) model of process planning was used to carry out a structured analysis and review of the process planning activities of white goods manufacturer[1]. The rationale for the case study was an investigation of current practice to support the companies long term intention to implement Computer Aided Process Planning (CAPP). As a precursor to the research reported in this thesis a generic model of process planning (Colquhoun 1988, Colquhoun et al. 1989) for batch manufacture was developed to evaluate the functionality of CAPP systems in a CIM environment. The generic model has been used in this research to test the use of reference models for manufacturing systems analysis and design and extends the work published by Baines and Colquhoun (1991).

5.3.1 The application of a IDEF$_0$ reference model of process planning

This section demonstrates the use of a reference model as a framework for capturing knowledge about process planning in a batch manufacturing environment. (A brief review of process planning for batch manufacture is provided in appendix 9).

For this case study it was important to select an area of manufacturing that contained many of the features that characterise UK manufacturing. Process planning for batch, piece part manufacture was selected as an ideal area to test the use of reference models, it has a significant human element, relies heavily on information established working practices and the experience of the staff involved. In addition the case study company faces the sort of problems that exist in many areas of manufacturing; pressures to reduce staff costs, new

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[1] Cannon Industries, Wolverhampton.

technologies, an increased need for accurate information control of quality and the need to change established working practices.

A generic IDEF$_0$ model is one that represents the generally accepted or intrinsic activities that exist within a defined process or system and will represent all occurrences of those activities. In this demonstration the generic model is used as a reference structure from which an AS IS model is developed. An AS IS IDEF$_0$ model describes a situation as it exists in practice, that is, the inter-relationship between activities, information, objects, people and facilities that make up a system, defined in company specific terminology. The AS IS and generic models provide a means of examining the relationship between activities to evaluate how a change in one activity may impact on other activities to influence the performance of the overall system. An analyst with a previously prepared generic model of a situation uses the generic activities and ICOMs to structure the knowledge gathering necessary to build an AS IS model. The AS IS model is thus developed using company specific descriptions of activities and ICOMs. The AS IS and generic models can then provide the basis for development of a model of the target system, i.e. a TO BE model using company specific terminology.

Figure 5.4 is the node index illustrating the extent of decomposition used in the generic model of 'Plan Manufacturing' where six levels were considered necessary to clearly expose selected aspects of process planning. To construct an AS IS model using the generic model the context diagram is the starting point, in this case A-0 - 'Plan Manufacturing' (figure 5.7, p.95). This would then be used to identify the person (expert or 'mechanism' in IDEF terms) responsible for the activity. In the case where the mechanism is software then the person responsible for its operation is identified. The expert in turn identifies those experts responsible for child activities, in this case activities A1, A2, and A3 (shown in figure 5.8) and in particular A2 'Plan how to manufacture'. The activities A1 'Design product' and A3 'Plan when to manufacture', although an essential part of the context, are outside the scope of process planning and remain as the context of the AS IS model.

A-1	Produce new product	A22241	Select machine
A-11	Market and manage product	A22242	Derive process sequence options
A-12	Plan manufacturing	A22243	Derive capacity requirements
A-13	Execute manufacturing program	A22244	Assign sequence priority
A-0	Plan manufacturing	A223	Establish auxiliary requirements
A0	Plan manufacturing	A2231	Select tools
		A2232	Retrieve tool information
A!	Design product	A2234	Establish workholding requirements
		A2235	Retrieve workholding information
A11	Establish design concept		
		A224	Establish operation information
A111	Produce design ideas		
A112	Select design principle	A2241	Establish operation details
A113	Evaluate design		
A114	Formalise design	A22411	Retrieve operation data
		A22412	Analyse operation
A12	Carry out functional design		
		A224121	Establish component criteria
A121	Identify major assemblies	A224122	Derive machining parameters
A122	Retrieve assembly design	A224123	Establish operation characteristics
A123	Establish critical design features		
A124	Design assemblies	A22413	Update operation data
A125	Finalise product design		
		A2242	Generate programs
A13	Carry out detail design		
		A22421	Establish cutter path requirements
A131	Identify component form	A22422	Produce machine movement data
A132	Retrieve existing/similar	A22423	Produce part programs
A133	Design component		
		A224231	Establish system requirements
A2	Plan how to manufacture	A224232	Post process
		A224234	Prove part programs
A21	Plan product assembly methods		
		A2243	Derive operation times
A211	Analyse product		
A212	Establish assembly technique	A22431	Derive machining times
A213	Establish assembly requirements	A22432	Retrieve synthetic times
		A22433	Produce operation times
A22	Plan component manufacture		
		A2244	Format information
A221	Analyse component		
		A3	Plan when to manufacture
		A31	Produce aggregate production plan
		A311	Derive production levels
		A312	Assess resource capability
		A313	Establish resource requirement
A2211	Retrieve component analysis	A314	Establish production plan
A2212	Separate features		
A2213	Derive feature dependant geometry	A32	Establish master production schedule
A2214	Determine geometric component elements	A33	Establish manufacturing and resource plan
A222	Derive manufacturing method	A331	Establish component demand
		A332	Establish purchase requirement
A2221	Determine raw material	A333	Derive manufacturing requirement
A2222	Select process options	A334	Assess capacity
A2223	Select process	A335	Establish manufacturing program
A2224	Select process sequences		
		A34	Schedule resource and manufacturing

Figure 5.4 IDEF$_0$ Node index for Plan Manufacturing (source: Colquhoun 1988)

The experts responsible for A2 activities (shown in figure 5.9) identifies those responsible for A21 'Plan product assembly methods' and A22 'Plan component manufacturing' activities. Experts associated with A221, A222, A223 and A224 (shown in figure 5.10) are next identified. The generic model is focused on process planning for manufactured components and thus the decomposition of activity A21 'Plan product assembly methods' is not considered. Similarly all experts who can contribute to defining process planning throughout the decomposition are identified and subsequently interviewed. The interviewing process can either take place immediately an expert has been identified or after all experts likely to contribute have been found. Naturally the latter has the advantage that conflicts and overlaps can be dealt with before the interview process starts. In practice the expert is questioned using appropriate activity diagrams. The objective of the questioning is primarily to make the activities, controls, inputs and outputs of the generic model company specific. This means finding precisely the document or terms used by the company. At the same time additional or missing inputs, outputs, controls and activities may be identified.

During the interview process the expert is shown the appropriate activity diagram and is prompted by the interviewer for company specific information on an activity by activity basis. This procedure is completed for all the activities within the generic model. In simpler process planning situations the number of activities could be less than the generic model but should not normally be more. As activities and activity diagrams change through different levels so may the experts change. Indeed it is critical that experts involved with each activity are those interviewed so that the true AS IS model can be identified.

5.3.2 Deriving an AS-IS model using a generic model of process planning

By definition the generic model of process planning should be able to cope with any type of manufacturing situation. This proved to be true using the model to derive an AS IS model in a case study company. The company produces domestic cookers, employs 800 people and has a turnover of in excess of £3m (in 1990), with a process planning function that concentrates mainly on press work for sheet-metal components. In all, five experts were identified and subsequently interviewed. The study took a total time of 5 hours. It is significant that the process planning functions were completely recorded by the researcher with no previous experience of the company and in collaboration with experts having no previous experience of the IDEF$_0$ method.

During the interviewing exercise thirteen activity diagrams from the generic model were used comprising a total of forty-seven separate activities. The same thirteen corresponding company specific activity diagrams, this time with only forty-four activities, were necessary to fully describe process planning in the company and provide the AS IS model. The same node titles were used and in practice the generic model diagrams were simply annotated to indicate the company specific terms and differences from the generic model.

5.3.3 Conclusions on the use of a reference model

The purpose of the case study was to investigate current process planning activities in the context of the introduction of a CAPP system and to use the study as a means of examining the use of a reference model for a manufacturing system. Figures 5.7 to 5.13 are used to illustrate the important findings from the case study. Node numbers for Generic and AS IS model diagrams are suffixed A and C respectively.

Using the generic model proved invaluable in identifying those experts at various levels in the organisation that were able to assist the interviewer in the data gathering process. The three experts responsible for the generic model activity A22 'Plan component manufacturing (in figure 5.10) are identified in the corresponding AS IS diagram, the Work Study manager, the Production engineering manager and a Project and CAM systems engineer (shown in figure 5.11, node C22 'Plan component manufacturing'). The subsequent decomposition of node A222 (figure 5.12) to A2221 to A2224 was used to develop the corresponding node C222 to activities C2221 to C2224 (shown in figure 5.13). It showed that the same experts were directly responsible for lower level activities such as C2221 'Determine raw material'. In the lowest levels of the AS IS model some devolution of responsibility took place. For example the company relied on a machine setter as the expert responsible for activity C224122 'Derive machining parameters'.

Using the individual activity diagrams in the interviews was found to be an excellent way of stimulating the expert into providing a thorough review of activities. The diagram itself also structured the recording, critique and correction process directly using the box and arrow notation. It is possible that using the diagrams could constrain the replies the expert gives so it is important to emphasise that the diagrams are a framework for discussion.

Throughout the generic model specific company terms were identified as replacements for the generic terms where possible (shown in bold italic text in AS IS model diagrams). For example in the AS IS model activity diagram C22 (figure 5.11) activity C222 is subject to the control 'Design change note' and activity C221 has the control 'detail design drawings and parts list' whereas in the equivalent generic model activity shown in figure 5.10, these controls were described as 'Method change request' and 'Manufactured component design'. Similarly in C22 (figure 5.11), activity C224 has an output 'Master op. card' that has replaced the 'Operation information' used in the generic model activity A224, in figure 5.10.

The AS IS model exposed extensive use of heuristics for example, activity C224 'Establish operation information', (figure 5.11) has 'Process and material information (Heuristic)' as a control in contrast to the equivalent generic model activity A224 in figure 5.10 which has 'Process and material information' as a control. This drew attention to the practice that the staff carrying out the activity made no reference to standards or company data, but relied on their unrecorded experience or estimates to make decisions on operation parameters. Too many heuristic controls on activities flags a potential vulnerability for the company which could result in a dependency on individual staff and potential implementation problems if the company decided to use computer aided process planning in the future.

Missing controls or inputs suggest that the system is operating in an open loop mode that could lead to uneconomic operation. For example, in establishing the AS IS activity diagram

C222 (figure 5.13) the information 'Aggregate annual demand (verbal)' was identified as a control on all activities using the equivalent generic model information 'Component quantities and problems' shown in figure 5.12. This comparison exposed that the source of the generic model information was a result of activity A3 'Plan when to manufacture' (figure

5.8) based on actual batch sizes whereas the company relied solely on aggregate quantities based on marketing estimates of annual product demand.

The generic model also highlighted the company's use of process planning activities to produce outputs not normally associated with process planning. For example in figure 5.13, activity C2224 has an output 'Capital expenditure application' and activity C2223 has a control 'Product tool budget', no direct equivalent control or output exists in the generic model diagram in figure 5.12. The AS IS activity involved financial evaluation of capital plant and resulted in a formal documented application for capital expenditure. A process not considered part of the routine process planning activity when building the generic model. A response to this could be to modify the generic model for future use.

A comparison of the number of activities in the Generic and AS IS model revealed that the AS IS model contains 3 fewer activities. For example in the generic model A22411 'Retrieve operation data' (see the node index of figure 5.4) had no equivalent in the AS IS model. The reason being that the company re-defined its operation data each time a new component was planned. For the same reason activity A22413 'Update Operation data' also had no equivalent. Similarly the diagram A22423 'Produce part programs' in the generic model contains activity A224231 'Establish system requirements' before 'Post processing', since the company had only one programmable machine and thus a single system the activity or its equivalent did not appear in the AS IS model.

Previous knowledge of the IDEF_0 method was not found to be necessary for those interviewed. Nor was there a need for researchers to know the company organisation or operating methods before undertaking the investigation. The approach proved to be good at drawing attention to weak practices in the process planning functions across the organisation. For example, it became quickly obvious that process planning at the company had only weak links with the Production Control department highlighted by the use of aggregate demand quantities referred to earlier. In addition the most recent process planning activities relating to CNC programming were developing entirely independently of the manual system because the Project and CAM system engineer carried out all planning related to CNC machining.

The AS IS model also showed that staff with the title manager were also found to be working very much at an operational level in process planning activities.

Of particular concern in generic modelling is the depth and breadth of decomposition necessary to provide sufficient detail. The node index, figure 5.4 shows that the decomposition of nodes A1 and A3 provided sufficient detail after decomposition of three levels. Whereas to describe process planning activities fully, node A2 has been decomposed to six levels. The breadth of the model was limited by the need to identify those interfaces necessary to support process planning activities. On the other hand the depth was limited to retain generic descriptions of activities. It was considered that taking the model to further depth would introduce the need for non- generic activity descriptions. This is a limitation to the use of generic models as reference models for low level detail.

The diagrams provide structure to interviewing and, using a valid generic model, are exhaustive in terms of identifying information flow. It could also be claimed that less skill in $IDEF_0$ modelling is necessary but practice is still necessary to conceive valid generic models. The generic model also has the potential to limit the variability of different analysts if they were to address and model the same problem.

This application of the generic model serves as an example of the capability of $IDEF_0$ as a general purpose functional modelling technique to provide a clear picture of a complex aspect of a manufacturing organisation. The model could be developed to interface with other models of other areas of a manufacturing organisation such as product management or manufacturing to provide a complete generic model of batch manufacturing. The limitation of this approach is the potential number of models that would be necessary to cover all manufacturing systems. However some recent research has pursued the use of $IDEF_0$ models as reference models for manufacturing, Maull et al. (1995) for example, his EPSRC Grant GR/J 95010 'Good practices in Business Process Re-engineering in manufacturing engineering' has $IDEF_0$ models describing standard business processes as a deliverable. The US National Institute for Standards (NIST) proposes template-driven systems development with $IDEF_0$ and $IDEF_{1X}$ models using 'a Template Re-use Library containing ($IDEF_0$ and $IDEF_{1X}$) models which have been developed, tested and approved as standard templates for use in particular classes of systems, or system types e.g. payroll system, radar system etc.' (Law, 1992). Interestingly the research also proposes that 'best of breed' models could be reverse engineered to produce standard generic models for re-use.

5.4 A MANUFACTURING ENTERPRISE MODELLING FRAMEWORK.

This part of the research presents a proposal for a manufacturing enterprise modelling framework to provide a structure for managing change in a manufacturing enterprise.

To select and use a modelling method it is important to establish the capability of the method in the context of alternative methods and in terms of those aspects of an enterprise it has to describe. To justify new methods, to propose developments to existing approaches, and to integrate existing methods demands a reference framework from which modelling capability can be evaluated in a manufacturing context. The framework is a graphical way of presenting and organising modelling methods having different notations and syntax. It differs from the CIM-OSA architecture approach that proposes a 'finite but comprehensive set of modelling concepts' (Jorysz and Vernadat, 1990a) to provide an integrated *processable* model of a manufacturing enterprise. The framework defines a viewpoint for interpreting the role of a modelling concept and as a basis for the classification of modelling concepts.

The rationale behind the manufacturing enterprise modelling framework proposed in this research (shown in figure 5.5) is the need to develop a framework for manufacturing enterprises that does not have the strong IS characteristics of existing approaches. It provides a context for the use and development of modelling methods where the object of modelling is to achieve manufacturing system change and improvement which may not be specifically related to software system implementation or design. Three modelling *focuses* are represented as columns in conjunction with four rows representing *perspectives* of an enterprise. The *focuses* indicate the key aspects of an enterprise that could be modelled. The intersection of columns and rows gives the twelve framework cells numbered from 10 to 120. Each cell distinguishes an aspect of a manufacturing system from a particular *perspective* and *focus*. Modelling methods or tools are mapped on to the appropriate cells, there is no significance in the ordering of cells and no methodology is implied by the cell numbers.

Column a: Models of 'configuration' answer interrogatives such as what?, who?, where?, i.e. the objects, material, products, information, data and resources used by an enterprise together with their relationships. For example, what resources are needed, who uses them, and what information and materials are necessary to run them.

Column b: 'Behavioural' models describe how manufacturing is conducted, for example to represent the manner in which the enterprise operates, how a product is produced, when events occur, what initiates, enables, constrains and inhibits manufacture.

Column c: 'Quantitative' models predict measures of enterprise performance for example the quantity of products produced for a particular capacity, what the manufacturing times are, how many staff are necessary, volumes of material flow and other measurable performance parameters.

The four framework perspectives are approaches an analyst can take in modelling a manufacturing enterprise:

Row 1: An 'enterprise' perspective is a high level view that considers the manufacturing scope of an enterprise, the products, its overall goals, operation and values and the manufacturing strategy that it uses to achieve its goals.

Row 2: A 'structural' perspective examines the relationships between the elements of an enterprise. It is a static functional view that describes the interfaces, links and relationships that exist. For example a *structural* perspective modelling approach to the *configuration* of a manufacturing process indicated in cell 20, might define the information required to run the facility such as a works order, a computer program, a process sequence together with the

FOCUS PERSPECTIVE	a *CONFIGURATION* What, Where, Who	b *BEHAVIOURAL* How, When	c *QUANTITATIVE* How Much, How Quickly, How Many
1 ENTERPRISE Values, Goals, Scope	10	50	90
2 STRUCTURAL Functional Relationships, Interfaces	20	60	100
3 PROCESS The stages involved in information and material flow	30	70	110
4 DYNAMIC The activation of information or object flow	40	80	120
ENTERPRISE OPERATION	Product, Material, Resources, Locations, Information.	Constraints, Material flow, Schedules and timing.	Resource consumption, Output, Performance

Figure 5.5 The manufacturing enterprise modelling framework.

material and personnel necessary. A *structural* perspective modelling approach to the *behaviour* of the same situation, indicated in cell 60, would identify at what stage information was needed or whether it was required simultaneously, and who initiates, monitors, stops and maintains the process.

Row 3: A 'process' perspective looks at those aspects of an enterprise concerned with the actions that take place to change the state of material or information and the sequence of events and the cause and effect of events. A *process* perspective of the *configuration* of a manufacturing process indicated by cell 30 might, for example, describe the sequence of starting, loading and running and any alternative associated processing sequences. A *behavioural* focus and *process* perspective, cell 70, might examine the temporal aspects, tooling and information availability and decisions that constrain the various alternative processing sequences.

Row 4: A 'dynamic' perspective views the representation of the actuation of aspects of an enterprise to expose material, information or object flow. A *dynamic* perspective and *configuration* focus of a manufacturing process indicated by cell 40 could examine the relative positions of material, processes and tooling by modelling material flow. A *dynamic* perspective and *behavioural* focus, cell 80, might model material flow to examine the implications of various scheduling approaches used by the process.

5.4.1 Conclusions from the manufacturing enterprise modelling framework

It could be argued that the framework, although another way of classifying modelling methods, has little value other than intellectual neatness. However this research proposes developments to the IDEF methods that needed a context for their development to outline relatively the role and extent of modelling methods in manufacturing systems terms and to see the significance of the modelling developments. The framework, through its two axis, provides the fundamental 'viewpoints' and 'purposes' of modelling methods themselves from which evaluations are possible. In an application context the framework is a management or modelling strategy that lies above the modelling process itself where the issue is the part modelling plays in effecting a change. The framework can also be used as a common representation where the modelling possibilities i.e. the various viewpoints and contexts can be related to the objectives of problem solving (the research however does not attempt to prove this point). Its simplicity relative to the frameworks that have influenced its development, Zachman and CIM-OSA, re-enforces a case for its routine use. The framework could be developed in a third axis using Generic, TO BE, and AS IS cells but further partitioning adds to the complexity without contributing to understanding or clarity.

The intersection of *focus* and *perspective* axis defines twelve cells. Each can be assigned (or mapped) to a modelling method to characterise an understanding or carry out an analysis from a *perspective* and area of *focus* bounded by the particular cell. Cells can be seen as a taxonomy of a manufacturing enterprise against which IDEF modelling methods can be mapped as shown in figure 5.6. IDEF modelling methods may only partially populate cells and may overlap cell boundaries. IDEF$_0$ has a significant capability in cell 20 and a partial capability in cell 10 and 30. The capability of IDEF3 (Process flow networks) is largely confined to cell 70 with partial capability in cell 30. The ideal is to populate as many cells as possible with appropriate, single or combined modelling methods. The purpose of the modelling approach proposed by the research (reported in chapter 6) is to synthesise IDEF$_0$ and IDEF3 extending their scope in an integrated method that has the potential to significantly contribute to modelling in cells 10, 20, 30, 50, 60 and 70 of the framework.

FOCUS PERSPECTIVE	a *CONFIGURATION* What, Where, Who	b *BEHAVIOURAL* How, When	c *QUANTITATIVE* How Much, How Quickly, How Many
1 ENTERPRISE Values, Goals, Scope	10 IDEF$_0$	50	90
2 STRUCTURAL Functional Relationships, Interfaces	20 IDEF$_0$	60	100
3 PROCESS The stages involved in information and material flow	30 IDEF$_0$ IDEF3	70 IDEF3	110
4 DYNAMIC The activation of information or object flow	40	80	120
ENTERPRISE OPERATION	Product, Material, Resources, Locations, Information.	Constraints, Material flow, Schedules and timing.	Resource consumption, Output, Performance

Figure 5.6 The manufacturing enterprise modelling framework and IDEF methods.

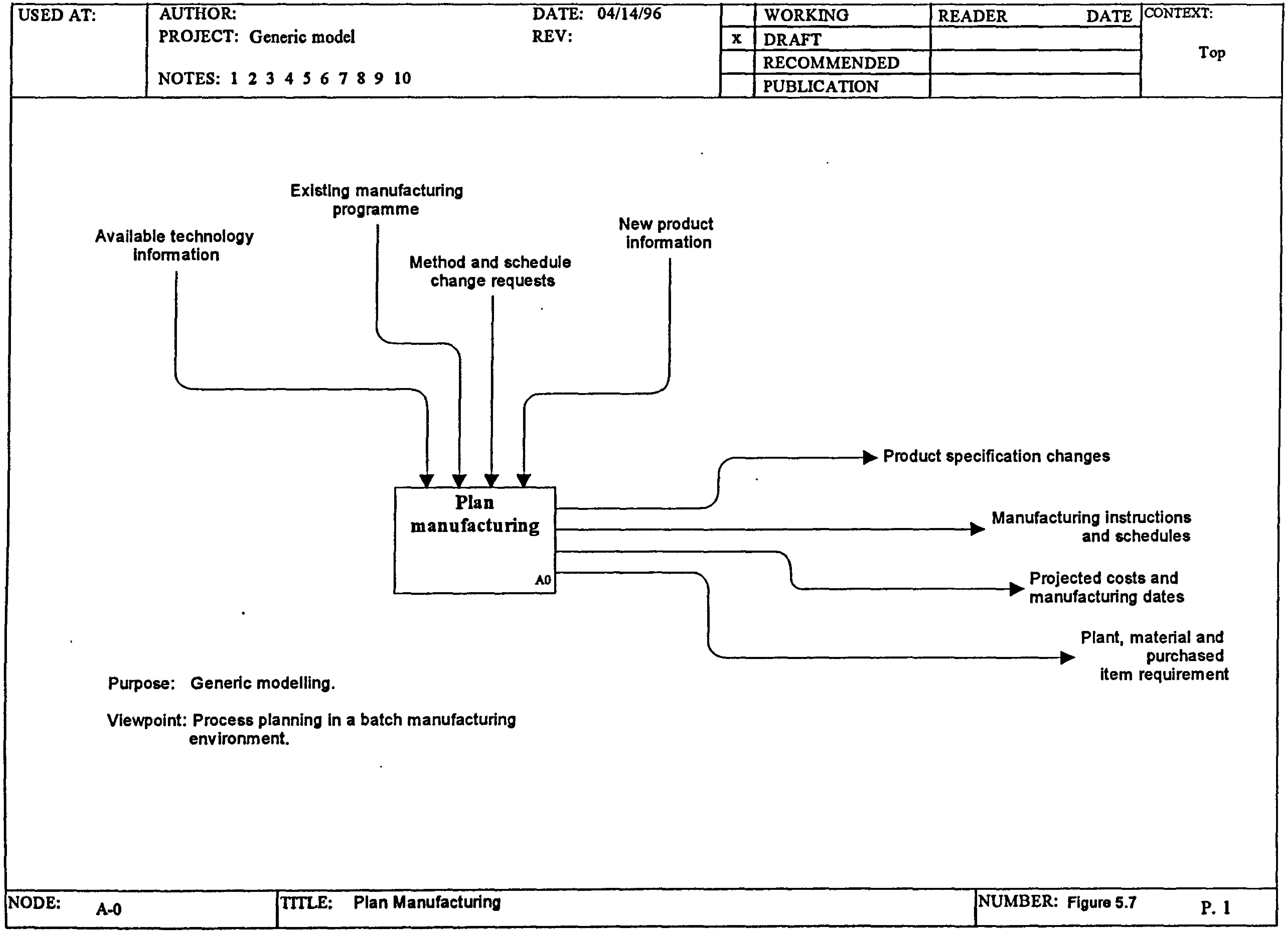

Figure 5.7 Node A-0 Plan Manufacturing (the context)

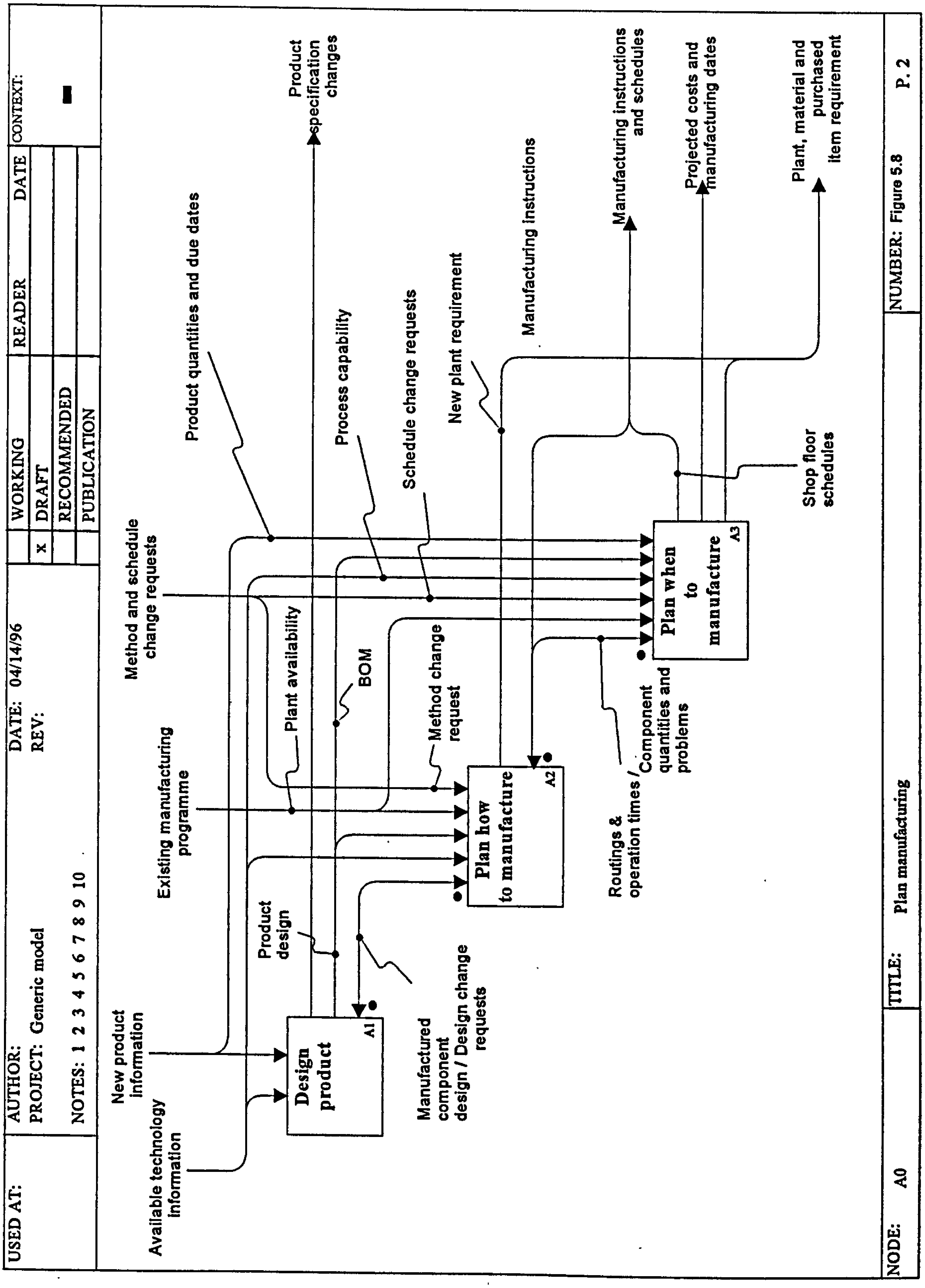

Figure 5.8 Node A0 Plan Manufacturing (the viewpoint).

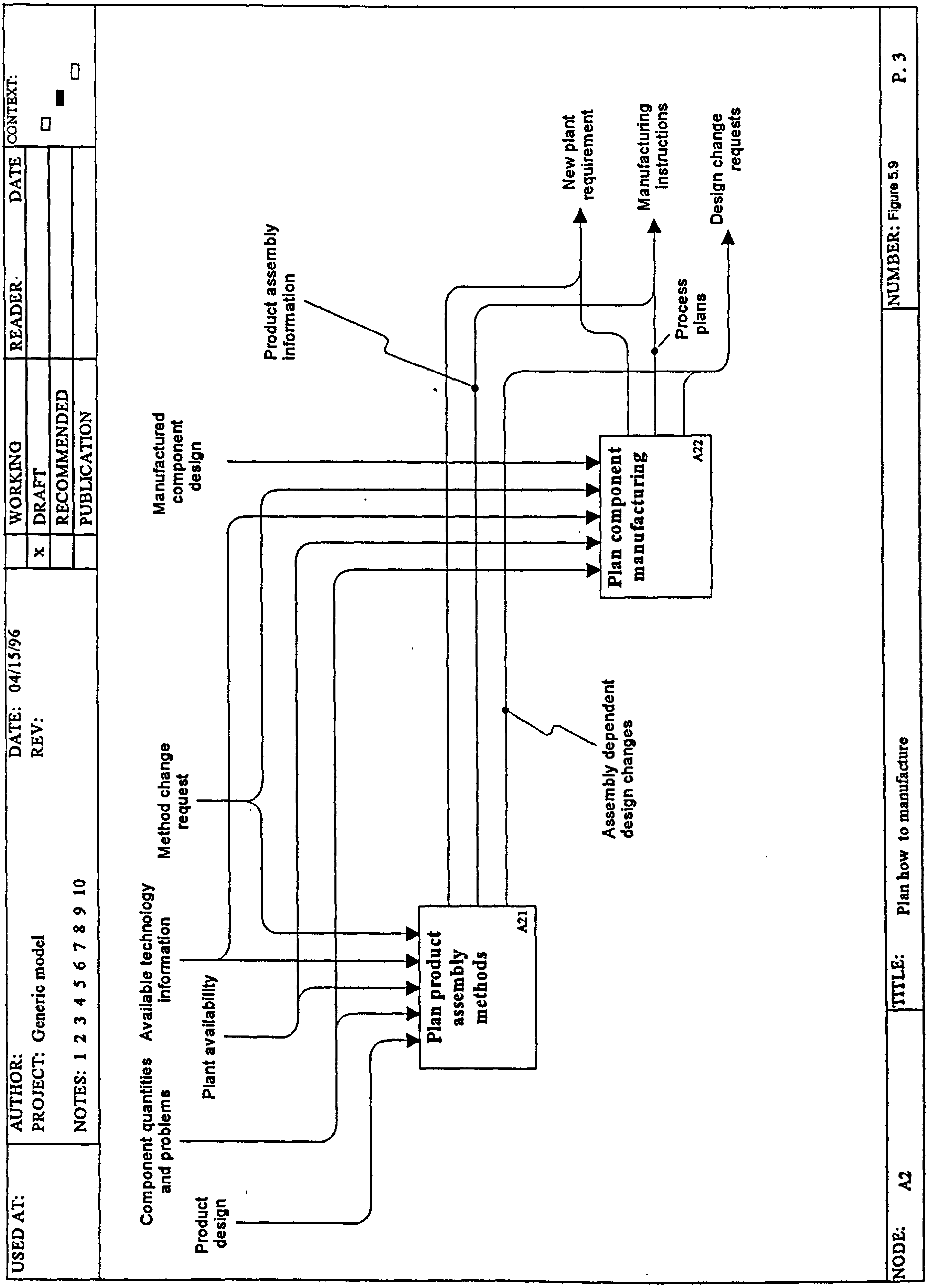

Figure 5.9 Node A2 Plan how to manufacture

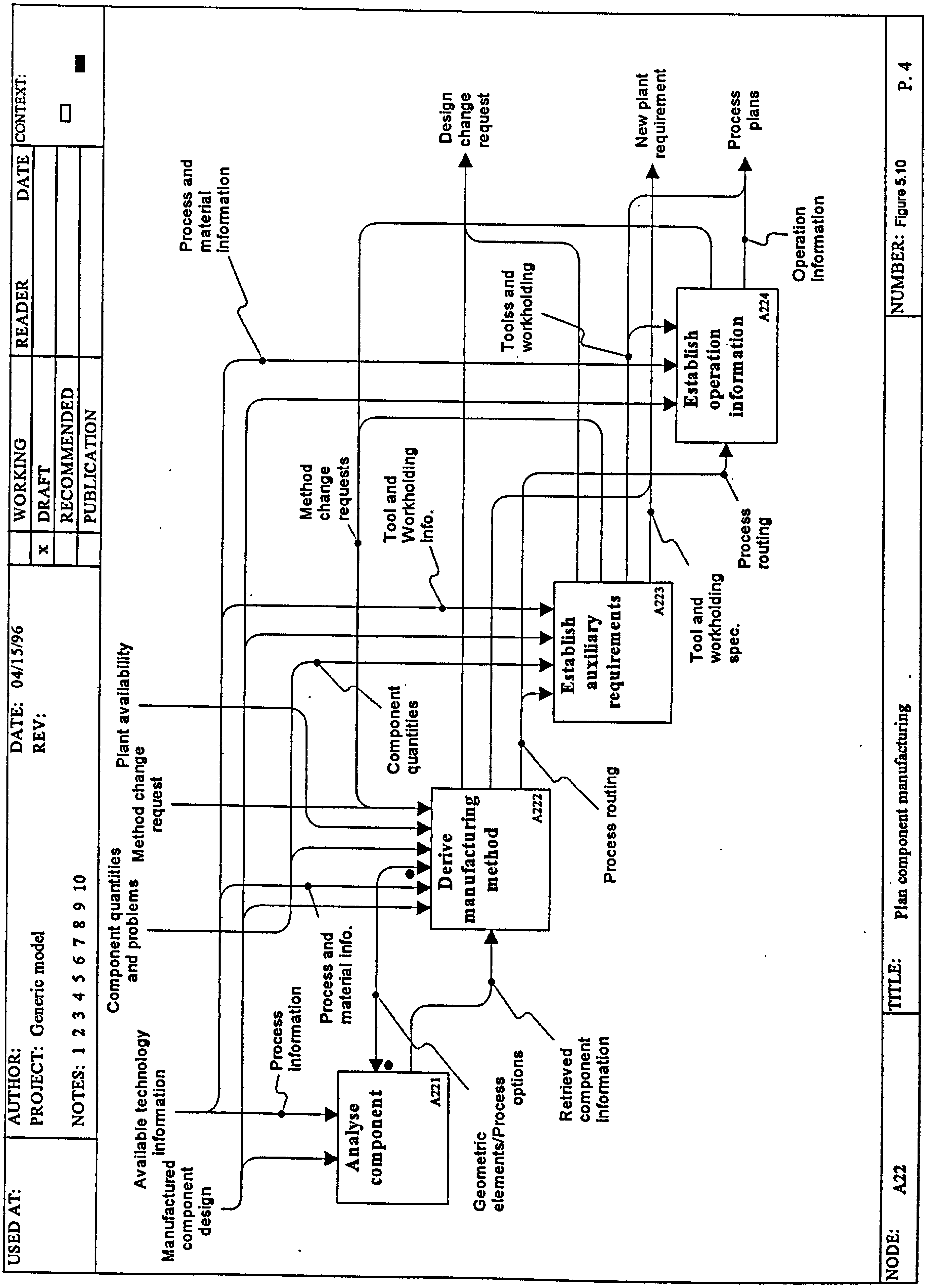

Figure 5.10 Node A22 Plan component manufacturing.

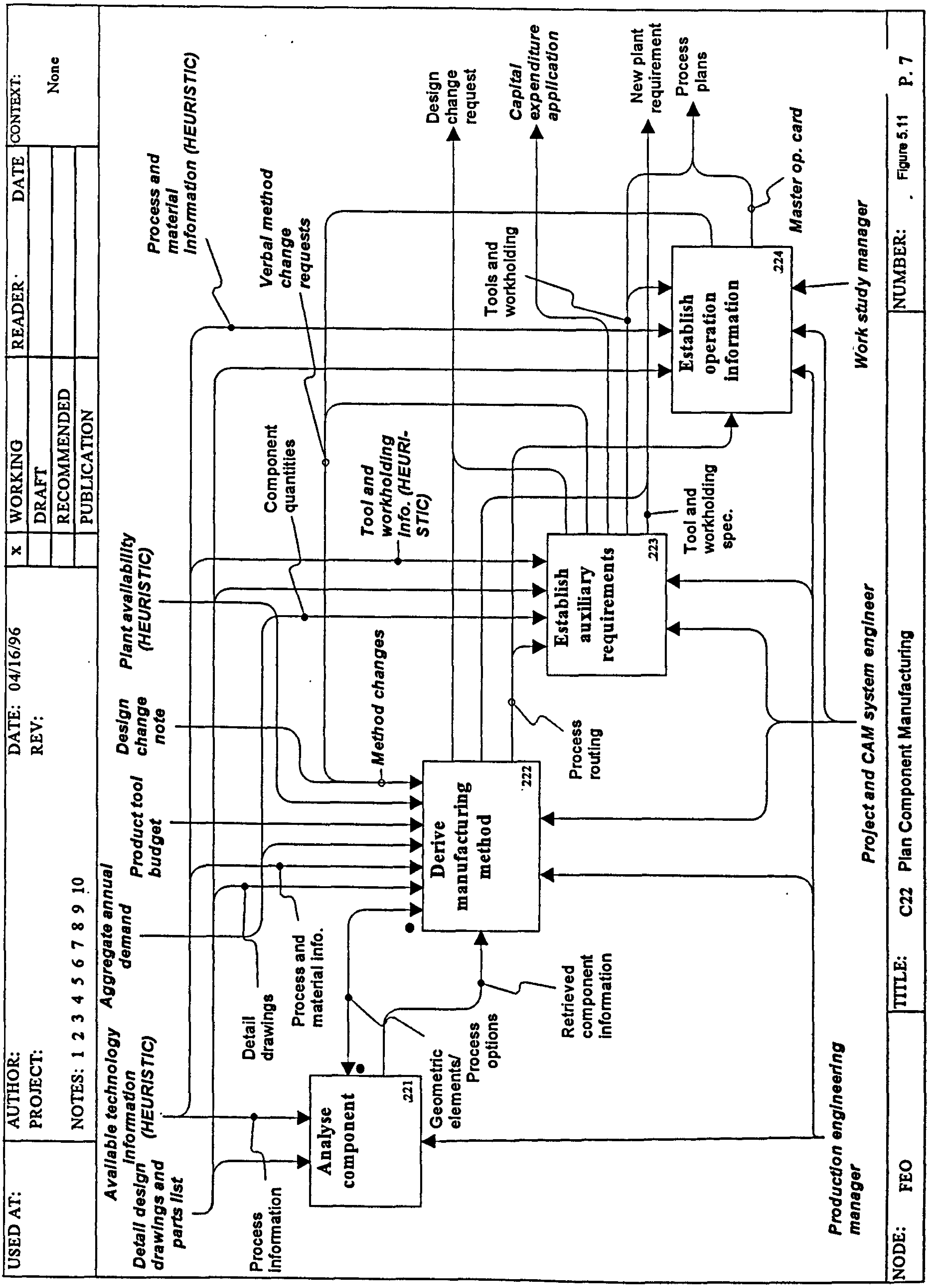

Figure 5.11 Node C22 Plan component manufacturing.

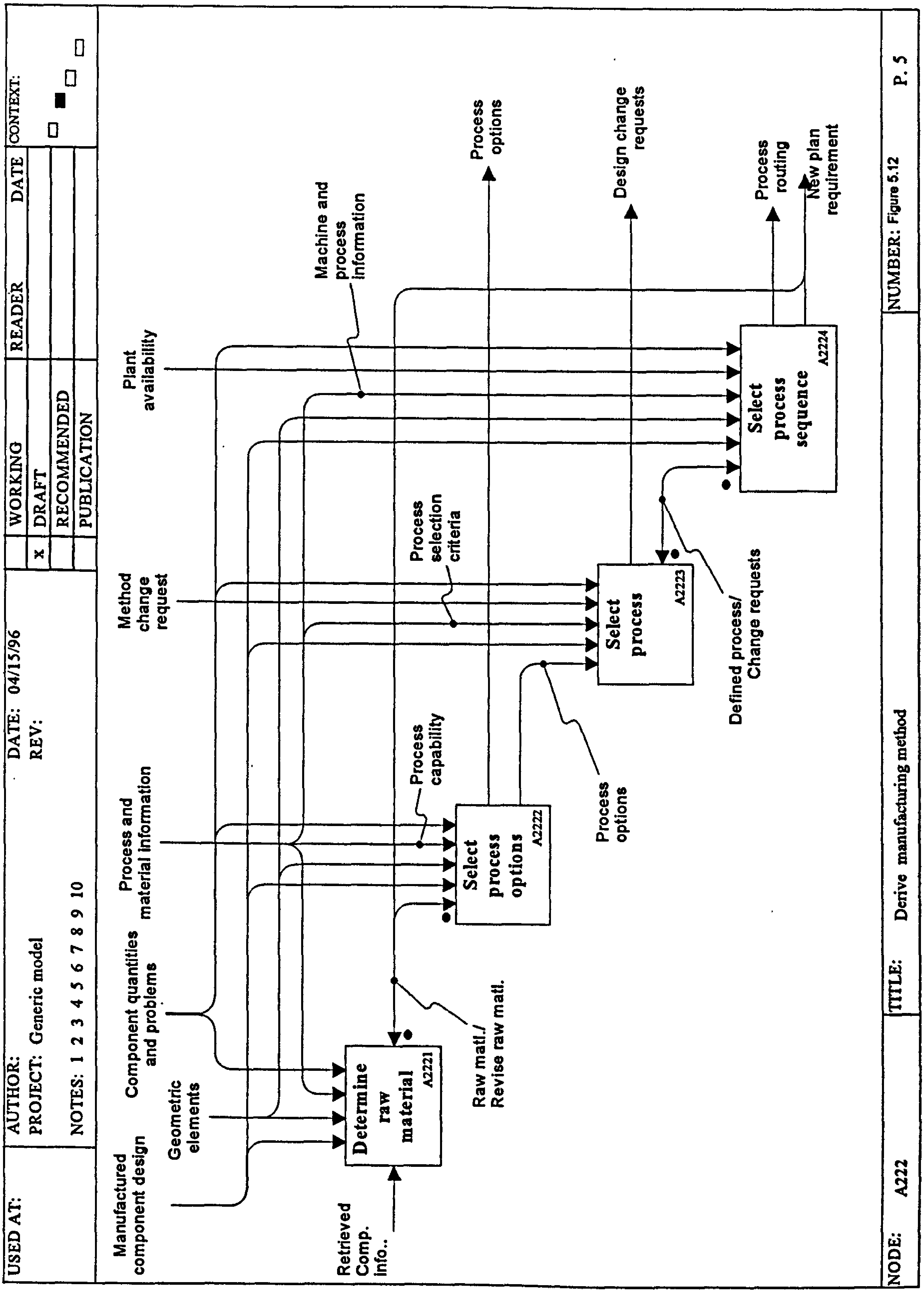

Figure 5.12 Node A222 Derive manufacturing method

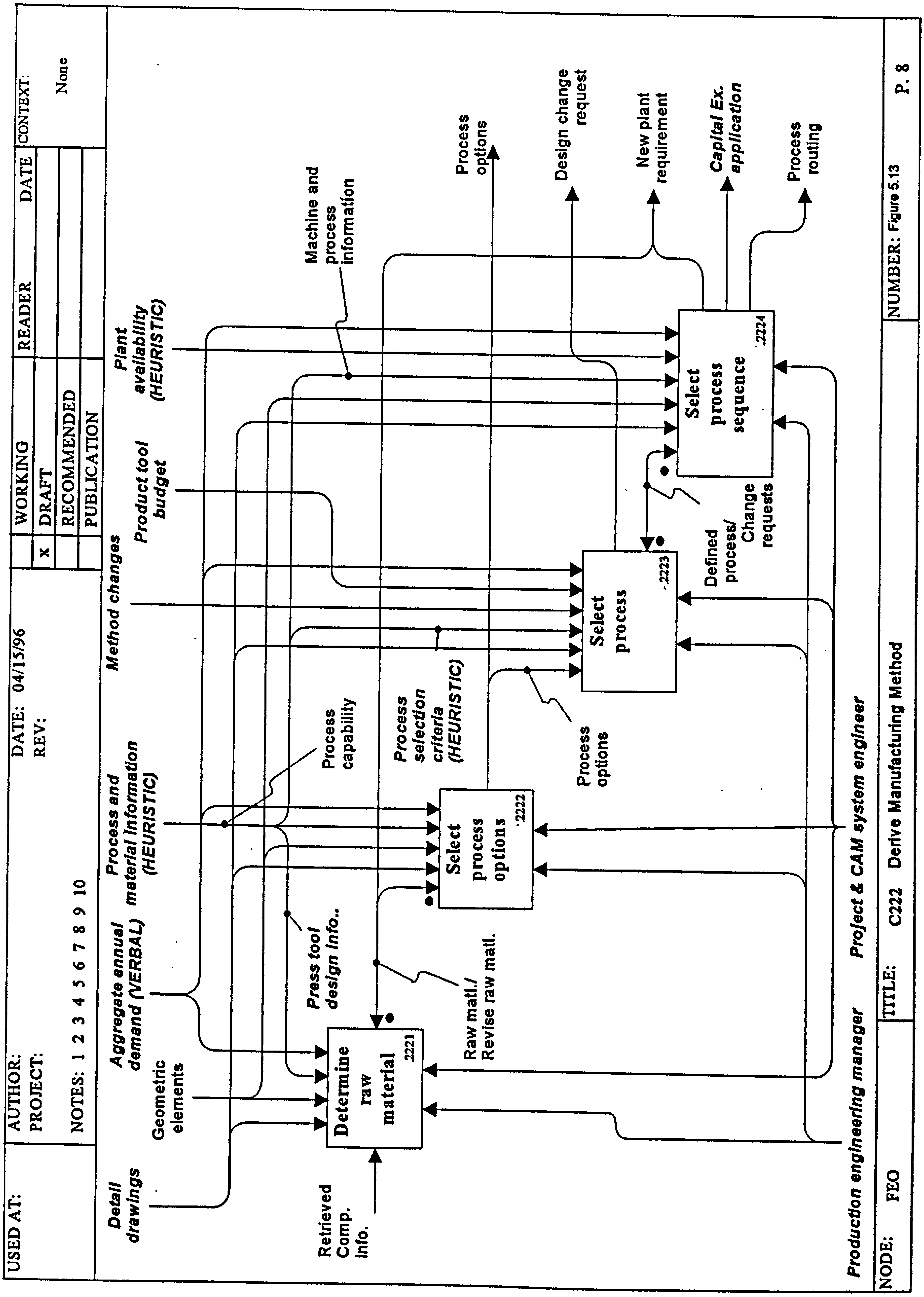

Figure 5.13 Node C222 Derive manufacturing method

CHAPTER 6

A COMPOSITE BEHAVIOURAL MODELLING APPROACH

6.1 INTRODUCTION

In this chapter a synthesis of the established IDEF$_0$ method and the IDEF3 process description method is described in the context of the manufacturing enterprise modelling framework. The composite approach, called IDEF0-3 (Colquhoun and Baines, 1994, Colquhoun et al., 1996), is proposed to increase the acceptability and promote the use of modelling in manufacturing enterprises by extending the scope of individual IDEF methods to provide a behavioural view of manufacturing systems that can contribute to modelling in cells 10, 20, 30, 50, 60 and 70 of the manufacturing enterprise modelling framework. The combination of methods is used to provide the additional capability to model concurrent and simultaneous activities, the nature of constraint dependency and the temporal aspects of manufacturing systems.

Three stages in the development of the IDEF0-3 method are described:

Stage one is an account of a case study that demonstrates the potential for the modelling approach that uses IDEF$_0$ diagrams to configure an IDEF3 analysis. The two methods are shown to be complementary and the case study provides an example of how the two methods can be used to structure and potentially speed up the analysis process.

Stage two explores a formal approach for integrating the two methods and proposes a Meta-model to show where links between the graphical elements of the two methods are necessary and to re-enforce the case for integration.

Stage three uses the findings from stages one and two in a case study that demonstrates the application of the concepts behind IDEF0-3.

The chapter concludes by presenting the IDEF0-3 approach in the context of the manufacturing enterprise modelling framework prior to a case study in chapter 7 to validate the approach.

6.2 A BLUEPRINT FOR ENTERPRISE MODELLING METHODS

The investigative work of chapter 2 and the analysis provided in chapters 3 and 4 has re-enforced the view that enterprise modelling approaches have largely developed from IS methodologies and are in general focused on data and information flows and transformations. The exhaustive detail required by IS approaches is not necessary to the same extent in manufacturing enterprise modelling and IS approaches lack the facility to model important manufacturing system characteristics. Modelling behavioural aspects of manufacturing systems is critical for guiding the change process.

The manufacturing enterprise modelling framework described in chapter five has provided a manufacturing context for 'behaviour'. The behaviour column (figures 5.5, and 5.6) is focused on the manner in which an enterprise operates. It considers; decisions, the cause and effect of alternative sequences of events, what initiates, monitors, stops, enables and inhibits. Timing is an important aspect of behaviour and the modelling considered in this research has been defined as static graphical modelling (section 1.3) which precludes the facility to model changes over time. However a static approach can provide a temporal description that places events, processes, functions, etc. in relative chronological order. Such a description can be a precursor to dynamic modelling.

Manufacturing enterprise modelling should not be seen as an isolated activity carried out as a fragmented consultative exercise but as a routine element of the management process. For a modelling method to contribute and gain acceptance as a routine part of planning and management certain features are essential.

1 It must be able to explicitly describe an aspect or aspects of an enterprise in a way suitable for managing change in manufacturing where a knowledge of functional structure and process behaviour are necessary prior to implementing a change or enhancement.

2 It must be capable of capturing and representing the perceptions of participants in a system in a way that makes it possible to identify qualitative or quantitative differences between those perceptions. This ability is necessary if a method is to have sufficient resolution to allow meaningful analysis and to provide the potential for optimisation. The method should also be capable of aggregation and decomposition but should not encourage the distortion of a system description to fit the characteristics of the method.

3 The resulting model or diagrams should be simple enough to be used as a basis of communication between system participants and the analyst. The method needs in its initial form to be graphical, capable of being produced with or without a CASE tool and having a minimal number of diagrams to complete a model. For intuitive use simple graphical constructs are required negating the need for an extensive knowledge of the modelling technique.

4 The modelling method should require minimal time to gather the information necessary to construct diagrams, to build models and to validate and analyse them.

5 It should be useful in the change process in allowing decision making to take place using more complete and realistic information. The model must also facilitate analysis and evaluation to assist in predicting the performance and behaviour after a change has been implemented.

6.3 STAGE 1 - A CASE STUDY USING IDEF$_0$ AND IDEF3

The case study reports an investigation of a manufacturing cell engaged in manufacturing and packing a fabric based health care product. The work was part of an initiative by the company[1] to simplify processes and organisation with the ultimate objective of improving product quality. IDEF3 was used to structure information gathered from participants in the cell and to use the resulting description to assess the impact of machine problems and contribute to improving cell performance.

The work of gathering and validating the information took a total of eight hours and was done by the author who had no previous experience of the company. Information gathering focused on how the processes of the cell were actually carried out using an approach loosely based on that of Mayer (1993b) i.e. a knowledge capture approach to identify the following:

- The individual processes involved.
- The conditions to start, maintain and stop each process.
- Responsibility for the process.
- Preceding and subsequent processes and the logic of processes.
- The nature of the process, i.e. time to complete, or type of occurrence; continuous, repeating, single instance.
- The information, verbal or documented, required to carry out the process.
- The objects that take part in the process, tools, material, resources, etc.
- The constraints on the use or involvement of objects.
- The exceptional operating conditions of a process.

The initial investigative work using the IDEF3 method exposed a 'pool' of twenty-five related processes and it was evident at that stage that a structure for building PFN diagrams was necessary to resolve conflicting narratives from the staff interviewed. An IDEF$_0$ diagram was therefore produced to quickly provide a functional view of the system without the constraint of considering process logic.

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[1] Scholl Consumer Products, Derby

The IDEF$_0$ model of the cell (called ZENO) was produced to provide the framework. The initial diagram in the IDEF$_0$ model is shown in figure 6.1 node A-0 'Run ZENO', this shows purpose, context and viewpoint of the IDEF$_0$ model. Decomposition to A0, the viewpoint diagram, identified six aggregated activities A1 - A6. The diagram is shown in figure 6.2 describing relationships between the activities in terms of objects and information. The diagram does not attempt to indicate the logic of activities, for example, activities A3 'Run 400 press' and A4 'Monitor process' are carried out concurrently and both are initiated at the same time. The IDEF$_0$ diagram cannot explicitly depict this aspect of cell operation.

It does however provide a framework for building an IDEF3 model. The processes established in the IDEF3 model building exercise could now be assigned to activities in the IDEF$_0$ diagram and an equivalent 'Run ZENO' IDEF3 (PFN) diagram was produced (shown in figure 6.3).

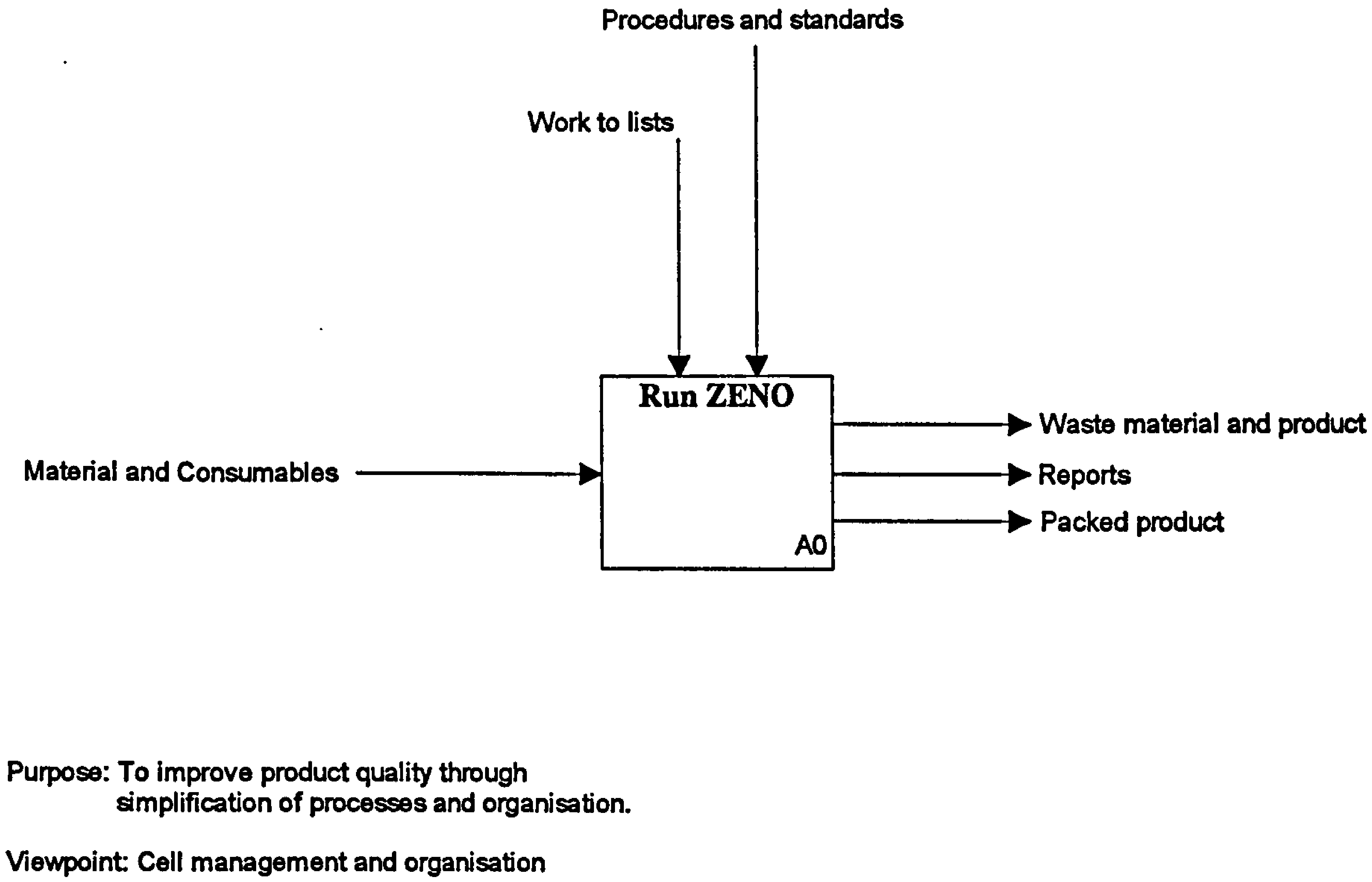

Figure 6.1 Node A-0 Run ZENO

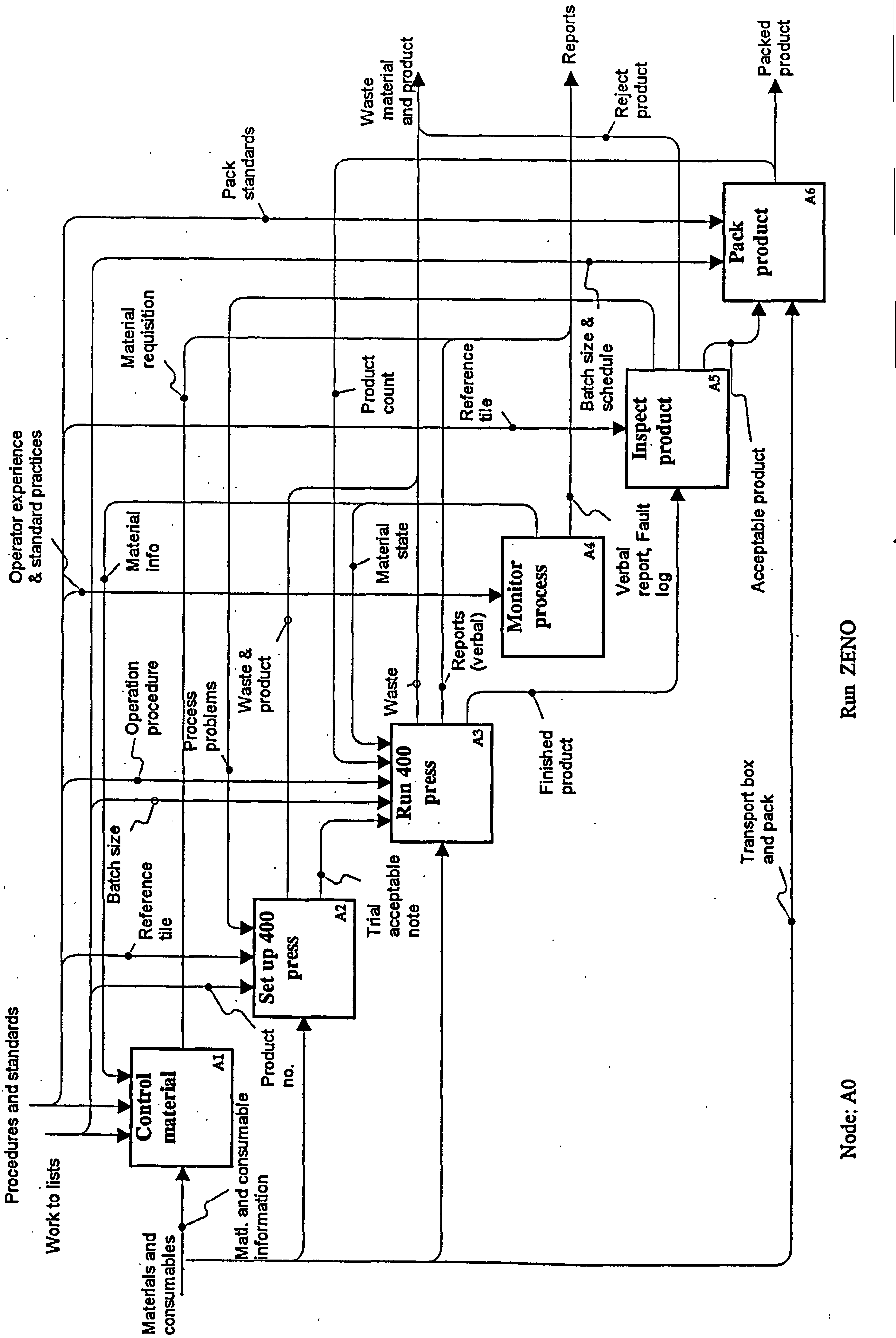

Figure 6.2 Node A0 'Run ZENO'

The IDEF3 method is a process description capture method where process information, process logic and sequences are gathered piecemeal from system participants to build a larger picture, the method is not designed to model conceptual activities. It is a bottom up approach in contrast to the top down approach of IDEF$_0$ where aggregated, (often conceptual) activities are a model starting point.

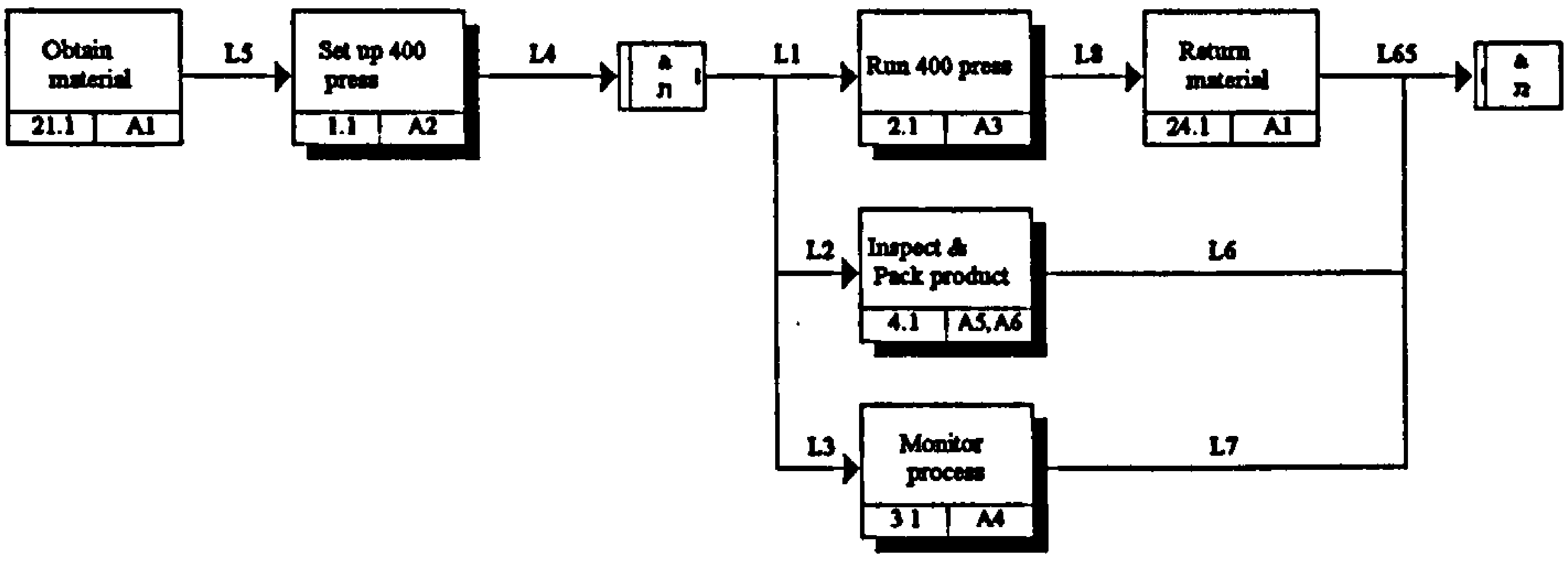

Figure 6.3 The IDEF3 PFN 'Run ZENO'

Each activity (or process) in the IDEF$_0$ diagram formed the basis of discussion with the cell experts based on; firstly agreeing on the aggregated activity description and the objects and information used in the activity. Secondly by grouping activities from the process pool into aggregated UOBs.

The IDEF3 description of the cell describes the logical and temporal relationships of the aggregated processes. In figure 6.3 the processes, 21.1-'Obtain material' and 1.1- 'Set up 400 press' are sequential and the occurrence of 'Obtain material' must be complete before the 'Set up 400 press' process can take place. The asynchronous fan out junction J1 indicates that the processes 'Run 400 press and Return material', 'Inspect & pack product', and 'Monitor process' all take place concurrently but do not necessarily start at the same time.

In total forty three processes were identified and are depicted on six PFN diagrams (presented in appendix 7). The model was decomposed to three levels to expose sufficient detail (in figure 6.3 shadowed boxes indicate that a UOB has been decomposed). OSTN diagrams were not considered in this application.

An Elaboration Document was produced for the 'Run 400 press' process that was the aspect of the process of particular interest to the company in this application.

ELABORATION DOCUMENT	
UOB Label: Run 400 press	
UOB Number: 2.1	
Objects: Operator 1 Operator 2 Roving Inspector Line supervisor Finished Product	Plating paper Reference Tile Work to list (batch size) Material Solvent
Facts: Throughput fixed at 90 products / min Fault free run times variable and not documented Predicted efficiency 63% Faults types are not documented Operators informally exchange tasks every 2 hours	
Constraints: ***To initiate*** -Guards Closed Proving run accepted ***To continue process*** - Product quality acceptable (Operator or roving inspector decision)	In-feed Plating paper available In-feed Material available ***To stop*** - Batch complete Shift end Supervisor stop (split batch) Machine fault Unacceptable product

Figure 6.4 A UOB Elaboration document for 'Run 400 press'

It was evident when gathering the information for Elaboration Documents that there is a close correlation between it and the information necessary to build an ICOM structure for an $IDEF_0$ diagram. This fact was not pursued in this case study but it is considered in the proposals discussed in section 6.5.

6.3.1 A review of stage 1

Two aspects of the case study can be examined (i) the behaviour of the cell and (ii) the capability of a new approach that correlates $IDEF_0$ and IDEF3 models.

(i) Three findings were revealed as a result of modelling;

- The application of IDEF3 revealed that the line operators were largely monitoring raw material and finished product in order to respond to frequent machine operation faults.
- It exposed that an operator on the output side of the press is required to check seven features of each product and if necessary reject it in a completely unrealistic time window of only 0.7 seconds. The operator rejected a batch of components by sweeping the output conveyor in the vicinity of the faulty items thus rejecting many acceptable components.
- It exposed that the operator on the input side of the press unnecessarily monitors previously inspected in-feed material.

Gathering information and building the process description provided an objective, structured view from which process rationalisation can proceed. Those processes that can be combined, that are a response to machine performance problems or that can be carried out automatically can be examined in more detail. The PFN diagrams together with performance data gathered over a longer term can be the basis of deciding which area to tackle first. In this case the line operators are largely concerned with monitoring raw material and finished product to respond to regular machine operation faults, if monitoring is unavoidable machine operation itself should be monitored.

(ii) Rigorous application of the IDEF3 method provided some quantitative information for analysis of system behaviour. It was initially difficult to define the boundaries for the analysis when taking the 'bottom up' IDEF3 approach. This problem was solved by constructing a 'top down' $IDEF_0$ model to give an investigative framework for IDEF3 modelling which has provided the basis of the methodology shown in figure 6.5. The method proved to be a rapid means of structuring the necessary information. It is conventional to describe a process as a sequence of activities and it was noticeable during the interview stage that IDEF3 lends itself to capturing information in this way. Gathering information for the open format of the

Elaboration document proved time consuming. The format is generic and it is possible that a more defined structure for Elaboration documents in specific cases would avoid missing information and could speed up the process.

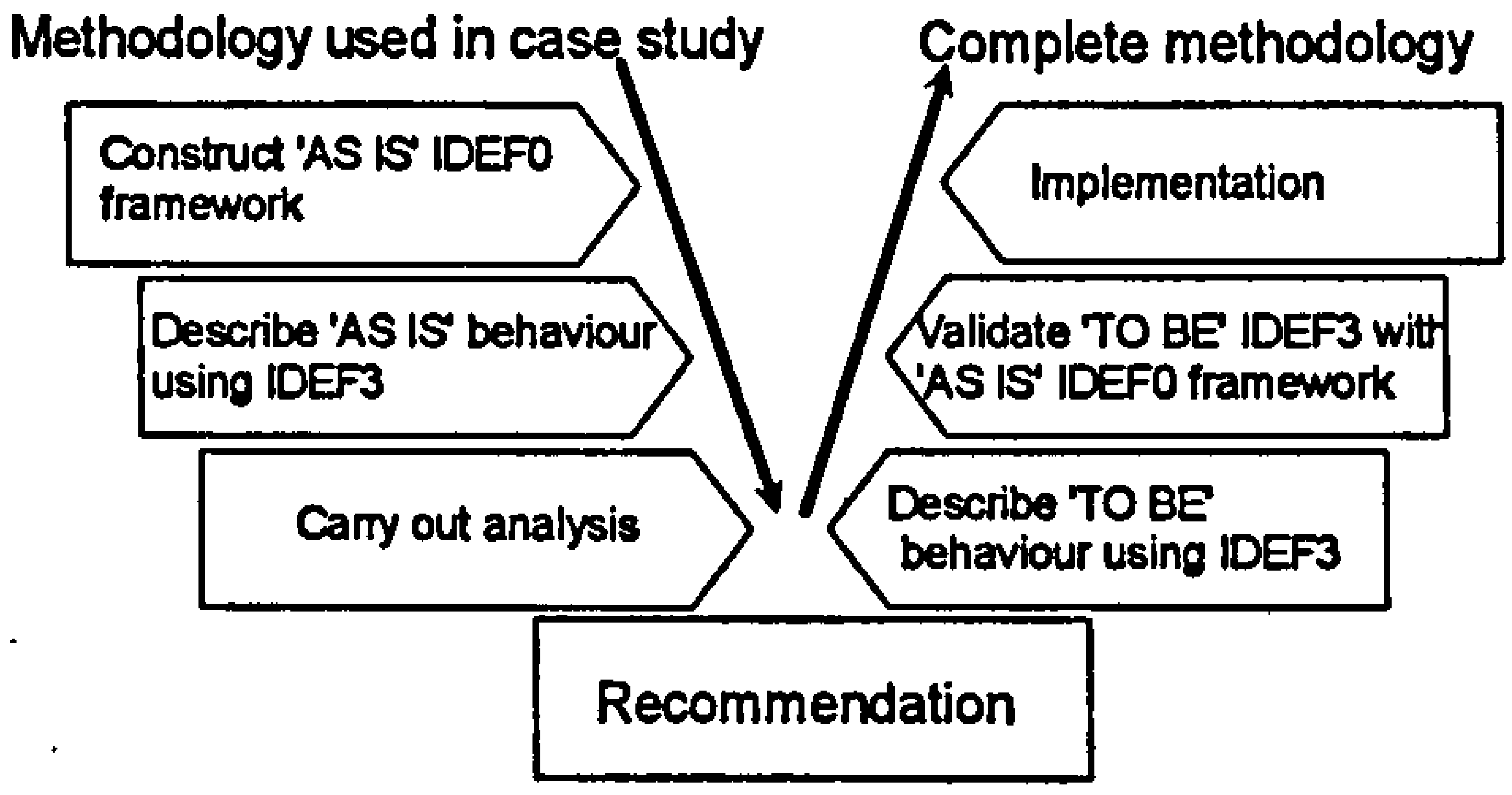

Figure 6.5 The methodology to use IDEF$_0$ and IDEF3 diagrams

The case study highlighted areas of further work to examine the possibility of relating IDEF$_0$ ICOM structure to an IDEF3 elaboration documents or PFNs.

6.4 STAGE 2 - FORMAL REPRESENTATION OF A COMPOSITE MODELLING METHOD - IDEF0-3

The IDEF3 method has been developed to capture a representation of a process centred view of system operation. It can represent processes (UOBs) connected by temporal, causal and logical relationships in a Process Flow Network (PFN). It is this capability to describe aspects of system behaviour, together with IDEF$_0$ functional modelling capability, that forms the composite behavioural approach IDEF0-3.

Mayer et al. (1992a) recognised that there is a relationship between the 'activities' in an IDEF$_0$ model and the 'Units of Behaviour' (UOBs) in an IDEF3 process flow description. They acknowledge that the IDEF3 method was designed 'with interaction in mind' and that 'the IDEF3 syntax recognises the relationship by providing a means of referencing associated

$IDEF_0$ activities from within an IDEF3 UOB'. They also define a UOB as a 'neutral term' representing information about an event, act or process. Whereas the $IDEF_0$ method uses Functions to describe 'collections of related activities' clearly both a UOB and a 'function' can represent the same aspect of a system. All UOB boxes in an IDEF3 diagram have a field to provide a reference number to an activity in an $IDEF_0$ model. Benjamin et al (1993) have proposed an integrated approach to utilise both methods for activity based costing applications. Similarly in a US Defence Logistics Agency funded project Cesarone and Dobrzeniecki (1992) advocate a hierarchy of both methods in the design of the 'next generation of manufacturing system' however no methodology or modelling syntax has been developed to correlate the two methods. Both methods produce models in a class that Ackoff (1962) defines as 'symbolic' models that only take on meaning 'when the symbols and things they represent are defined'. Central therefore to any correlation of the two methods is a structured analysis of relationships (in terms of symbols) between $IDEF_0$ 'Functions' and IDEF3 'Units of Behaviour' (UOBs).

The relationships between model elements and modelling concepts or syntax used in both $IDEF_0$ and the Process Flow Network (PFN) of IDEF3 are presented in graphical form in figure 6.6a and b. This graphical approach is an alternative to the algorithmic approach to analyse $IDEF_0$ and IDEF3 model structure used by Kusiak et al. (1994). Figures 6.6a and b describe the relationships between the graphical building blocks (symbols) used to describe the real world or tangible elements of systems and the concepts used to describe relationships between those elements.

Figure 6.6a shows the fundamentals of $IDEF_0$ model diagrams. The $IDEF_0$ method uses diagrams to describe the relationship between two tangible (real) elements of a system:

'Entities' - information, objects, material or data used by an enterprise.

'Functions' - carried out in an enterprise.

The $IDEF_0$ method uses descriptive devices in diagrams to represent the relationship between the two tangible elements of a system. In order to do this modelling 'concepts' are used.

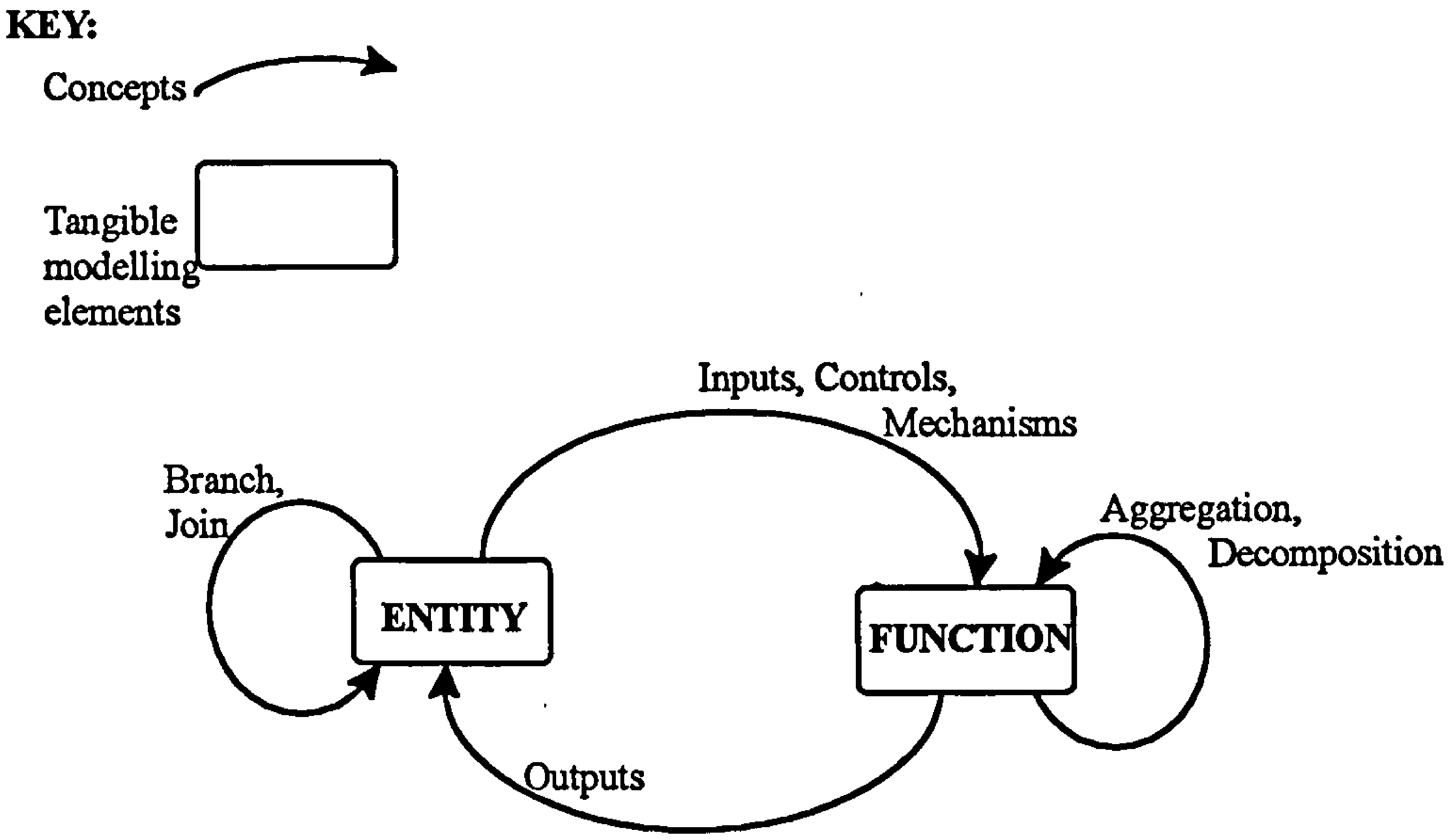

Figure 6.6a A meta-model of IDEF$_0$

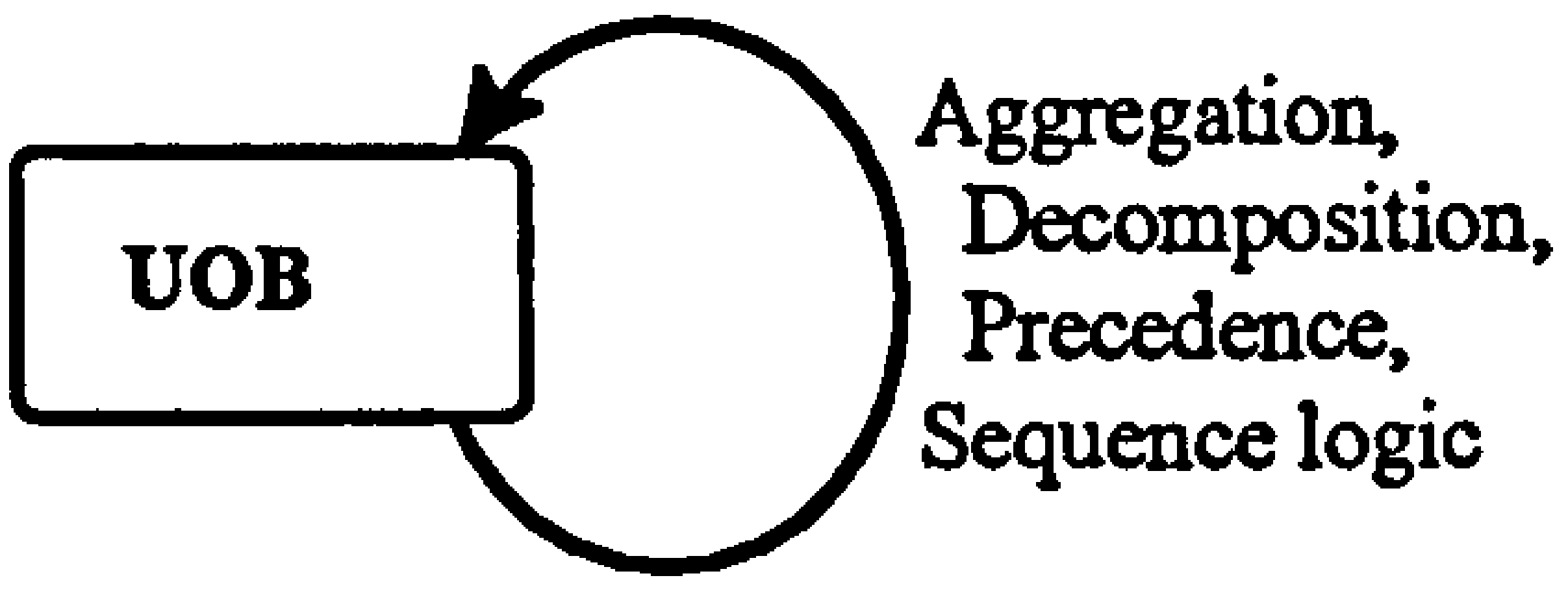

Figure 6.6b A meta-model of IDEF3

Participants in the system would not necessarily recognise them as concepts, they are the descriptive devices used to represent relationships between the two basic elements. For example the three concepts used to relate entities to functions (i.e. the three relationships that can be described by IDEF$_0$) are Input, Mechanism and Control. Similarly:

- the concept used to relate functions to entities is an Output.
- the concepts used to relate functions to functions are Aggregation and Decomposition.
- the concepts that relate entities to entities are Branch and Join.

Similarly figure 6.6b shows the corresponding representation of an IDEF3 Process Flow Network where the one tangible element described by the method is a Unit of Behaviour (UOB) that can be related by the concepts: Aggregation, Decomposition, Precedence and Sequence logic.

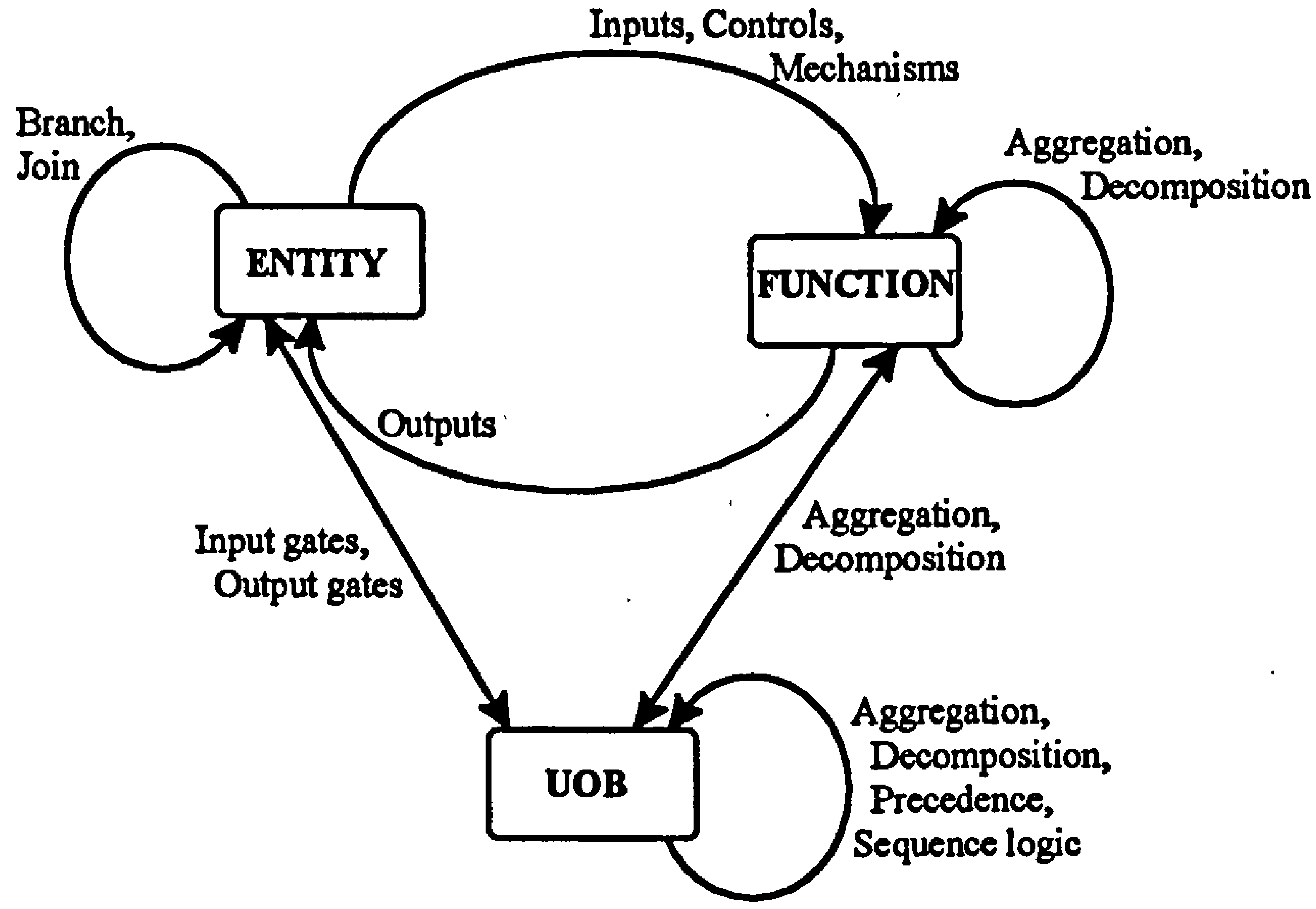

Figure 6.7 A meta-model of IDEF0-3

A correlation of the two methods to develop a composite approach - IDEF0-3, is shown in figure 6.7. New concepts are introduced to relate the three tangible elements (function, entity and UOB) used by $IDEF_0$ and IDEF3 respectively. In IDEF0-3 an $IDEF_0$ function becomes a context or 'scenario' for decomposition (the linking concept) to IDEF3 UOBs in a process flow network. Conversely aggregation is the concept used to take a functional view of a UOB in a process flow network. To complete the IDEF0-3 structure and correlate $IDEF_0$ entities to IDEF3 UOBs the linking concept of input and output 'gates' is introduced. Gates are used to identify and correlate inputs, outputs, mechanisms and controls from

$IDEF_0$ scenarios to UOBs in $IDEF_{0\text{-}3}$ process flow networks diagrams. To enable relationships between ICOMs, process precedence and process sequence logic to be identified whilst maintaining consistency in decomposition.

6.5 STAGE 3 - AN APPLICATION OF IDEF0-3 CONCEPTS

The modelling concepts developed in stage 1 and 2 have been applied in a case study. The study takes place in a one of the UK's major suppliers of health care products[2]. Due to the high volume production, sales turnover and retail competition, stores control is an order winning criteria for the company and thus knowledge of is operation is critical. Figures 6.8 and 6.9 are context and viewpoint diagrams, nodes A-0 and A0 respectively, of a model being used to examine the operation of a raw material and finished product stores. Node A0 'Run stores' comprises three activities: Receiving material, Controlling material and Dispatching product. The diagrams represent phase 1 of the IDEF0-3 methodology (shown in figure 6.12 and discussed in section 6.6). A sequence of activities is not indicated by the positioning of activity boxes in the diagram. In practice all three activities are carried out concurrently, the activity boxes could be positioned in any order and providing the corresponding arrow structure is maintained would be equally valid. In an $IDEF_0$ diagram no logical relationship necessarily links two activities, each activity box is functionally independent. In this case study examination of the staff or equipment used to carry out activities was not considered essential to the investigation. It was therefore decided that 'mechanisms' i.e. the staff or systems carrying out activities, would not be included in the model unless it was of particular importance to the analysis and so no mechanisms were subsequently used.

The 'Receive material' activity was of particular interest to the company and has been used as the basis of the case study. The $IDEF_0$ node A1, in figure 6.9, has provided the scenario for decomposition to an IDEF3 PFN (figure 6.10) and subsequently to the IDEF0-3 diagram shown in figure 6.11.

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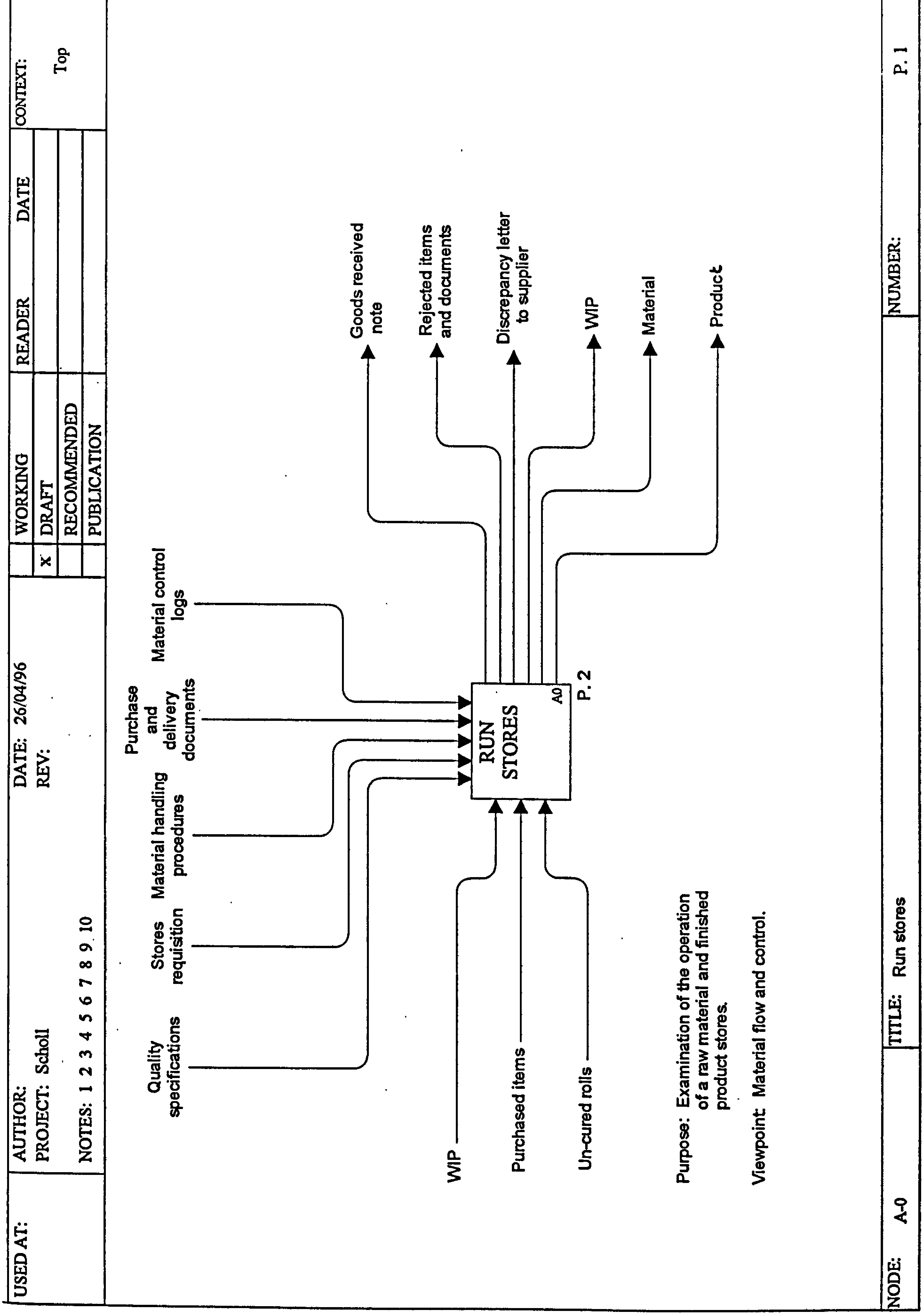
[2] Scholl Consumer Products, Derby



Purpose: Examination of the operation of a raw material and finished product stores.

Viewpoint: Material flow and control.

Figure 6.8 Node A-0 'Run stores'

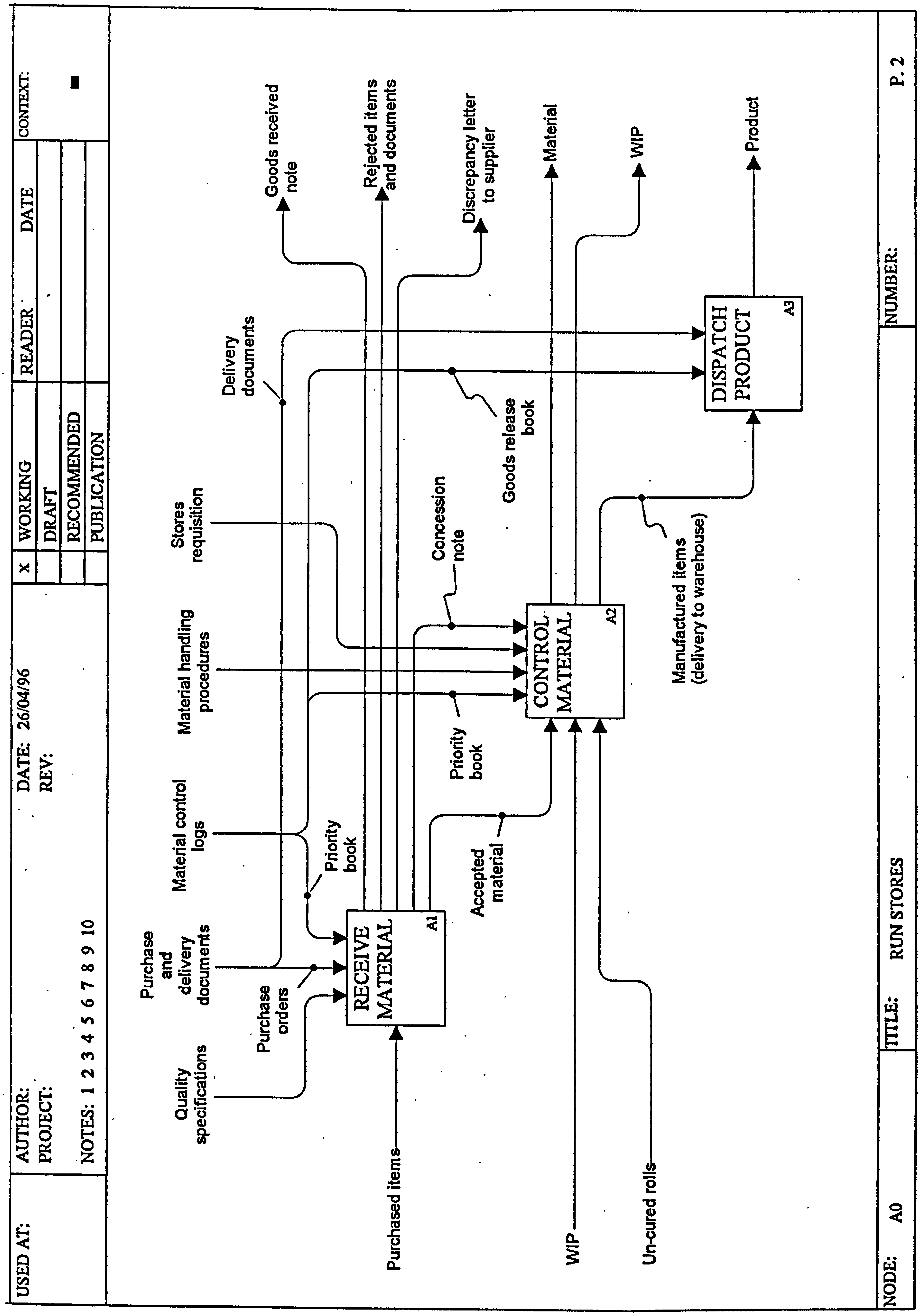


Figure 6.9 Node A0 'Run stores'

In figure 6.9 controls on activities are described, using IDEF$_0$, by arrows entering the top of activity boxes using nouns to indicate the objects or information that govern the activity. For example in node A3 the activity 'Dispatch product' has two controls, 'Goods release book' and 'Delivery documents'. The activity is 'constrained' by the two controls together with the input 'Manufactured Items'. The circumstances under which controls act are not explicitly described in IDEF$_0$ i.e. are they required sequentially?, are they mutually exclusive?, are they complementary?, or how do they influence the process?. The IDEF0-3 approach can help to clarify this.

The next step is to build an AS IS IDEF3 PFN from the IDEF$_0$ framework. This is done by grouping the UOBs (or processes) into the activities identified in the IDEF$_0$ diagram. Figure 6.10 is the PFN describing the sequence and the logical relationships of all the UOBs in the 'Receive materials' activity. For example the first process is 'Accept material' followed by 'Identify priorities' followed by two processes either, hold items in goods receiving or process items, the existence of these alternatives indicated by the fan out asynchronous 'OR' junction J2.

Finally to correlate the IDEF$_0$ scenario with the IDEF3 PFN an IDEF0-3 diagram is derived by considering the following:

Fan out OR and Exclusive OR junctions represent potential alternative processing paths. They therefore implicitly involve control or decisions dependent on the availability of material, data, information or objects to facilitate, to allow or to choose a process sequence path. In figure 6.9 the IDEF$_0$ Node A1, 'Receive material', has three controls 'Quality specifications', 'Priority book' and 'Purchase orders'. Using the IDEF0-3 diagram (figure 6.11) the three controls can be correlated with the four fan-out junctions J2, J4, J9 and J10.

Junction J2 involved deciding whether to 'Hold items' or 'Process items'. Goods inward staff used a 'Priority book' as a control that simply identified those part numbers and in some cases quantities that required immediate processing.

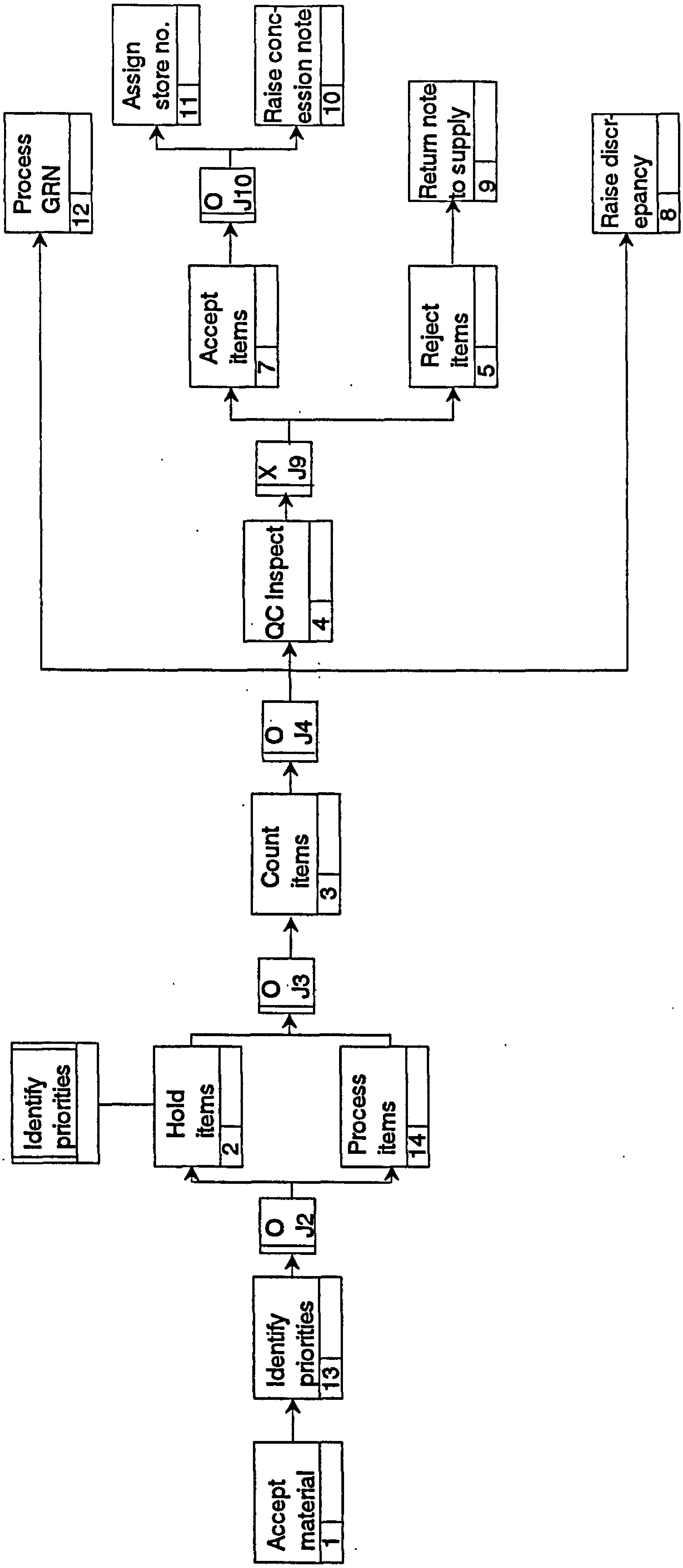


Figure 6.10 IDEF3 PFN - 'Receive material'

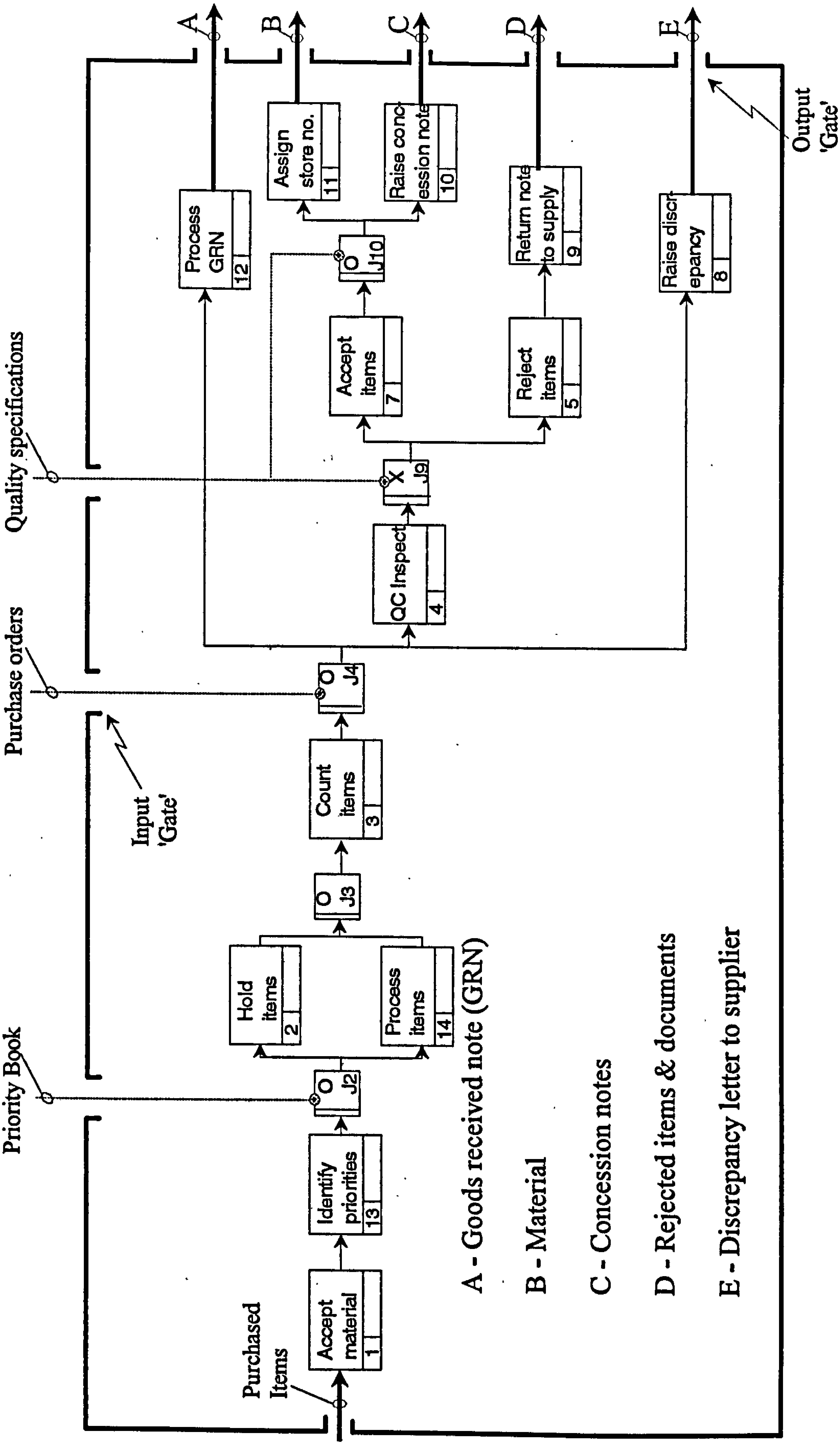


Figure 6.11 IDEF0-3 diagram 'Receive material'

Junction J4 involved a decision to; either except the counted quantity and produce a goods received note (notifying Quality Control (QC) staff that parts or material were awaiting inspection) or raise a discrepancy note to send to the supplier. In order to make the decision a copy of the purchase order was necessary to define, as a minimum, a part number and order quantity.

Junction J9 involved a decision by QC staff to accept or reject parts or material. If they were accepted a concession note could be raised (as a result of a decision indicated by junction J10) if some aspect of the item did not conform to specification but was still acceptable. For these decisions the only documented control used was the part or material specification that could be a drawing or text description.

Figure 6.11 also illustrates how the open ended process paths of the PFN (in figure 6.10) can be correlated with the inputs and outputs of node A1 (figure 6.9). The outputs of IDEF$_0$ node A1 are;

- Goods received note
- Material
- Concession note
- Rejected items & documents
- Discrepancy letter to supplier

All of which are produced as the result of the from the five process paths that terminate the PFN in figure 6.10. The IDEF$_0$ diagram therefore correlates in two domains, IDEF$_0$ outputs with the 'open ends' of the PFN and IDEF$_0$ controls with separate stages in the IDEF3 PFN.

Similarly the single IDEF$_0$ input to 'Receive material' (node A1 in figure 6.9) is 'Purchased items'. 'Purchased items' are objects necessary for the first process (Receive items) of the sequence of processes in the PFN of figure 6.10.

The complete IDEF0-3 diagram is presented in figure 6.11 showing the correlation of input, output and control structure from the IDEF$_0$ diagram with the IDEF3 Process Flow Network. 'Gates' (discussed in section 6.4) are used as the symbol representing the boundary between IDEF$_0$ and IDEF0-3 diagrams. For the purposes of this case study an

IDEF3 PFN (figure 6.10) and IDEF0-3 diagram (figure 6.11) of 'Receive material' were produced. In practice this is not necessary, $IDEF_0$ diagrams can be directly decomposed to IDEF0-3 diagrams.

6.5.1 A review of stage 3

The approach and resulting model significantly contributed to the analysis. Suppliers had, in the past, been receiving both goods return and discrepancy notes separately from the company related to the same batch of components or material. The effect over the long term was; a lack of trust between company and supplier, the need to deal with two company departments (Goods inward and QC) to resolve problems and the cost of material shortages and administration when communications were not timely. The IDEF0-3 diagram (figure 6.11) demonstrated that the three decisions influencing UOBs at J2, J4 and J9 were not co-ordinated and the following points revealed by the model were the focus of discussion with the management staff responsible for re-structuring:

1. Once Goods Inward staff had accepted material, split batches could occur as a result of decisions at J2 which could result in discrepancy notes being raised. This was particularly evident after shift changes.

2. Counting and Inspection were sequential processes involving two separate groups of staff acting on separate decision criteria and could in some cases involve removing and replacing material on pallets twice before acceptance.

3. After acceptance by QC staff (UOB-7 in figure 6.11) items were assigned to store locations and in some cases concession notes for production were raised. No documented controls, procedures or guidelines were used to decide whether a concession note was raised and this lack of control meant in most cases concession information was not sent to suppliers.

Points 1 and 3 were made apparent by the IDEF0-3 approach and could not have been explicitly described by building $IDEF_0$ or IDEF3 models in isolation. Point 2 could have been deduced from building an IDEF3 model.

In practice documenting and model building is an iterative process and it was found that although the $IDEF_0$ diagram was a necessary starting point it was refined as the IDEF0-3 diagram was developed. The bottom up approach used to group sequences of UOBs for the IDEF0-3 diagram forced the analyst to examine the criteria used to select sequences of UOBs which in turn highlighted deficiencies in the corresponding $IDEF_0$ diagram. Similarly an open ended process path in the PFN forces the analyst to consider the validity of the outputs in a corresponding $IDEF_0$ diagram.

6.6 CONCLUSIONS

For modelling methods to be useful in manufacturing enterprises they must provide an analyst with a means of understanding and solving problems by either gaining insight into existing systems or contributing to the design of new systems. The case study using the IDEF0-3 approach proved how critical it is to provide an insight into the behaviour of systems. The IDEF0-3 model required fewer levels of decomposition in comparison to typical $IDEF_0$ models of similar situations (in the authors experience). $IDEF_0$ and IDEF3 diagrams validate each other and ICOM gates in an IDEF0-3 decomposition force an analyst to examine the consequences of functional 'Control' in terms of process logic or decisions and the significance of process sequence in terms of 'Outputs'. The approach uses robust, well understood principles and a commonly accepted set of diagramming symbols whose use is already understood by analysts and engineers.

For the IDEF0-3 approach the objectives of an analysis are defined in the purpose statement, as in a conventional $IDEF_0$ model. The statement along with the $IDEF_0$ context and viewpoint diagrams are the initial steps in the modelling process. Gathering the necessary information for model building is conducted using the approach described in the $IDEF_0$ manual (US Air Force, 1981a). The results of which are represented as a series of $IDEF_0$

diagrams decomposed from the viewpoint diagram. A functional analysis is thus the first phase of the methodology.

The case studies suggested that it is easier and quicker to establish a common understanding of the essential activities in an enterprise using $IDEF_0$ initially than to take a process view and deal with the detailed logic of process sequences. This is in contrast to Mayer et al. (1992a, p.4) who suggest that $IDEF_0$ models can be constructed after gathering information in IDEF3 models.

The IDEF0-3 methodology requires consideration of the transition from $IDEF_0$ format to IDEF0-3 diagrams. This should take place at the stage that functions in $IDEF_0$ diagrams become scenarios for IDEF3 process flow networks. Developing the graphical aspects of the IDEF0-3 approach allows balancing the need to model as many important variables as possible but still maintain useful, but simple, descriptions that provide an understanding of the relationships between them. During information gathering it was found that, as domain experts explain situations, the finer the level of detail the more likely their description moves away from describing simply the functions that occur. At this stage an expert's narrative is often the logical flow of activities that supports representation as a process flow network. This finding echoes Mayer et al's (1992a) assertion that 'experts express their problems in terms of an ordered sequence of events'. The point at which it is useful to decompose an $IDEF_0$ diagram to an IDEF0-3 diagram is dependent on the actual situation being modelled and the use to which the model is to be put however three potential pointers are in evidence:

(i) When decomposition of an ($IDEF_0$ activity) exposes an obvious or simple sequence of dependent processes.

(ii) At the stage in analysis that requires an understanding of how controls identified using $IDEF_0$ affect activities. - Are they all required, are they required simultaneously, what decisions do they influence and what is their influence on the logical relationships of sub-activities.

(iii) when the knowledge of domain experts was expressed as a waterfall - a sequential description of processes, activities or events using their relative positions in the sequence as a framework for discussion.

A key to using the approach is correlation of $IDEF_0$ and PFN levels of a model using an IDEF0-3 diagram to examine all fan out junctions and to identify the presence of a control in the parent function (scenario). What constrains the decision or actions necessary to follow any of the subsequent alternative sequences of UOBs. If no constraint is evident that point in the UOB sequence requires further investigation. If open ended flow paths that start and end the process flow network do not correlate with $IDEF_0$ inputs and outputs this points to an investigation to see if there are unnecessary, redundant or missing processes that have no influence on the inputs or outputs identified at the $IDEF_0$ level.

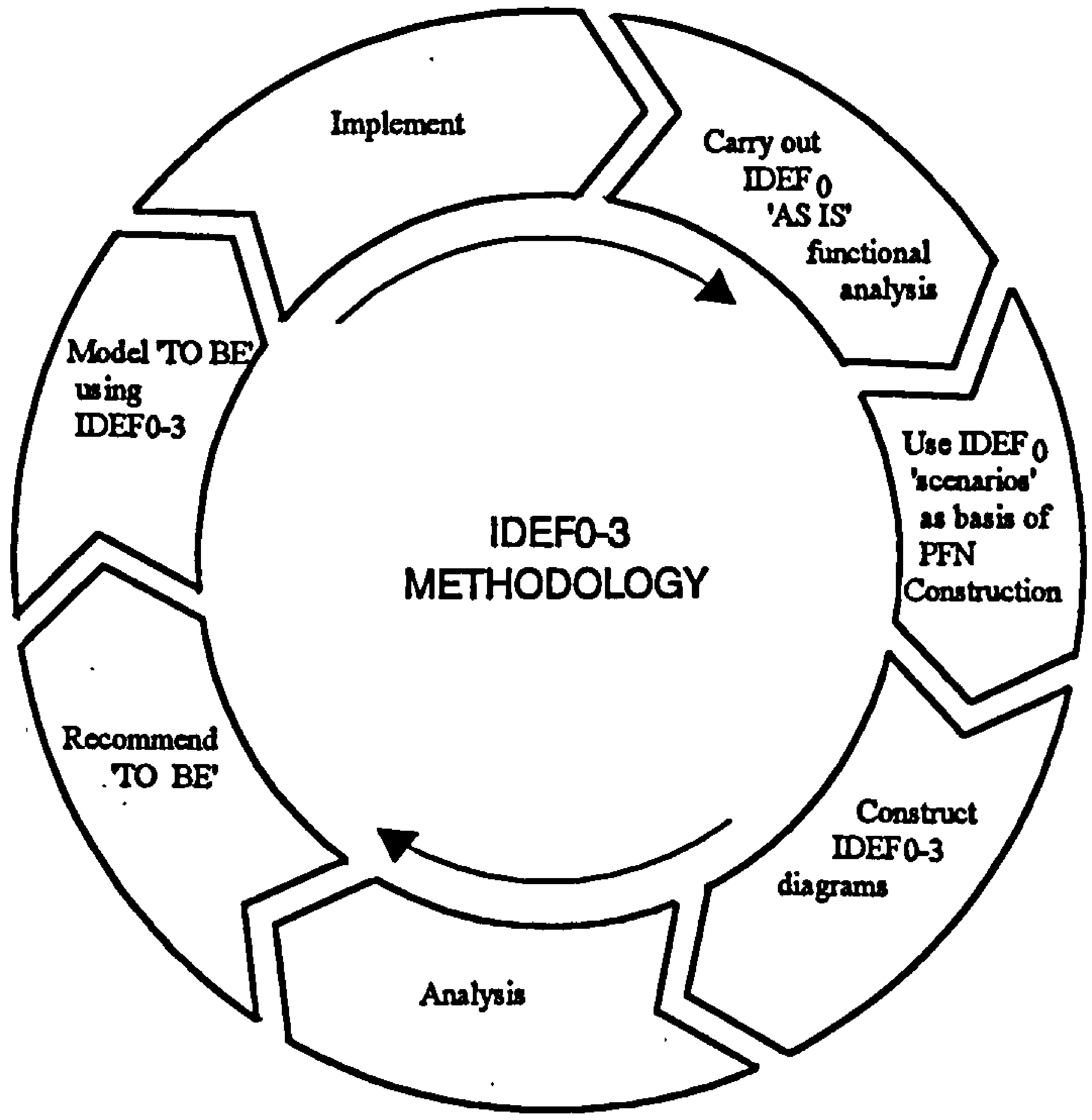


Figure 6.12 The IDEF0-3 methodology

In parallel to diagram correlation, validation of the accuracy of analysts view of the system is carried out using the author reader cycle in the usual way (US Air Force, 1981a) (although in the case study, validation was limited to the experts involved). After correlation of $IDEF_0$ and the PFN the resulting IDEF0-3 model can be used for analysis, followed by recommendations for change and the model has the potential to be used to describe the TO-BE proposals before implementation. The complete methodology has evolved into the form illustrated by figure 6.12 as a single cycle.

An outcome from the case study was the development of an IDEF0-3 methodology user guide (reproduced in appendix 2). It provides a guide to the method and syntax associated with phase 2 and 3 of the IDEF0-3 methodology i.e. Use $IDEF_0$ scenarios to construct PFNs and construct IDEF0-3 diagrams.

In the case study the Design /IDEF (MetaSoftware) tool was used to produce $IDEF_0$ diagrams and IDEF3 diagrams were produced with conventional graphics software. At this stage in the development of the approach the lack of software facilities for IDEF0-3 such as syntax checking and symbol configuration is a disadvantage.

The developed IDEF0-3 approach can describe or represent functional and behavioural aspects of a system for cells 50, 60, and 70 of the manufacturing enterprise modelling framework (shown in figure 6.13). It is not designed to support a dynamic perspective represented by the cells 40, 80, 120 of the manufacturing enterprise modelling framework.

A more extensive application follows in chapter 7 to re-enforce the findings, develop some of the features and demonstrate advanced aspects of the approach e.g.:

- At what level in decomposition the transition from functional diagrams to a PFN is most effective.
- How effective the approach is in a higher level manufacturing situation when considerable aggregation is necessary.
- The detailed diagram syntax associated with IDEF0-3.
- The suitability of the approach for TO BE models.

- Its usefulness in a larger scale project.
- To demonstrate the approach can be used by staff other than the analyst.
- To validate the IDEF0-3 User Guide.

FOCUS PERSPECTIVE	a *CONFIGURATION* What, Where, Who	b *BEHAVIOURAL* How, When	c *QUANTITATIVE* How Much, How Quickly, How Many
1 ENTERPRISE Values, Goals, Scope	10 IDEF$_0$ IDEF0-3	50 IDEF0-3	90
2 STRUCTURAL Functional Relationships, Interfaces	20 IDEF$_0$ IDEF0-3	60 IDEF0-3	100
3 PROCESS The stages involved in information and material flow	30 IDEF$_0$ IDEF3 IDEF0-3	70 IDEF3 IDEF0-3	110
4 DYNAMIC The activation of information or object flow	40	80	120
ENTERPRISE OPERATION	Product, Material, Resources, Locations, Information.	Constraints, Material flow, Schedules and timing.	Resource consumption, Output, Performance

Figure 6.13 Allocation of IDEF0-3 to the manufacturing enterprise modelling framework

CHAPTER 7

VALIDATION OF THE IDEF0-3 METHODOLOGY

7.1 INTRODUCTION

This chapter describes the validation of IDEF0-3 through its extensive use to design a manufacturing system. A case study is reported where the methodology contributed significantly to the success of a project to design a manufacturing system for fabricated component manufacture. The major UK manufacturing company where the case study was conducted is in the competitive global environment discussed in section 1.2. To survive and develop the company is using a combination of technology, organisation, management and the control of information and is demonstrating its ability to adapt to a new situation. The enthusiasm with which modelling was accepted by the staff involved is a reflection of the open approach encouraged by senior management in an effort to explore every potential route to gain a commercial advantage.

The company was selected because it contained many of the features that currently characterise change in UK manufacturing such as; the implementation of process automation, the need to use computers effectively, the need to reduce direct labour costs and change a legacy of operating practices and principles based on local knowledge and manual operations. Modelling was used to analyse and design the structure, operating principles and software requirements for a new manufacturing facility. The company also provided an opportunity to validate the IDEF0-3 approach, testing its functionality, capability and ease of use as a methodology to design a large manufacturing system.

The preliminary work covered modelling both system concepts and detail system design and took place over the period from November 1994 to May 1995. Other complementary approaches used in the analysis phase (not reported in this thesis) included production flow analysis and discrete event simulation.

7.2 THE CASE STUDY SITE

The case study was carried out in collaboration with the Dunlop and Rankin Steel Service Centre of British Steel Distribution (BSD) in Leeds. The centre is one of sixteen UK distribution centres for 'General Products' typically grade 43A plate, floor plate, beams columns and joists, hollow sections and bright bar-stock. The 200 acre Leeds site is used both for steel-stock storage and has the capacity to shear, profile, cold saw, shot blast fabricate and paint steel-stock to customer requirements. The site has been used to provide a distribution service for the past twenty years, however the business objectives of BSD have changed significantly over the last ten years and the need to process and add value to the steel-stock is now considered the key to commercial expansion.

Toronto Engineers Ltd. was established eighteen years ago as a fabricator for the mining industry. The collapse of the mining industry and a failure to diversify led the company into receivership before it was taken over by BSD in 1990. Re-named Toronto Industrial Fabrications (TIF) Ltd. and re-located to the BSD Leeds site, it is now a 5000m^2 general sub-contract fabrication unit for profiling plate and welding sub-assemblies. The success of the company has led to a long term commitment from a major manufacturer of earth-moving equipment for the supply of 'kits' (which are palletised sets of fabricated and profiled components). In order to achieve the quantity, consistent delivery schedules and quality of product demanded by customers BSD committed a £2 million investment for new plant and systems to expand the TIF workshop, equipment and staff. The decision to proceed with the investment was taken in March 1995 and the first orders for mechanical handling equipment were placed in April 1995.

7.3 THE PROBLEM DEFINED

The basis of the case study is a proposal by TIF to supply a fixed, daily quantity of fabricated kits to an earth-moving plant manufacturer. The BSD manufacturing facility (named the Construction Earth Moving Equipment (CEME) Centre during the development stage of the project) was to be an element of the customer's JIT supply chain. Business performance, product quality and schedule adherence were critical to the success of the unit and were the overlying consideration during design. At the stage of order acceptance and a commitment to supply kits by BSD, technical customer information comprised a proposed twelve month master production schedule for six kit variants and a complete set of assembly and detail drawings (modelling applications concerning refinements to the commercial relationship between BSD and their customers is not considered in the case study).

The existing TIF fabrication unit was a traditional jobbing shop supplying a range of customers with batch quantities of profiled plate and welded fabrications ranging from five kg to eight tonnes. The key processes were gas and plasma profiling with subsequent manual fettling, shot blast, manually controlled bending and piercing and manual welding. A small amount of machining was sub-contracted. Amongst the range of components manufactured, a 'Contract' unit processed 7000 tonnes of plate annually to produce the kits for earth-moving plant manufacturers.

Problems had been experienced with late deliveries and there was a history of kits being returned from customers due to quality problems. The manually operated shot blast, piercing, rolling and bending equipment was approaching the end of its effective life and contributing to the quality problems. All kit components were profiled from standard plates and the unit relied on manual profile nesting and gas profiling for this first process step. Bottlenecks had become increasingly common at the profiling stage as production levels rose. This situation in the fabrication shop together with the shift in business objectives to expand plate processing to 20,000 tonnes annually was the justification to embark on the CEME project.

Planning for the CEME centre was initially focused on plant layout and mechanical handling equipment, which is where the expertise of the existing staff lay. Capacity planning for manufacturing was largely overlooked until the volume of plate being processed and the subsequent importance of profile nesting together with the need for computer support for manufacturing were considered. When the significance of manufacturing capacity to the future of the centre was recognised new staff were assigned to the project and at that stage, in November 1994, the author became involved.

7.4 A PRELIMINARY ANALYSIS

The site had two closely related manufacturing units the 'Spot' unit and the 'Contract' unit. They were located in separate workshops with their own dedicated machines, tools, and shop floor supervision but they had common management and drawing office staff. The Spot unit was based on a sub-contract plate profiling service. It served a wide range of customers with profiled plate in quantities that could be in several hundreds but were usually less than twenty-off per order. Demand was considered relatively unpredictable and components were profiled with few subsequent processes being carried out on the profiled components. A decision had been taken to consider separation of the Contract unit (to become the CEME centre) from the Spot unit before this research work began.

Initial contact for the case study was made with BSD's engineering operations manager and after some discussions the company were convinced of the need to model and plan the change particularly in view of their relative inexperience in the manufacturing environment they were considering. Manufacturing control in terms of scheduling, material flow and processes was of particular concern.

The case study was carried out using the methodology described in the IDEF0-3 user guide presented in appendix 2.

The case study was initiated by considering the Manufacturing Enterprise Modelling Framework in the context of the initial phase (Carry out $IDEF_0$ AS IS functional analysis) of the IDEF0-3 methodology shown in figure 6.12.

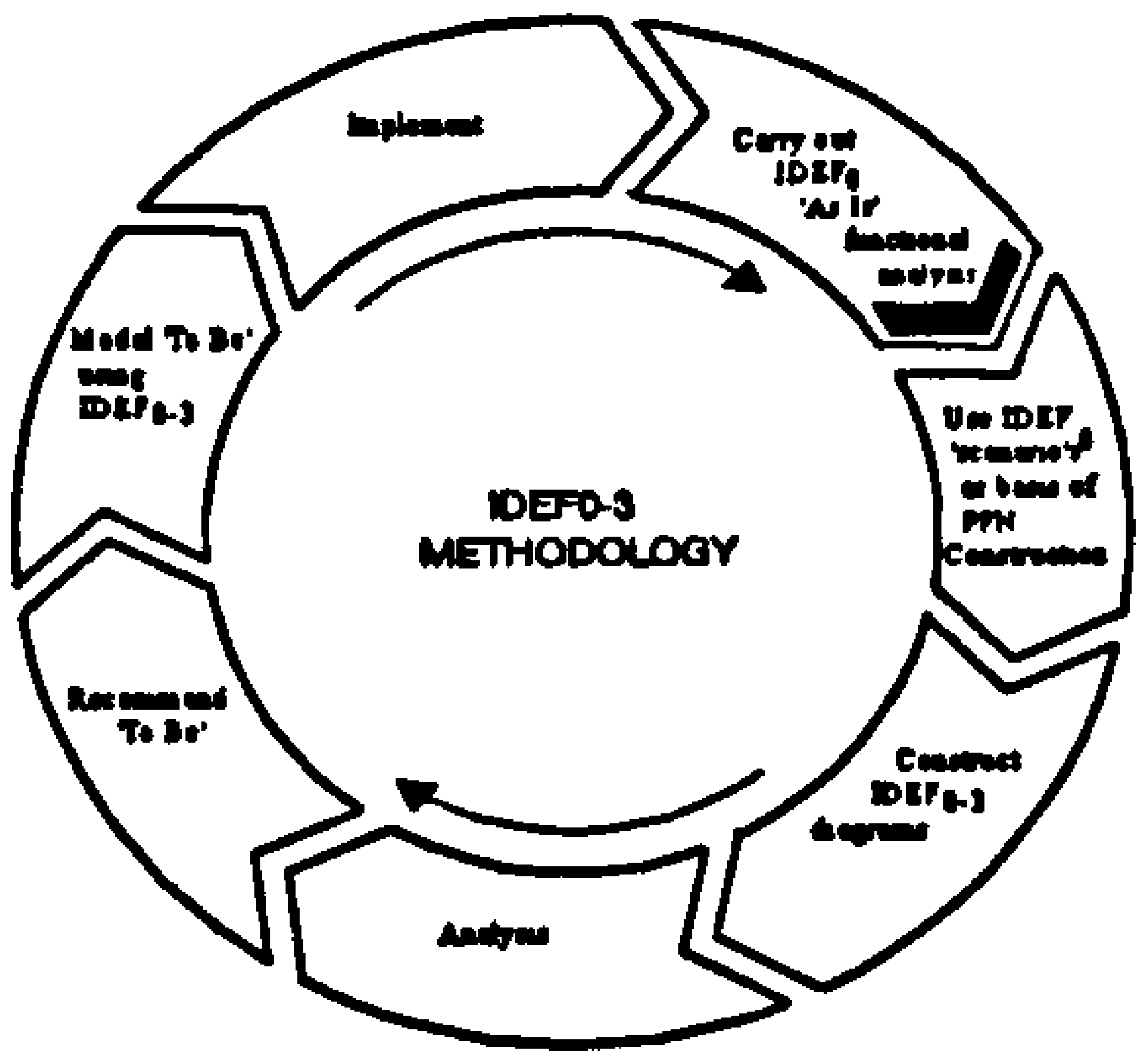
In order to understand the existing system, to analyse the situation and to provide a basis for re-configuring the system an AS IS IDEF0-3 model was generated. The context bounded by cell 20 of the manufacturing enterprise modelling framework shown in figure 6.13 provided a context for use of the model, i.e. a structural perspective focused on the configuration of the system using $IDEF_0$ diagrams.

It was decided, during the initial discussions, that aspects of control such as staff reporting and structures, budgets and commercial relationships with suppliers and sub-contractors would not be part of the core modelling effort. The models used in the case study reflect this approach. A pre-determined (at the stage that the author was involved in the project) decision to proceed with the CEME centre meant that enterprise perspective models (cells 10, 50, and 90 of the manufacturing enterprise modelling framework) were not of much value at the stage that modelling commenced. The goals and scope of the project had been established and the problem facing the company was how to proceed with the change. The enterprise perspective is not referred to again as the project continues.

7.5 THE AS IS IDEF0-3 MODEL OF 'RUN SPOT AND CONTRACT MANUFACTURING'

7.5.1 Phase 1 of the IDEF0-3 methodology

Carry out $IDEF_0$ AS IS functional analysis



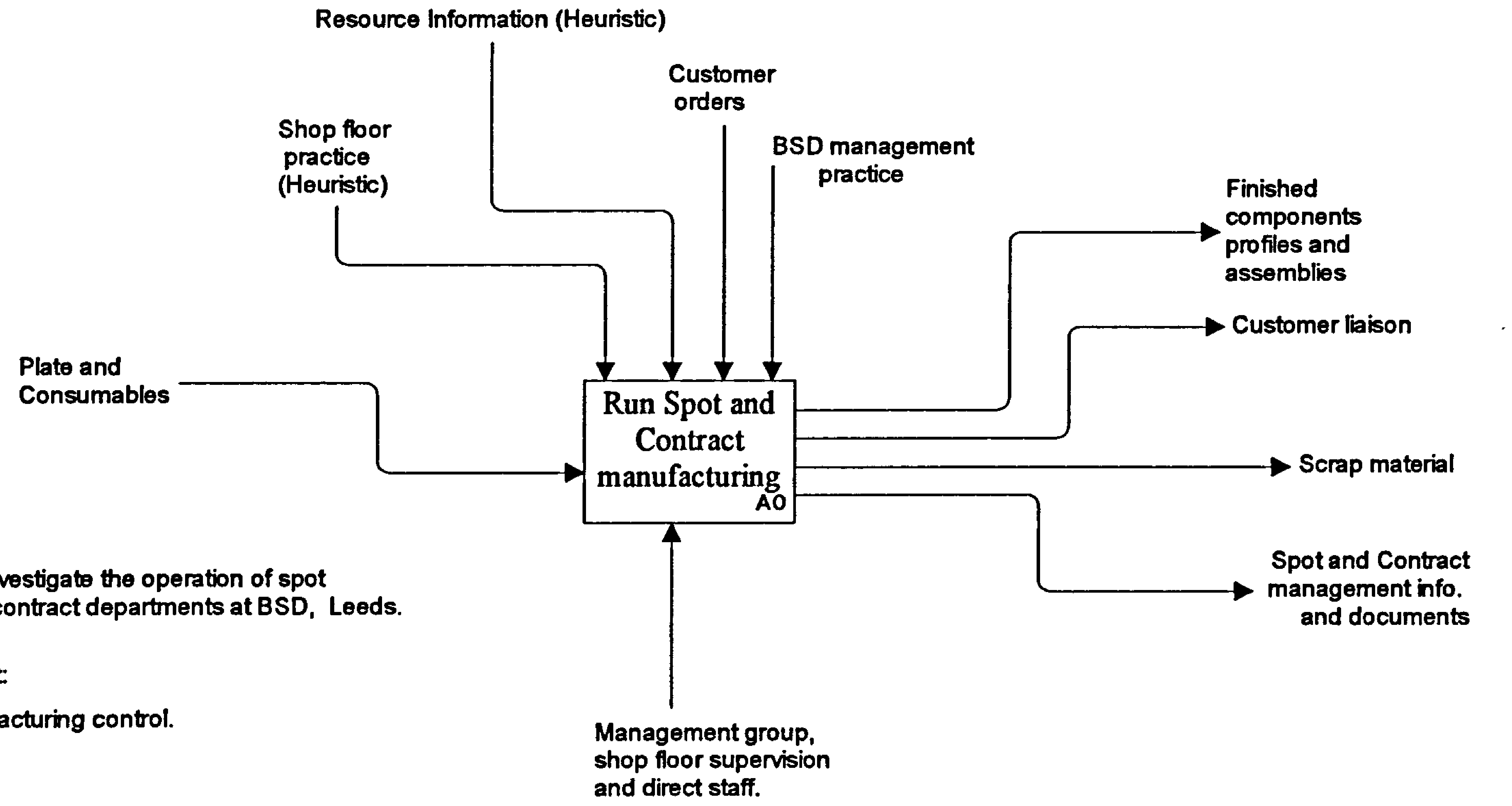
Interviews with the General manager, Manufacturing manager, Commercial manager, and project engineers were conducted to derive the AS IS model shown in figures 7.1 to 7.10.

The model starts with figure 7.1, the Context diagram (node A-0, Run Spot and Contract manufacturing) defining the '*Purpose*' of the IDEF0-3 model 'To investigate the operation of spot and contract departments at BSD Leeds'. The '*Viewpoint*' of the model reflects the immediate priority of BSD, that of manufacturing control in terms of material control, scheduling and the relationship between manufacturing processes.

The diagrams node A0, Run Spot and Contract manufacturing, figure 7.2 exposed the functional structure of the units. An analysis of node A0, revealed the autonomy of shop floor supervision in the two units. 'Spot schedules' and 'kit schedules' (highlighted) comprised of a parts lists in alphabetical order and a verbal statement of weekly quantities and customer due dates for Spot profiled parts and kits which left shop floor supervisors responsible for assigning priorities. The diagram also revealed a heavy reliance on heuristics and verbal instructions, a situation commented upon by local management when the draft versions of the diagrams were discussed and validated.

The inter-dependence of the two units in terms of profiling capacity can be analysed from the diagrams. Under-capacity in Contract unit led to 'Profiling requests' to the Spot unit. Similarly under-capacity of fettling or shot blast processes in Spot manufacturing resulted in 'Profiled components' being fed to the Contract unit for finishing (shown in figure 7.2). In addition supervisors in the two units were not explicitly aware of each others schedules again this is made clear by the diagram.

USED AT:	AUTHOR:	DATE: 18/04/96		WORKING	READER DATE	CONTEXT:
	PROJECT: BSD - AS IS	REV:		DRAFT	SH	Top
			x	RECOMMENDED		
	NOTES: 1 2 3 4 5 6 7 8 9 10			PUBLICATION		



Purpose:

To investigate the operation of spot and contract departments at BSD, Leeds.

Viewpoint:

Manufacturing control.

NODE: A-0	TITLE: Run Spot and Contract manufacturing	NUMBER: Figure 7.1 P. 1

Figure 7.1 Node A-0 Run spot and contract manufacturing

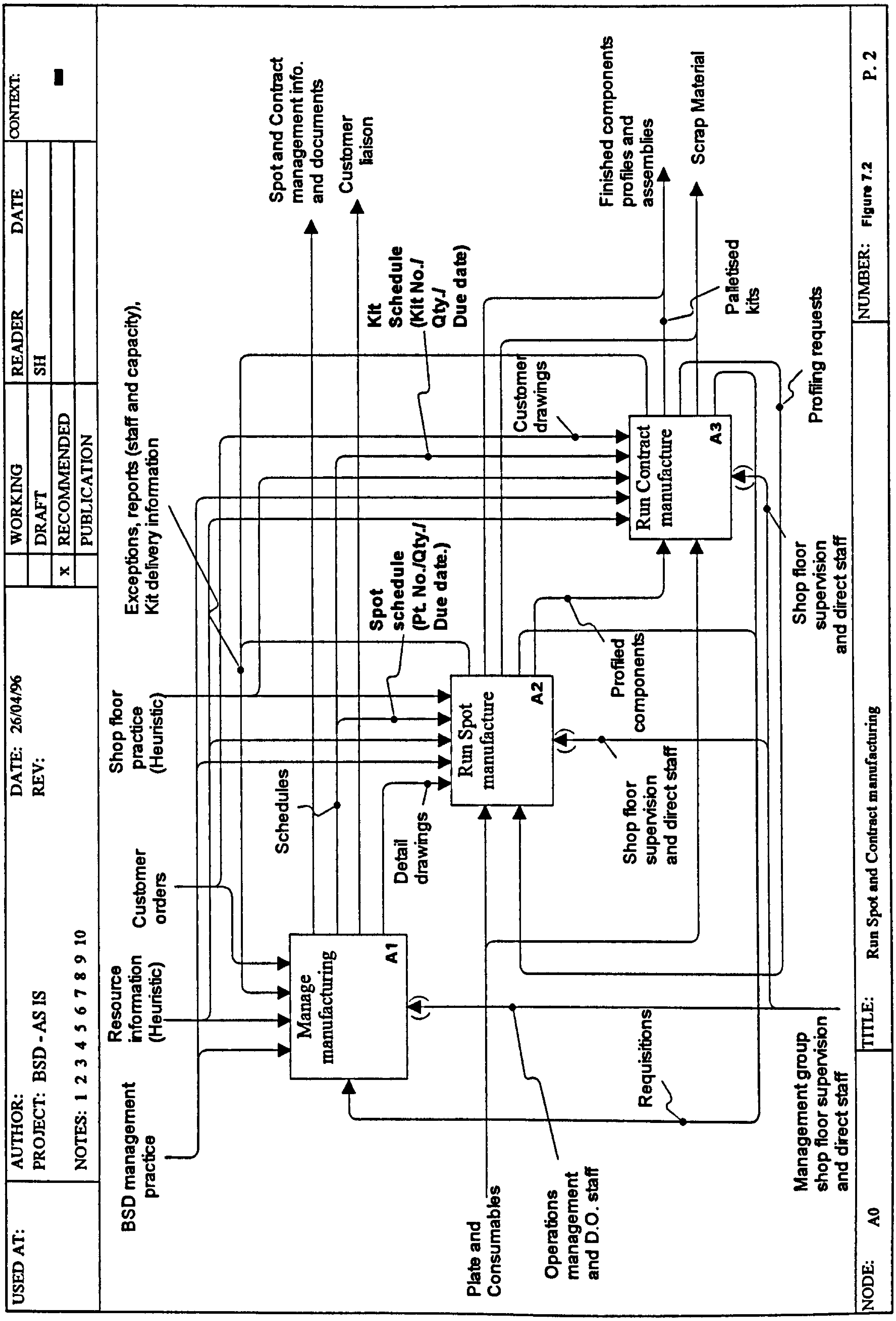


Figure 7.2 Node A0 Run spot and contract manufacturing

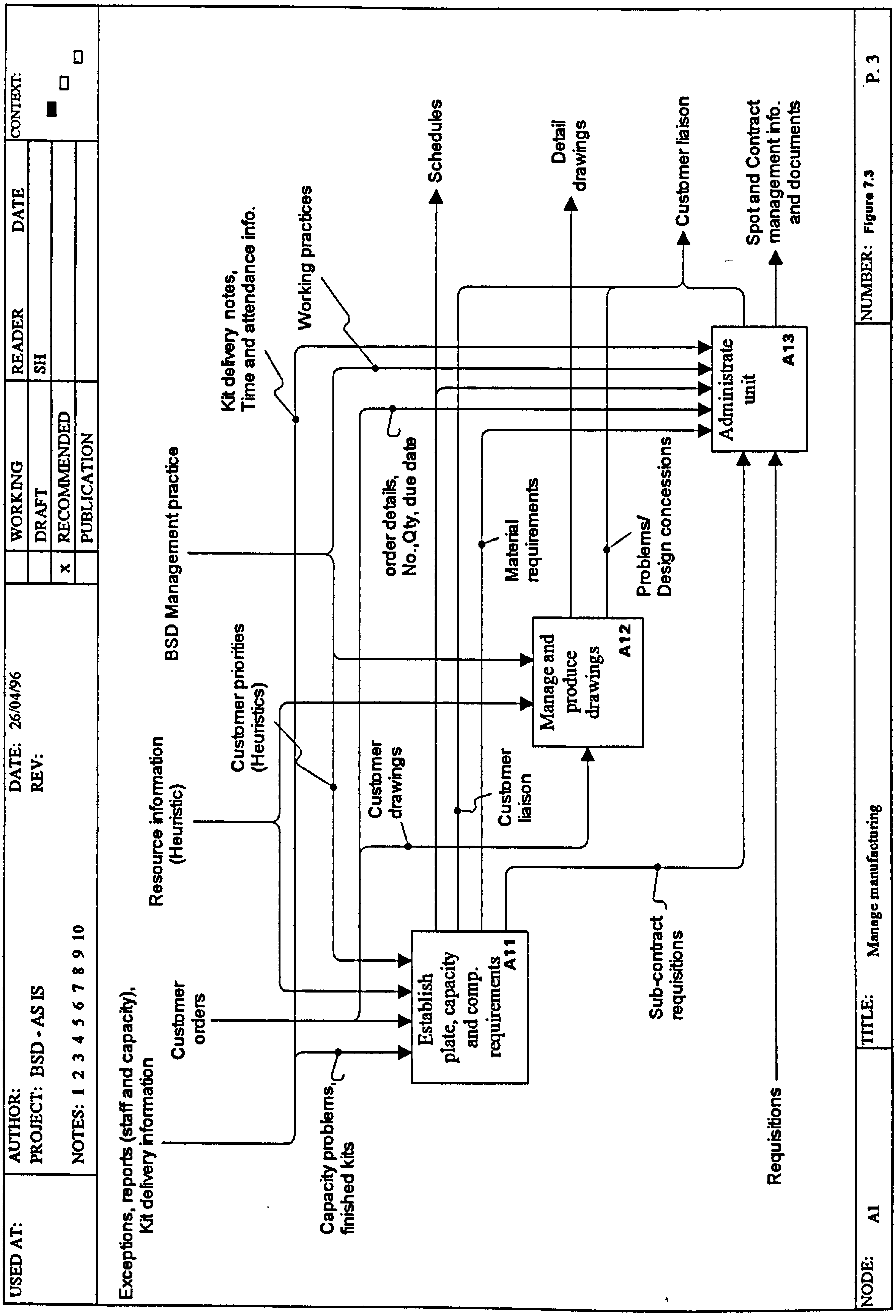


Figure 7.3 Node A1 Manage manufacturing

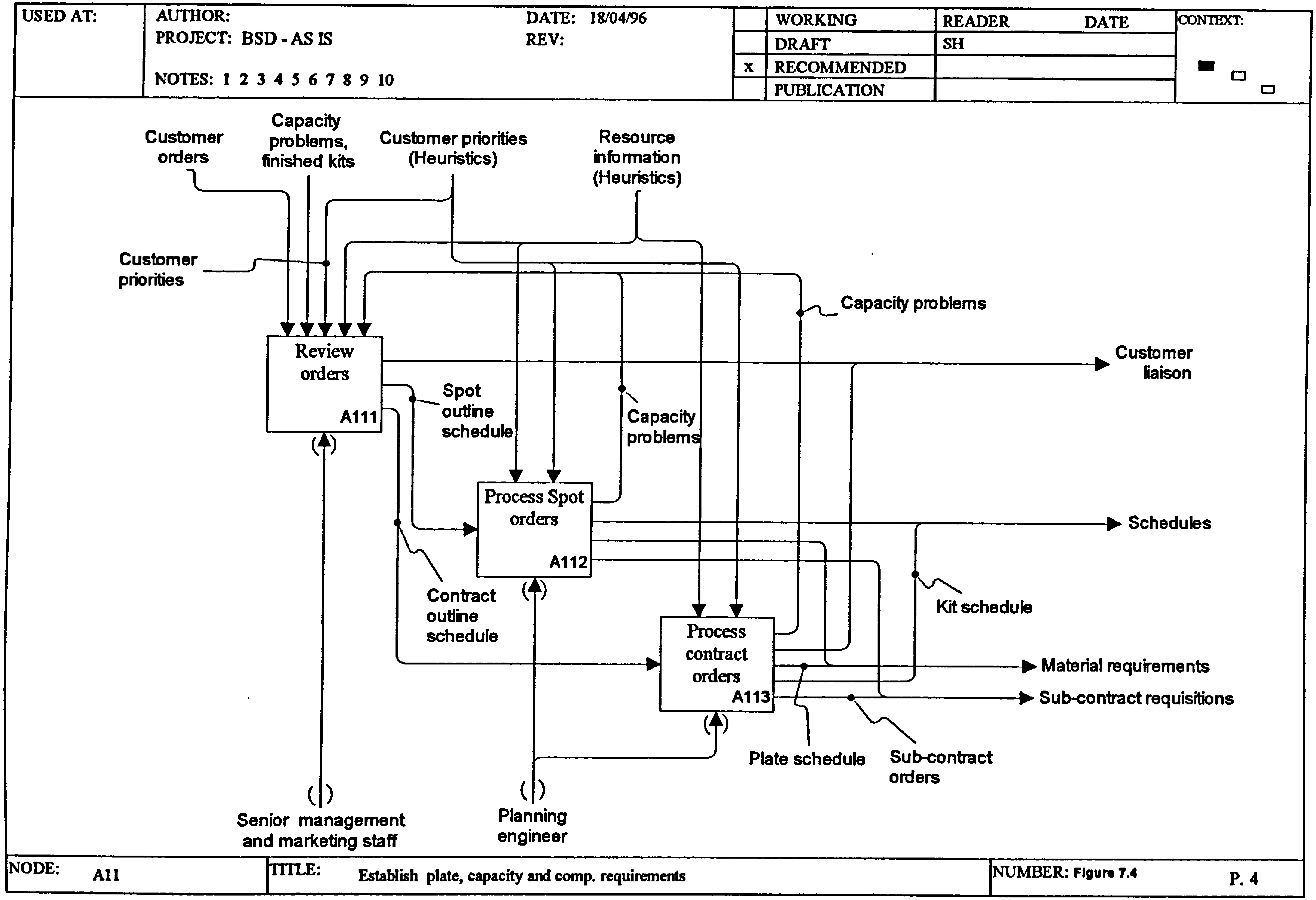


Figure 7.4 Node A11 Establish plate, capacity and component requirements

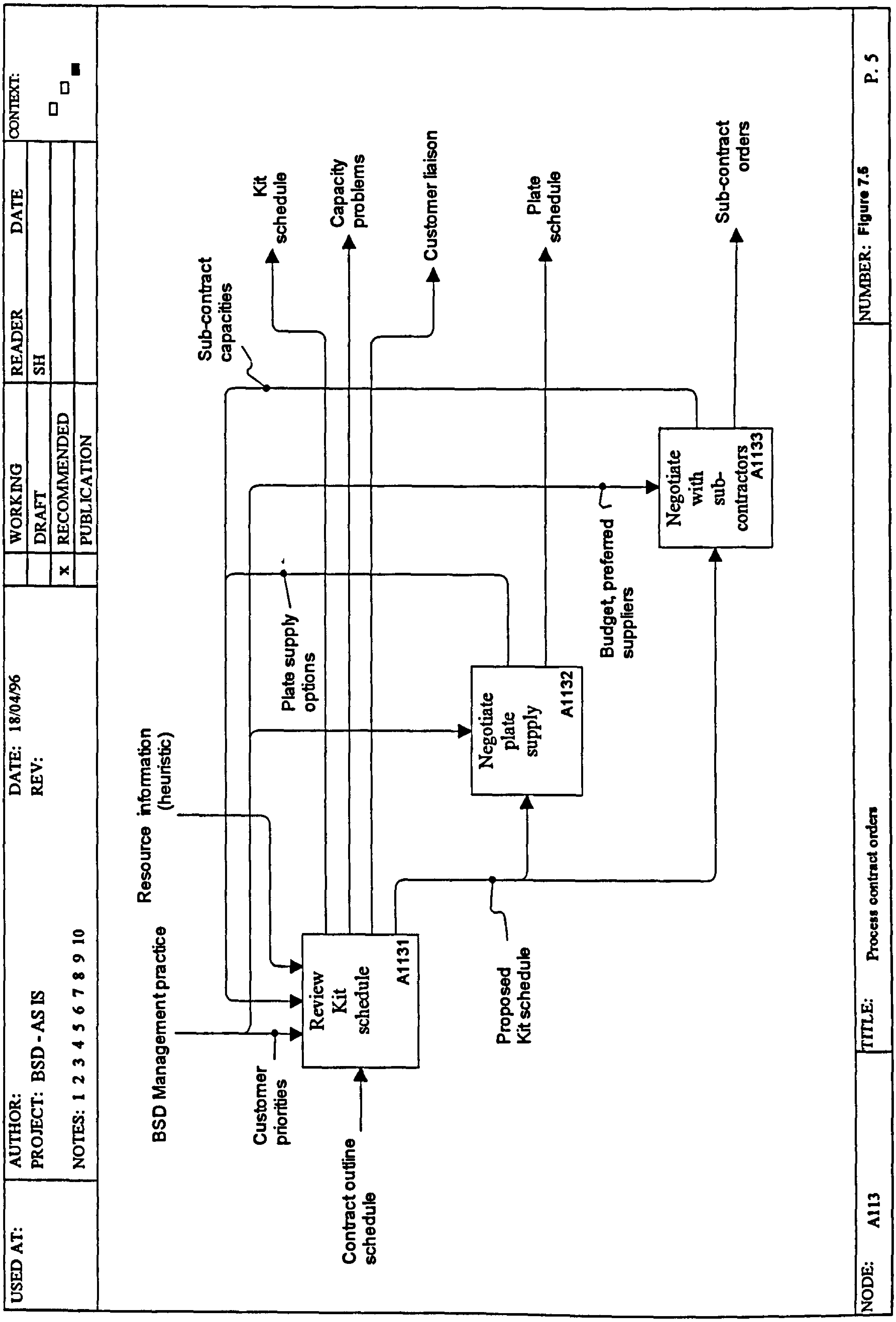


Figure 7.5 Node A113 Process contract orders

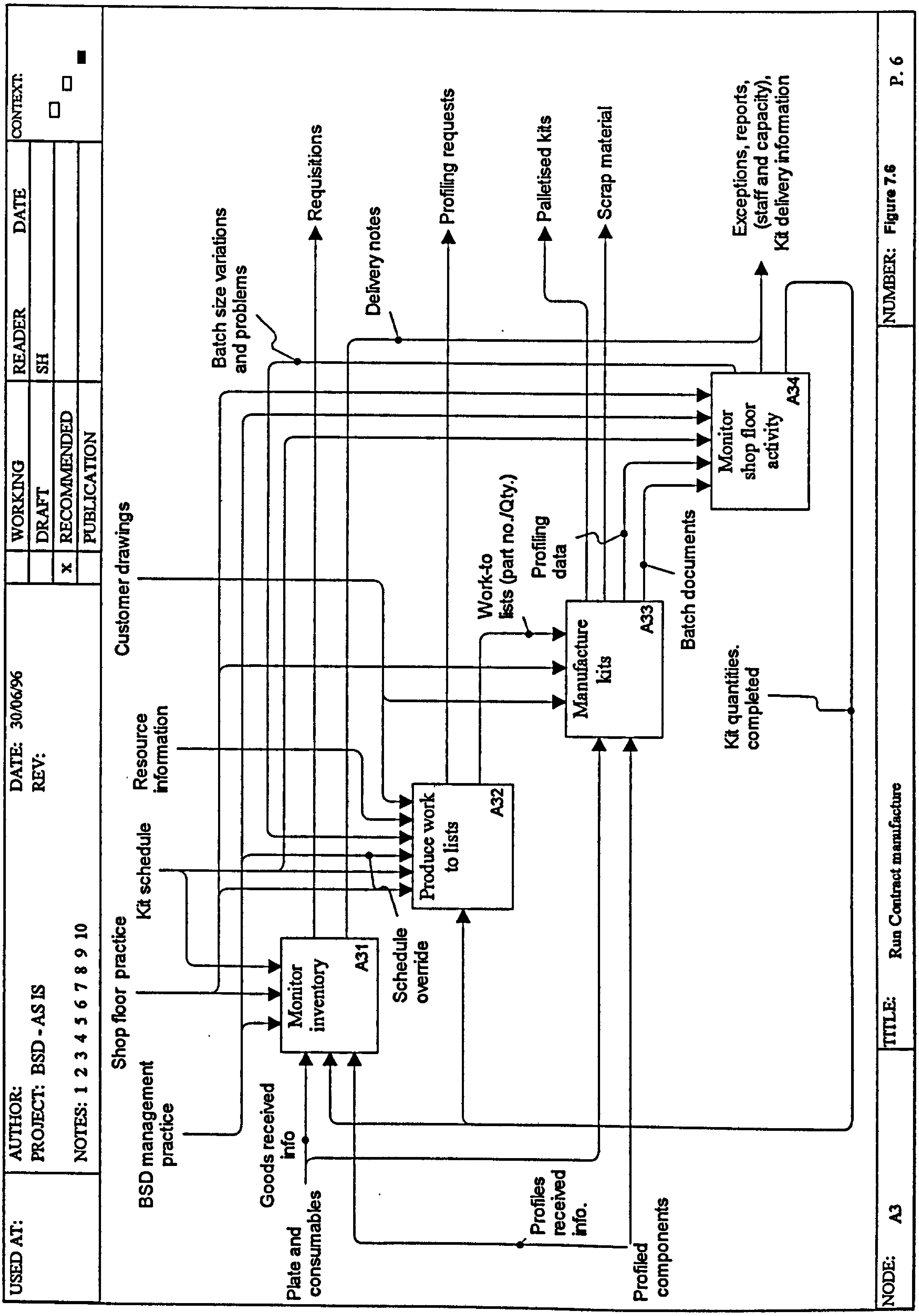


Figure 7.6 Node A3 Run contract manufacture

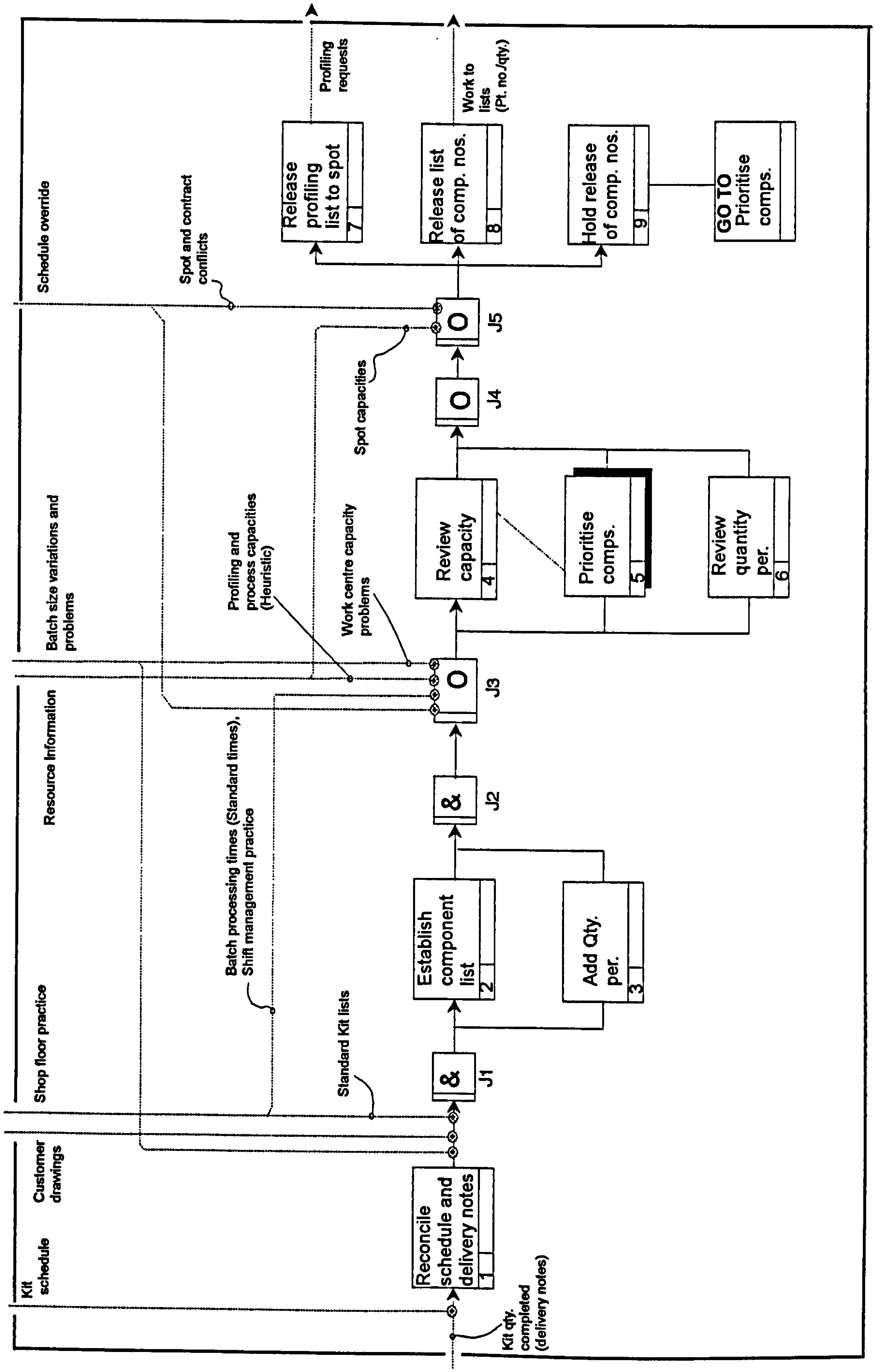


Figure 7.7 Node A03-32 Produce work to lists

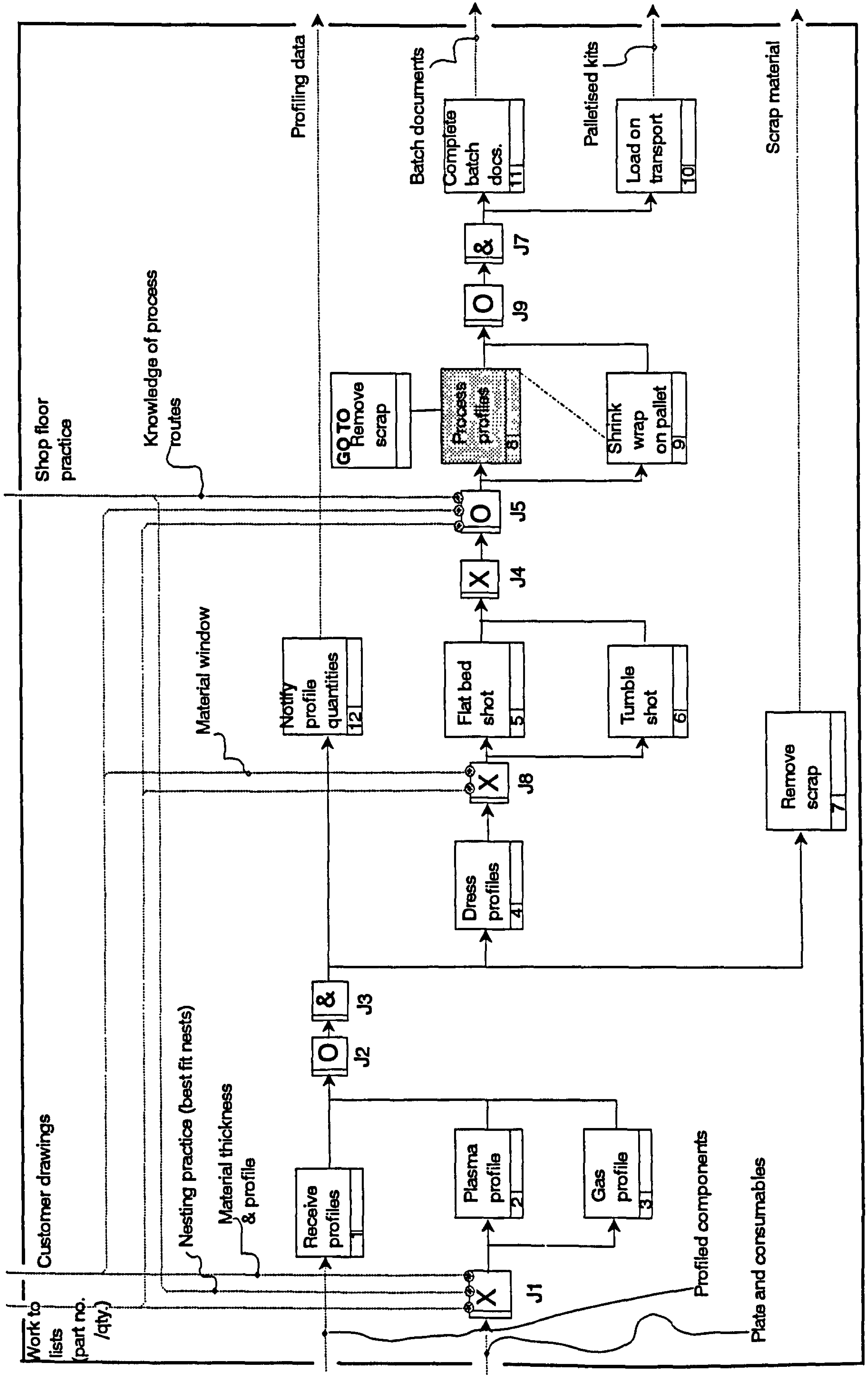


Figure 7.8 Node A03-33 Manufacture Kits

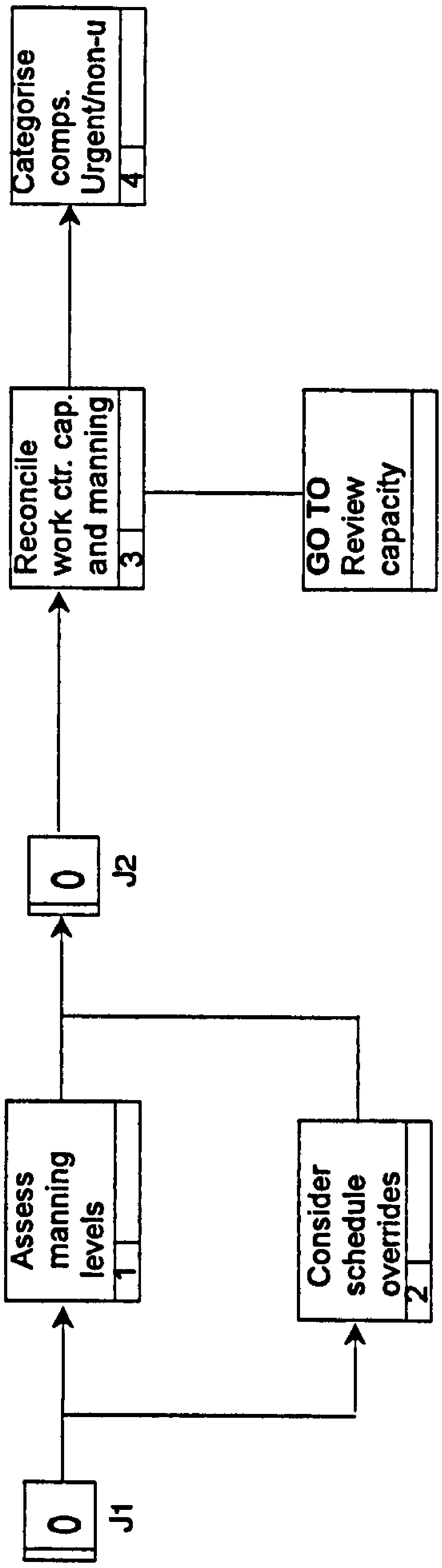


Figure 7.9 Node A03-325 Prioritise components

In validating nodes A0 and A-0 and discussing the situation with the staff involved it became evident that this long accepted practice was the cause of nervousness in contract manufacturing schedules.

The model revealed that shop floor reporting to operational management was based on exceptions and that performance measures at shop floor level were simplistically based on finished items (dispatch notes were signed and fed back to administration as kits and components were loaded on transport for delivery). Exceptions could be capacity, breakdown, material shortages, bottlenecks, etc.. The model showed that scrap, re-work and detailed work centre performance was not monitored (apart from time and attendance information for direct wages).

Analysis and validation of the model supported the proposal that the CEME centre be run as an independent unit comprising aspects of node A1 and A3 with its own management, schedules and manufacturing organisation. The success of the centre would depend on delivery reliability and modelling showed that shop floor schedule management was a cause for concern. As a consequence nodes A1 and A3 were decomposed for more detail using interviews with shop floor supervisors.

The decompositions of A1 and A3 are shown in figures 7.3 and figure 7.6. Figure 7.3 shows node A1 'Manage manufacturing' three functions were revealed and associated with A1: A11 - Establish plate, capacity and component requirements, A12 - Manage and produce drawings and A13 - Administrate unit.

> Node A11 'Establish plate component, and capacity requirements' is the activity that balanced customer orders with shop floor capacity (staff and processes) and the inventory of completed kits and components to produce shop floor schedules. Using customer orders a plan of throughput (in terms of the weight of steel) processed an outline of capacity requirements in terms of staff and processes was established.
>
> Node A12 'Manage and produce drawings' was found to be largely concerned with producing detail and fabrication drawings for Spot manufacturing. In addition it was found that the management, storage and reproduction of customer drawings for Contract manufacturing was also carried out together with some informal liaison with customers over design and manufacturing problems.
>
> Node A13 'Administrate unit' is the function that controlled the release of documents such as schedules for raw material (plate) requirements to BSD Leeds and the

ordering of purchased components, consumables and sub-contract manufacturing. The activity included the issue of dispatch notes, entering data into the site accounting system and dealing with other BSD administrative units such as Personnel and Finance.

In light of the '*Purpose*' of the model 'To investigate the control, organisation and operation of spot and contract manufacturing at BSD Leeds' and the manufacturing '*Viewpoint*' sufficient information had been gathered about nodes A12 and A13, however, node A11 was decomposed further to expose more detail about the control and operation of shop floor scheduling. By an analysis of node A11, Establish plate capacity and component requirements three activities were revealed: A111 - Review orders, A112 - Process spot orders, A113 - Process contract orders (shown in figure 7.4).

Node A111, 'Review orders' was an activity carried out by senior management and marketing staff. In the activity Spot and Contract orders were treated as separate items and no attempt was made to reconcile capacity in the two units. The activity was largely concerned with prioritising orders to achieve an aggregate balance of load on resources. The outline schedules were expressed at this stage as the number of kits or the weight of profiles per week for specific customers. Priorities could be influenced by a complex mix of customer priority, material shortages, shop floor manufacturing problems and management practice. With the additional constraint of a material flow policy of profiling batches of components, with common plate thickness, in groups.

Node A112, 'Process Spot orders' was the activity that produced detailed schedules and plate requirements for profiling Spot orders.

Node A113, 'Process Contract' orders was the activity that balanced the aggregate schedules for kits from node A111 with a knowledge of the available capacity and capability of the plate profiling equipment. A schedule for downstream processes after profiling was not considered. The activity was carried out by production planners with a detailed knowledge of the gas and plasma arc profiling machines. Component nesting and plate utilisation was considered to be of primary importance. The experience of the production planning staff, much of it not documented, and standard 'nests' (to provide maximum plate utilisation for existing customer profiles) had a large influence on schedule generation. As batches of profiles were produced they were transported to the next process, the profiling nests and schedules thus became the driver for all subsequent processes. This activity also produced a demand pattern for raw material (i.e. Steel plate in various grades and thickness) and produced requisitions for sub-contract processes.

The importance of this activity to the investigation prompted decomposition of node A113 to the next level of detail (figure 7.5 Node A113, 'Process contract orders') revealing three activities: A1131 - Review kit schedule, A1132 - Negotiate plate supply, A1133 - Negotiate with sub-contractors. This diagram revealed the influence of independent constraints on the generation of kit schedules. Developing the diagram exposed that, in practice, 'plate supply options' was a major constraint on the generation of schedules.

Figure 7.6 is a diagram showing node A3 'Run Contract manufacture', four activities were exposed in the analysis: A31 - Monitor inventory, A32 - Produce work to lists, A33 - Manufacture kits and A34 - Monitor shop floor activity.

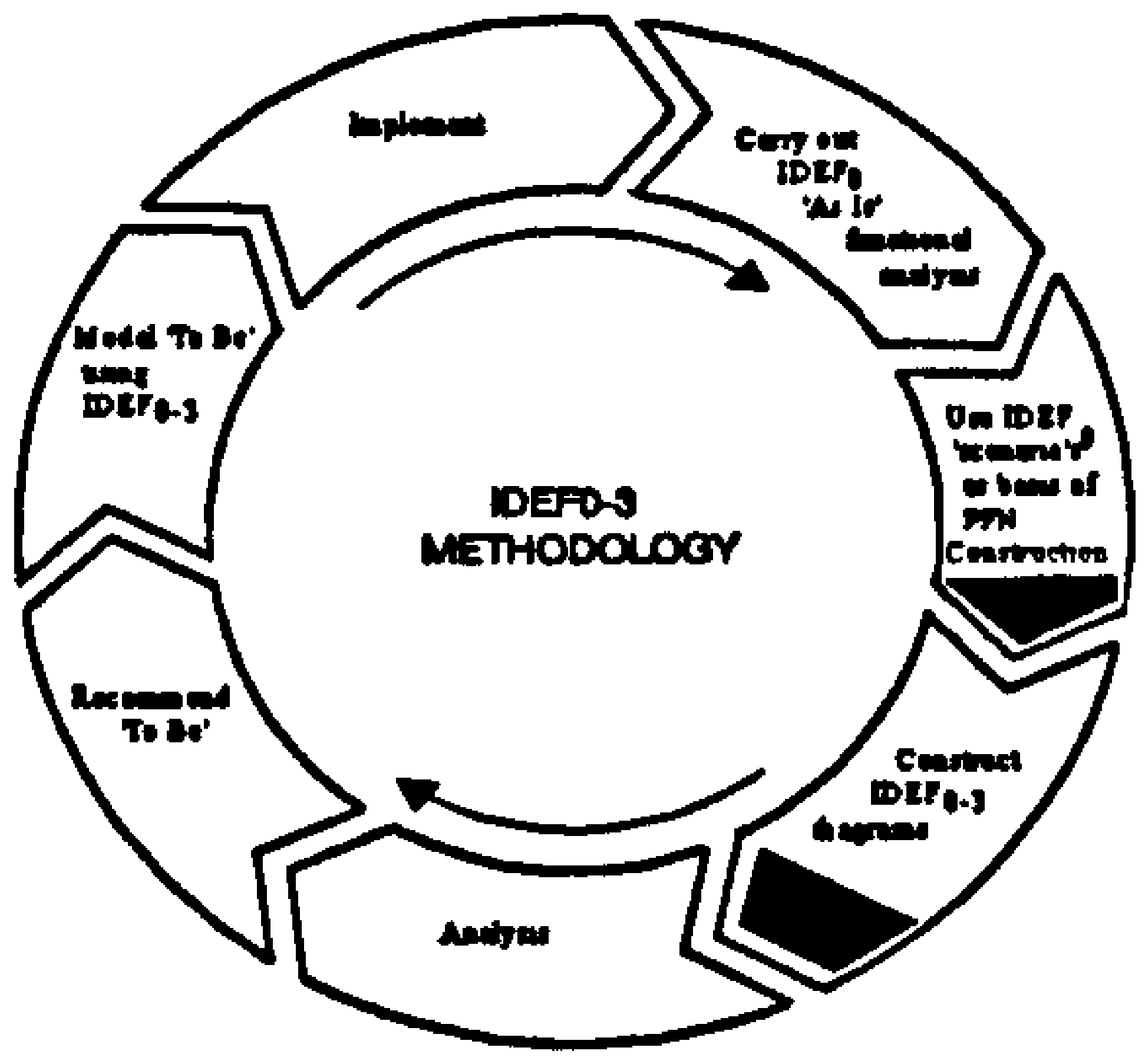
A31 - Monitor inventory, this activity was carried out on the basis of input and output control. Profile quantities received from Spot manufacturing were logged in to the Contract unit. Plates from BSD (or other suppliers) were received through acceptance of a goods received note. Consumables such as gas, welding spools (for Mig welders), abrasive disks for fettling, etc. were also received through acceptance of a goods received note. The output from the system in terms of kits was monitored using dispatch notes that were completed as kits were loaded on BSD trailers for delivery to customers. Requisitions were raised to replenish consumables, and for plates supplied by BSD.

A32 - Produce work-to lists, in this activity kit schedules were used to produce lists of individual component numbers using established knowledge of previous batches and customer drawings, formal BOMs were not used. Batch sizes for each component were based on lot for lot against kit requirements.

A33 - Manufacture kits, is the activity that describes the sequence of processes necessary to make each component and assembly. Work to lists were issued to 'profiling' (the first process for all components). As components left profiling they were distributed to subsequent processes. Priority for downstream processes therefore, was strongly influenced by the priority at profiling (unless progress chasing intervened). No formal sequence of processes was used for each component, batch moves were dependent on standard practice and expediting.

A34 - Monitor shop floor activity, involved collating staff time and attendance records, to produce aggregate direct labour hours, work centre and staff capacity problems were logged as exeptions. Delivery documents were assigned to completed kits and individual components were expedited to collate kits and achieve kit schedules.

7.5.2 Phase 2 and 3 of the IDEF0-3 methodology:
Use IDEF$_0$ scenarios to construct PFNs and Construct IDEF0-3 diagrams



At this stage in modelling it was evident that the complexity of two important functions, node A32 and node A33 (figure 7.6) needed to be understood. A description of these functions was necessary to develop proposals for shop floor control in the CEME centre. Further decomposition using IDEF$_0$ functional decomposition was not describing the behaviour of the two critical functions and it was at this stage in modelling that IDEF$_0$ functions were used as the scenario for IDEF0-3 diagrams.

Node A03 - 32 and node A03 - 33 are shown in figures 7.7 and 7.8. These two diagrams exposed some important behavioural characteristics of the contract manufacturing unit and the details are discussed in section 7.5.3. It was also found necessary to decompose node A03 - 325 the process is indicated on figure 7.7 as a shadowed box and shown in complete form in figure 7.9.

Figure 7.8 is an IDEF0-3 diagram that showed that all components undergo three fundamental processes; profiling, shot-blast and 'process profiles'. In investigating node A03-338 (process profiles, shown highlighted in figure 7.8) it was evident that the complexity of sequence and logic of the sub-processes involved for each component would be better described using a part number and process analysis. A part number/process matrix was used to describe the possible alternative routes that could take place in 'process profiles' and is shown as an FEO diagram appended to the model (figure 7.11). Figure 7.10 is an extract from the matrix, it shows ten of the thirteen possible processes that a component might undergo in the horizontal axis. Part numbers are shown in the vertical axis and processing times for each component are allocated to each process,. The matrix was subsequently used to classify components using process flow analysis, a part number/process matrix is shown in appendix 10.

CEME Centre floor to floor processing													
			Process Activity Cycle Activity Times (Sec)										
Part No.	No. off per Assy	Class	Profile Gas	Profile Plasma	Dress Chamf	Tum. Shot	Table Shot	Bend	Chamfer	Manual Weld	Robotic Weld	Re-work	Total ops
Boot 9R-8866		A								420	496	480	1396
9R-8866/1	2	A	192		120		60						372
9R-8866/2	1	B						30	30				60
9R-8866/3	1	B						30	30				60
9R-8866/4	1	C											0
9R-8866/5	2	C	80		120								230
Top hat		A								420	529	300	1249
9R-8514	2	A	88		120		60						268
9R-8514	2	B	94		120	90							904
9R-8514	1	C		26	60	30							116
9R-8514	1	B		16	60	30							106
Spacer	2	C		2									2

Figure 7.10 An extract from an analysis of alternative process routes

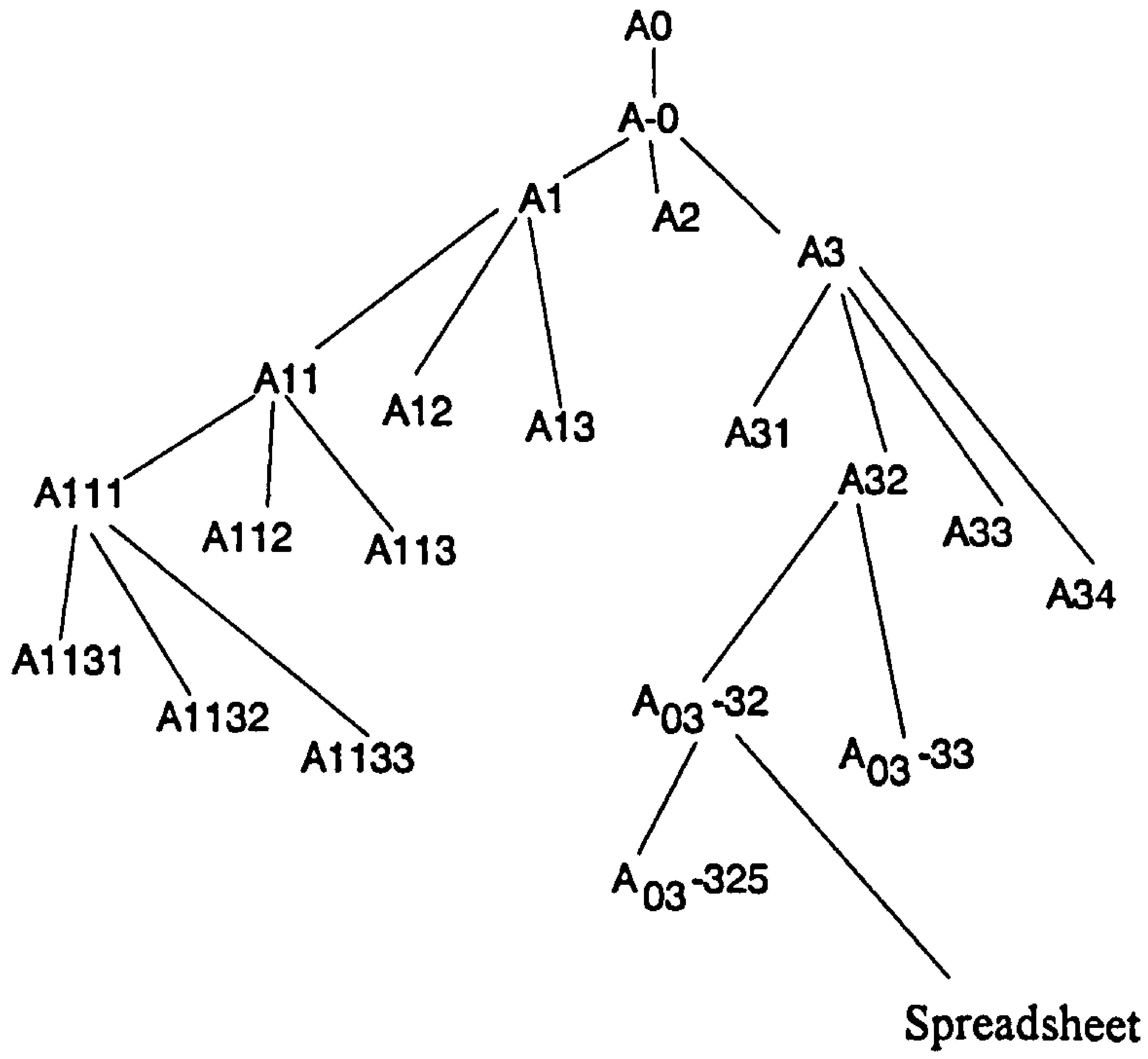
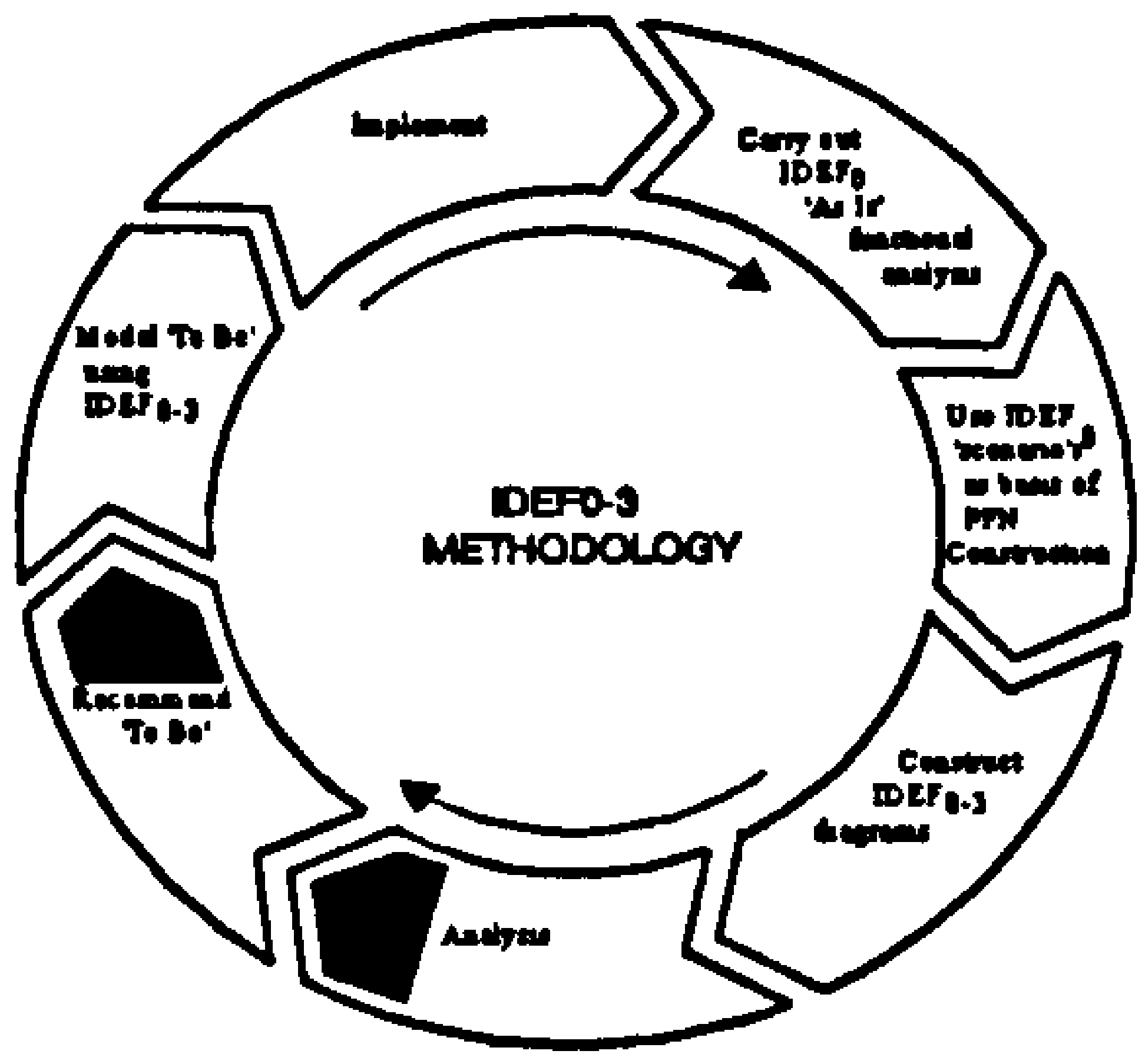


Figure 7.11 Node tree of IDEF0-3 model 'Run spot and Contract manufacturing'

A node tree diagram for the complete AS IS model is shown in figure 7.11 showing the depth and breadth of AS IS model decomposition.

7.5.3 Phase 4 and 5 of the IDEF0-3 methodology

Key findings and recommendations from the AS IS IDEF0-3 model analysis



Analysis of the AS IS model exposed a range of potential problem areas and formal presentations of the model to BSD staff were focused on the following points:

- The clear need to separate the two manufacturing units. To provide an interface using the 'Manage manufacturing' activity (figure 7.2) so that any requests for capacity between the two units would be considered by activity A11 (figure 7.3) and could therefore be evaluated on the basis of overall capacity and integrated into existing Contract or Spot schedules.

- No clear definition of product structures was available, bills of material were not used consequently the conversion from independent demand for kits to dependent demand for individual parts took place at shop floor supervision level (activity A32, figure 7.6 and node A03-32 junction J1, figure 7.7). No start time off-setting was carried out for components at different levels in product structures. As a result detailed capacity planning was not carried out and aggregating batches of similar components was only done in obvious cases by individual operators. Similarly the decisions involved in junction J3 and the UOB 'Prioritise components' (node A03-325, figure 7.7) do not consider product structure in prioritising component manufacture. Figure 7.8 describes the situation whereby all components are routed through profiling (nodes A03-332 or A03-333), dressing (node A03-334) and shotblasting (nodes A03-335 or A03-336) before 'Process profiles' (node A03-338). Here modelling led to a recognition of why material flow in downstream processes was being largely controlled by profiling and why the UOB 'Dress profiles' (node A03-334) was often a bottleneck and the cause of material flow problems.

- Process routes and operation details (tooling, settings, etc.) were based on operator knowledge and experience. Figures 7.8 and 7.10 showed that Process routes were relatively simple and known by the staff involved but the information was not documented and could not be collated to provide the detail necessary for planning capacity requirements.

- Inventory levels for individual components were not considered by shop floor supervisors when producing work to lists (activity A32, figure 7.6 and node A03-32, junction J3, figure 7.7).

- One of the most important findings of the analysis is described by figure 7.8 that shows the way in which shop floor monitoring is notified of profiled quantities. Profiling nests are based on standard practice and locally held data at the Plasma and Gas profiling machines (nodes A03-332 and A03-333, figure 7.8). Consequently planning batch sizes for components does not take into account the occasions in which plate utilisation requirements force profiling operators to over-produce batch quantities of many components (and in some cases split batches and under-produce batch sizes). Notification of variations to batch sizes only takes place after profiling, the design of the CEME centre must overcome this problem.

- Rework and WIP levels were not recorded in monitoring the shop floor activity (activity A34, figure 7.6 and UOB A03-337, figure 7.8).

- Customer liaison was carried out at several levels in the company with the attendant problems of conflicting information being passed to customer's staff, this is shown in figure 7.3 (node A11, A12 and A13).

- The model prompted a discussion concerning the need for drawing management and production facilities (node A12, figure 7.3) with the outcome that this activity, as far as the CEME centre was concerned, was not necessary and that drawings (hard-copy or graphics files) would be accepted directly from customers. In addition that liaison concerning designs would also not require a dedicated facility.

Outcomes from the this stage demonstrated the ability of IDEF0-3 to provide a clear analysis of current operating practices. The following steps were taken to fill some of the information gaps exposed by the analysis:

- A definition of the product was established, bills of material for each kit were produced and validated.

- Preliminary process routes for each component were designed to provide a basis for machine and capacity requirements planning. Subsequently the machine capacity requirements became part of quotation specifications for equipment vendors.

- BSD staff estimated operation and set up times in terms of machines and labour hours. Operation details such as plasma profiling times, robot weld cycle times and press brake tool change times were designed in conjunction with potential machine suppliers and existing shop floor personnel.

Many of the problems modelling exposed during the work were clearly concerned with the lack of documented information, the control of manufacturing and particularly with planning manufacturing capacity and providing shop floor schedules. As a result, the project and subsequent focus of the AS IS model shifted to develop a picture of running the CEME centre using a computer based approach for planning and controlling shop floor capacity and schedules.

7.6 THE DESIGN OF THE CEME CENTRE

The management and operational principles of the CEME centre were modelled over a series of extended site visits and meetings with senior BSD staff[1] over a two month period. The final agreed proposals for the centre are described by the model 'Run CEME centre'. The scope of the model is shown by the node tree diagram in figure 7.12 and node index in figure 7.13.

By this stage in the project, orders were being placed for mechanical handling equipment, profiling equipment and other plant on long delivery times. It was also considered important, at that stage, that the development of management and organisation of the centre took place in parallel. Consequently it was agreed that the TO BE model would be used as the primary means of establishing the characteristics of shopfloor control. The model was also intended to be used for presentations to shop floor supervisors and BSD group management.

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[1] Mr J. Backhouse, Managing Director BSD Leeds
Mr E Gibbs, Engineering Operations manager
Mr S. Hilton, Project Co-ordinator.

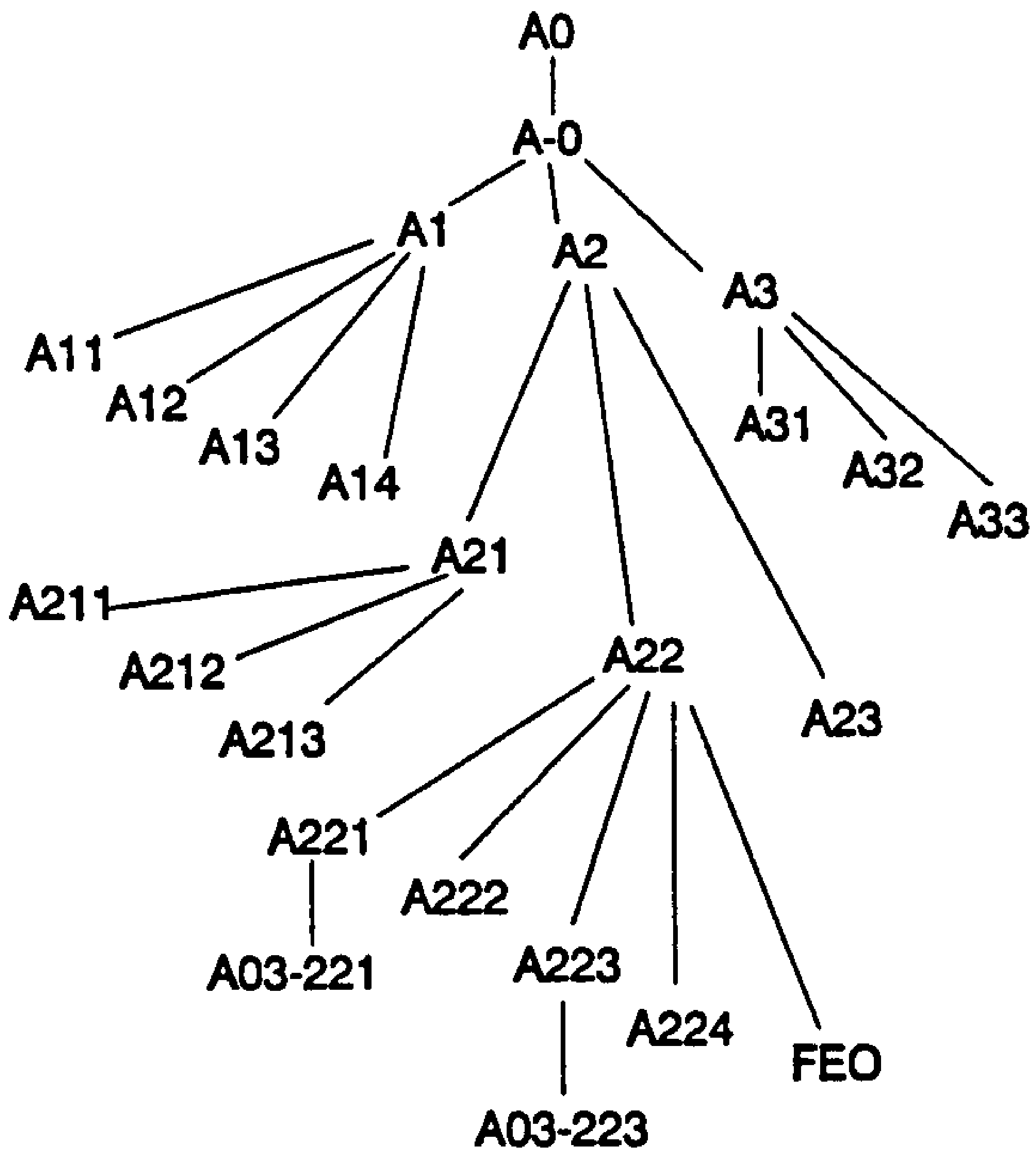
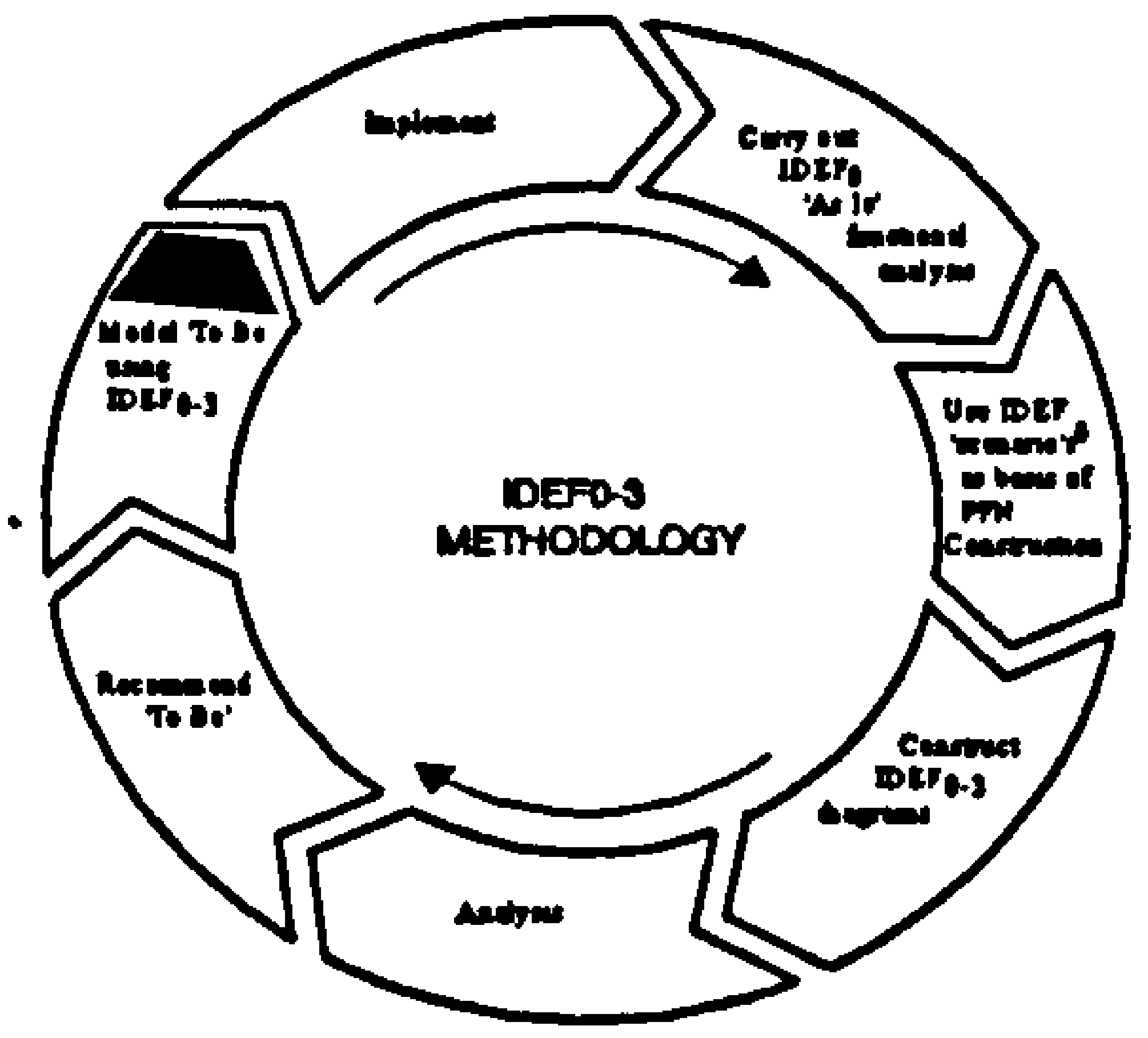


Figure 7.12 Node Tree for IDEF0-3 model 'Run CEME centre'

7.6.1 Phase 6 of the IDEF0-3 methodology

Model TO BE using IDEF0-3



The TO BE IDEF0-3 model comprises ten diagrams shown in the node index of figure 7.13.

The *purpose* of the model was to describe the operation and information requirements for control of CEME centre manufacturing and the *viewpoint* was that of operation management. The complete model is shown in figures 7.14 to 7.23. The key features of the new approach to kit manufacture using the CEME centre are described by the TO BE model:

- The CEME centre will operate as an independent manufacturing unit constrained by a unit business strategy (the details of the strategy was to be defined by BSD at board level at the time the model was produced) shown as a *control* in figure 7.14 and 7.15, node A1. The implication is that all components produced outside the centre, by BSD or outside suppliers, would be treated as sub-contract (shown as an *input* to node A0 in figure 7.14

and 7.15). Similarly all components, other than kits, manufactured by the centre would be treated as sub-contract components (shown as an *output* from node A0 in figure 7.14 and node A3, figure 7.15). Figure 7.15 shows the key activities in the centre and indicates the dedicated management and planning for activity A3 - Manufacture kits.

- Costing and planning information from (node A2, figure 7.15) will be made available to the centre management activity (node A1, figure 7.15). Costing and planning information (shown as a *control* on node A1, figure 7.15) consists of aggregate capacity and lead time information to allow realistic kit delivery dates to be discussed with customers (shown as an output - 'customer liaison'). This together with feedback from work centres ('work centre reports') will allow workable kit schedules to be produced (an output from A1, figure 7.15).

- Work centre schedules, routings and process documents will be issued by planning staff (outputs from activity A2 figure 7.15). In addition nesting information will be downloaded to profiling equipment and dispatch documents issued on kit completion (outputs from activity A2 figure 7.15). In the first stage of implementation the centre will rely on documents to record and control manufacturing. Software systems for the control of manufacturing will have be able to support bar code readers and remote terminals as input and remote screens as output in addition to paper reports. This is not explicitly described at this level in the model.

- Work centre reports (an output from activity A3 figure 7.15) will include batch manufacturing times, inspection information and scrap and rework records.

- Shop floor (work centre) performance information will be produced by activities A12 and A13 (figure 7.16). Liaison with customers and suppliers will be through the single activity (node A11, figure 7.16) and the staff involved will be the single point of customer contact.

- The activity 'Establish manufacturing schedules' (node A22, figure 7.17) provides schedules for the following outputs;
    - Plate
    - Profiling/nesting
    - Work centres
    - sub-contract machining

Graphical component data is shown as an input to A22 (figure 7.17). Clear part recognition will be provided by component profile drawings in addition to part numbers on work centre routings and component schedules.

- [A0] Run CEME centre
  - [A1] Manage Centre
    - [A11] Liaise with customers and outside bodies
    - [A12] Monitor machine performance
    - [A13] Control and monitor direct staff
    - [A14] Control and monitor finance
  - [A2] Plan manufacturing
    - [A21] Carry out manufacturing planning
      - [A211] Maintain drawings
      - [A212] Control Process info, tooling info, and NC data
      - [A213] Establish consumables requirement
    - [A22] Establish manufacturing schedules
      - [A221] Establish nesting data
      - [A222] Produce schedules and documents
      - [A223] Control work centre schedules
      - [A224] Track inventory
        - [A03-221] Establish nesting data
        - [A03-223] Control work centre schedules
        - [FE0 A22F] Establish manufacturing schedules
    - [A23] Control Inventory
  - [A3] Manufacture Kits
    - [A31] Make components and assemblies
      - [A311] Produce and finish profiles
      - [A312] Process profiles
        - [A3121] Set up for batch
        - [A3122] Run machining process
        - [A3123] Close batch
      - [A313] Configure and weld assemblies
    - [A32] Inspect components and assemblies
    - [A33] Palletise Kits for dispatch

Figure 7.13 Node index for 'Run CEME centre'

- Work centre capacities, BOMs, process routes and inventory levels will constrain shop floor schedules (activity A22, figure 7.17).

- Customer drawings will be maintained by NC programming staff, who are the primary users of contract customer drawings, to produce profiling instructions and robot welding data and part profiles for process route documents (nodes A211 and A212, figure 7.18).

- The generation of nesting data (activity A221, figure 7.19) and work centre schedules (activity A223, figure 7.19) will be an iterative process, shown by the feedback and feed-forward loops between the two activities ('rough cut profiling schedules' and 'variations to batch size' respectively).

- Inventory will be tracked (activity A224, figure 7.19) using predicted levels, inventory counting and exceptions (real time feedback from work centres).

The diagram 'Establish Manufacturing Schedules' (node A22, figure 7.19) was central to the design of the CEME centre. Therefore, as part of the TO BE model, an FEO diagram (figure 7.21) of 'Establish Manufacturing Schedules' was used to introduce the CEME centre proposals to shop floor supervisors and in preliminary discussions with software vendors.

The behaviour of two functions 'Establish nesting data' and 'Control work centre schedules' (node A223 and node A221 respectively, figure 7.19) was critical to shop floor control for the centre and both were decomposed to IDEF0-3 diagrams, figures 7.22 and 7.23. Figure 7.22 shows the relationship between the generation of nesting information and its influence on the control of work centre schedules, the three outputs from node A221 (figure 7.19) 'Plate requirement' 'Nesting information' and 'Variations to batch size' are correlated with three associated 'release' UOBs in figure 7.22. The asynchronous OR junction J1 represents the decision necessary to proceed to the one or more of the three 'release' UOBs and the 'Plan profile nests' *go-to* referent. The constraint on the decision can be correlated with the control on node A221 (figure 7.19) 'Profiling process information' which, when decomposed to J2, indicates that procedures for schedule variation and nesting together with planning horizons will be necessary. The IDEF0-3 diagram also describes the situation that in order for 'Plan profile nests' to proceed rough cut profiling schedules must be available as a result of 'Control work centre schedules' (node A223, figure 7.19). The approach adopted in the CEME centre will be to treat nesting schedules as a constraint rather than allowing them to be the driver for work centre schedules, this is described by the IDEF0-3 model.

The IDEF0-3 diagram figure 7.23 shows how the function 'Control work centre schedules' (node A223, figure 7.19) behaves. It shows the PFN initiated by a decision (junction J1) to 'Run scheduling software' or 'Use existing schedule'. The constraint on the decision is 'Changes to schedule' a control correlated with figure 7.19 (node A223). The constraint on proceeding with either UOB 3 or 4 (accepting or rejecting the schedule) is the need to balance routine or exceptional capacity with component demand and due dates. Work centre capacities and 'Component level detail Kit schedules' are the controls correlated with figure 7.19 (node A223).

A schedule can be tentative (to assess the implications of the component nests it creates) leading to the UOB - 'Release long term profiling schedule', or firm in which case the UOBs 'Establish predicted inventory levels' and 'Release short term work centre schedule' follow. The outputs from these three UOBs can be correlated with outputs from node A223 (figure 7.19). The IDEF0-3 diagram reflects the need to use rough cut profiling schedules as a constraint on 'Establishing nesting schedules' shown in figure 7.19 (node A221).

If a schedule is rejected (UOB 3, figure 7.23) the decision concerning which UOB follows is constrained by a balance between capacity, process route options and a detailed component schedule. The situation is described (in figure 7.23) by the relationship between junction J5 and UOBs 8, 9, 10 and 11 and the correlation of the controls 'Component level detail kit schedule', work centre capacities and process route options.

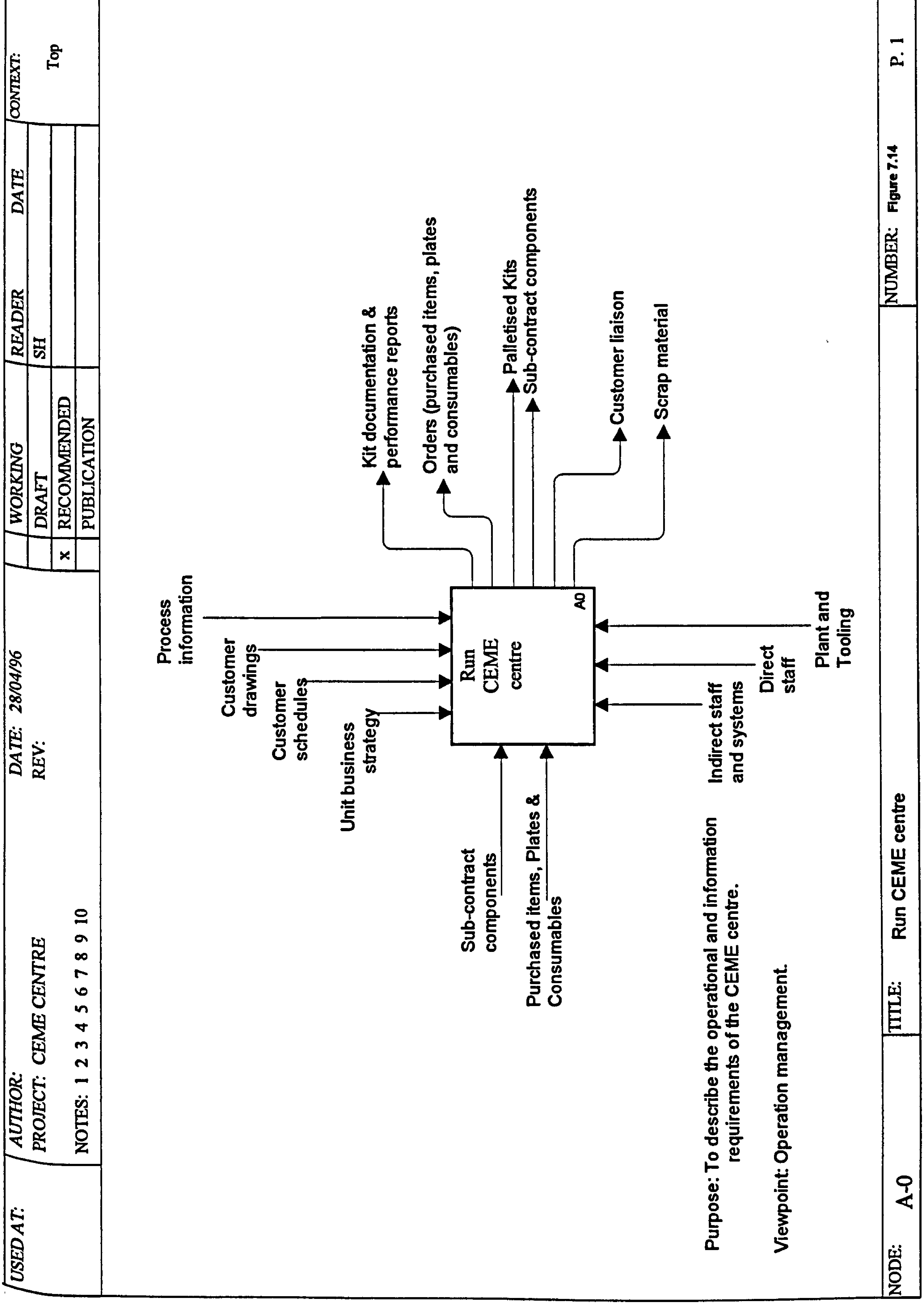


Figure 7.14 Node A-0 Run CEME centre

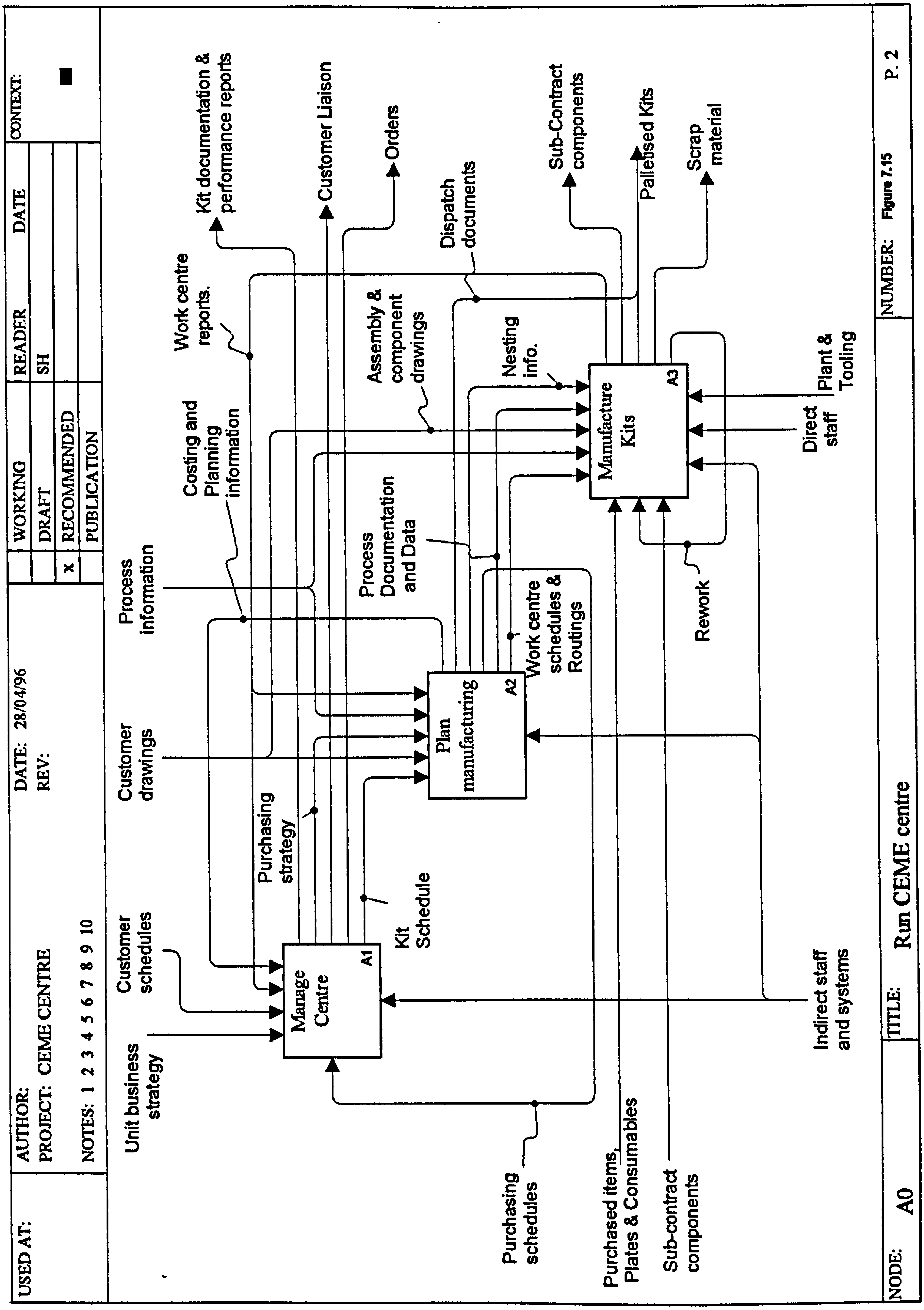


Figure 7.15 Node A0 Run CEME centre

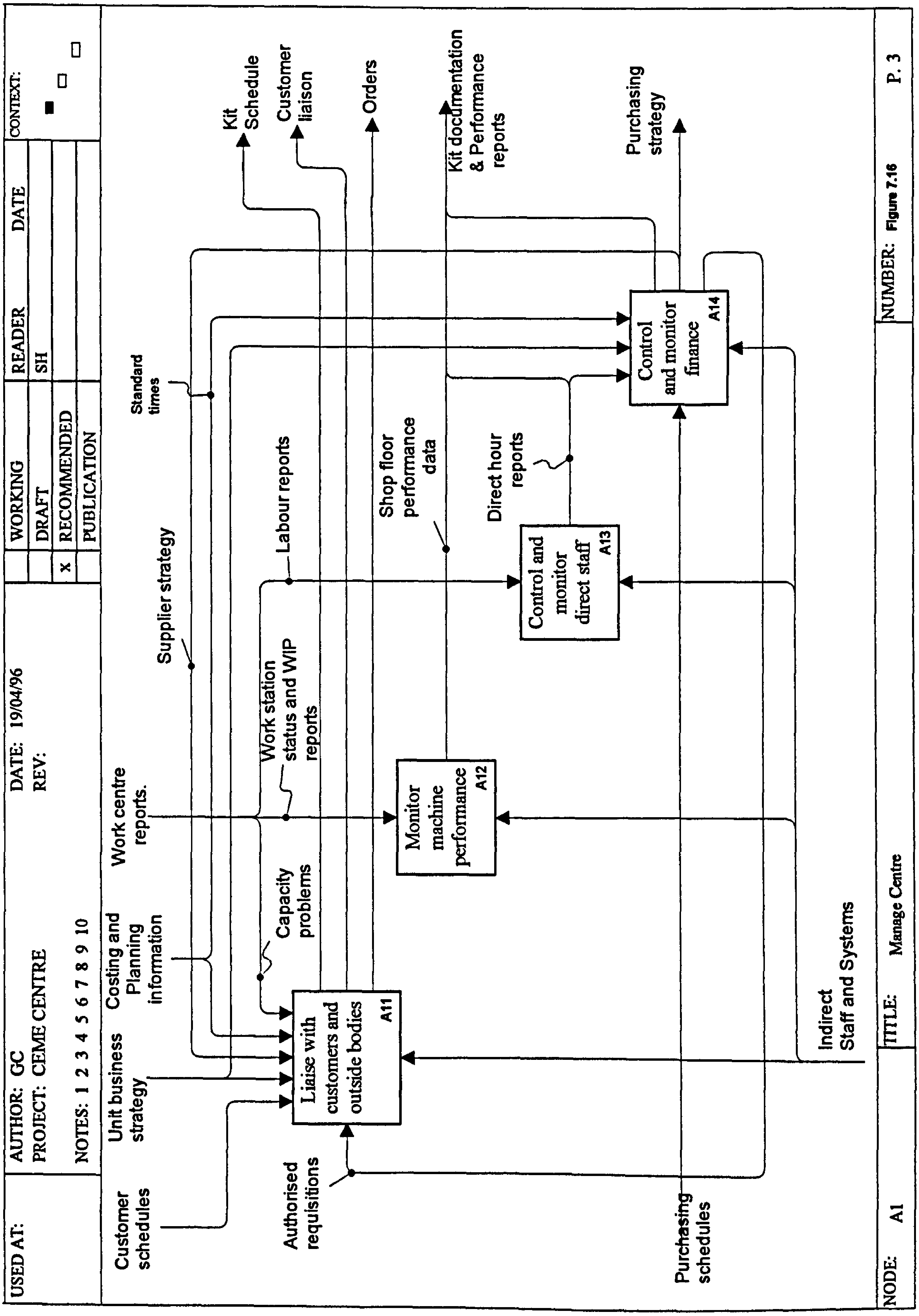


Figure 7.16 Node A1 Manage centre

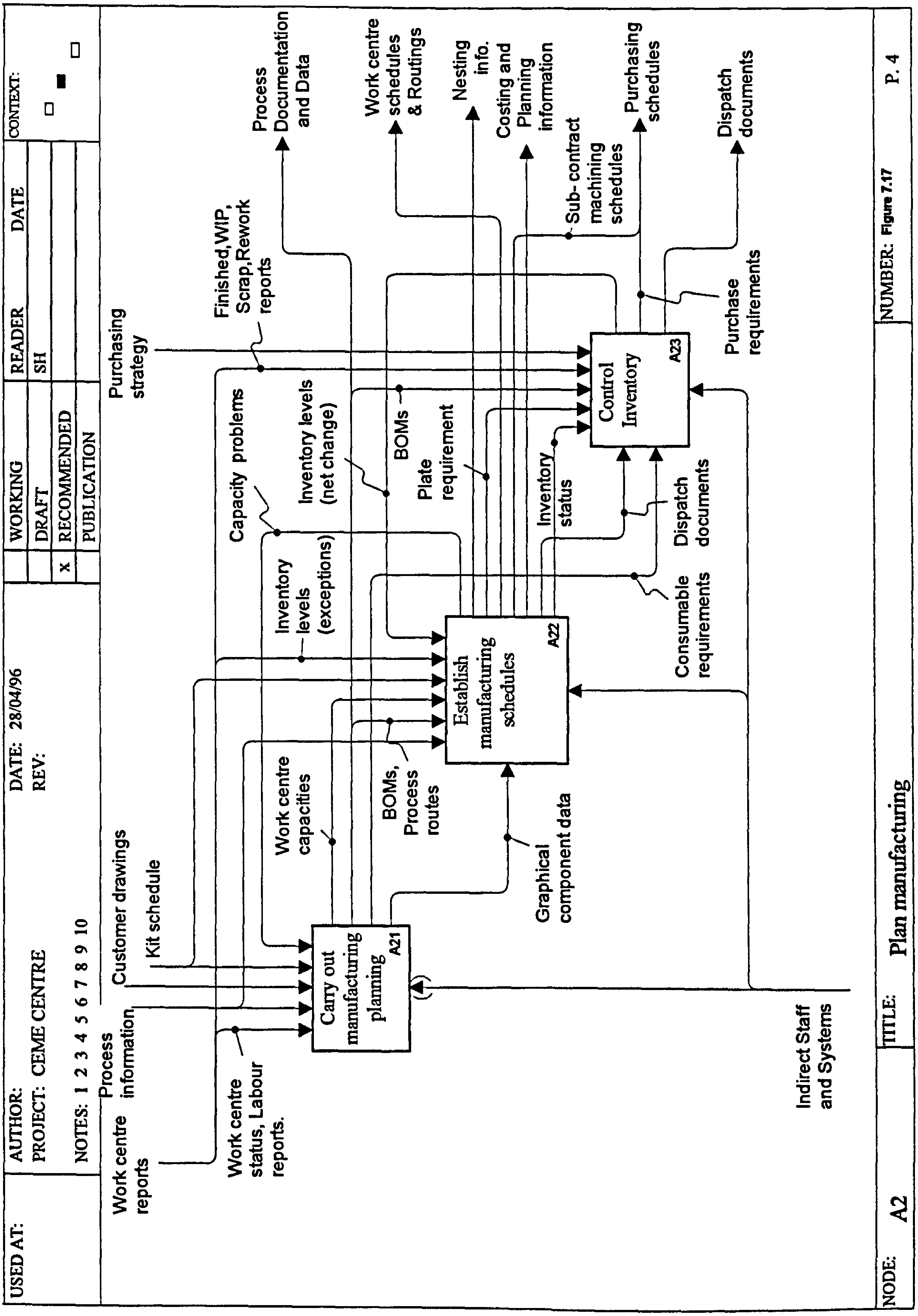


Figure 7.17 Node A2 Plan manufacturing

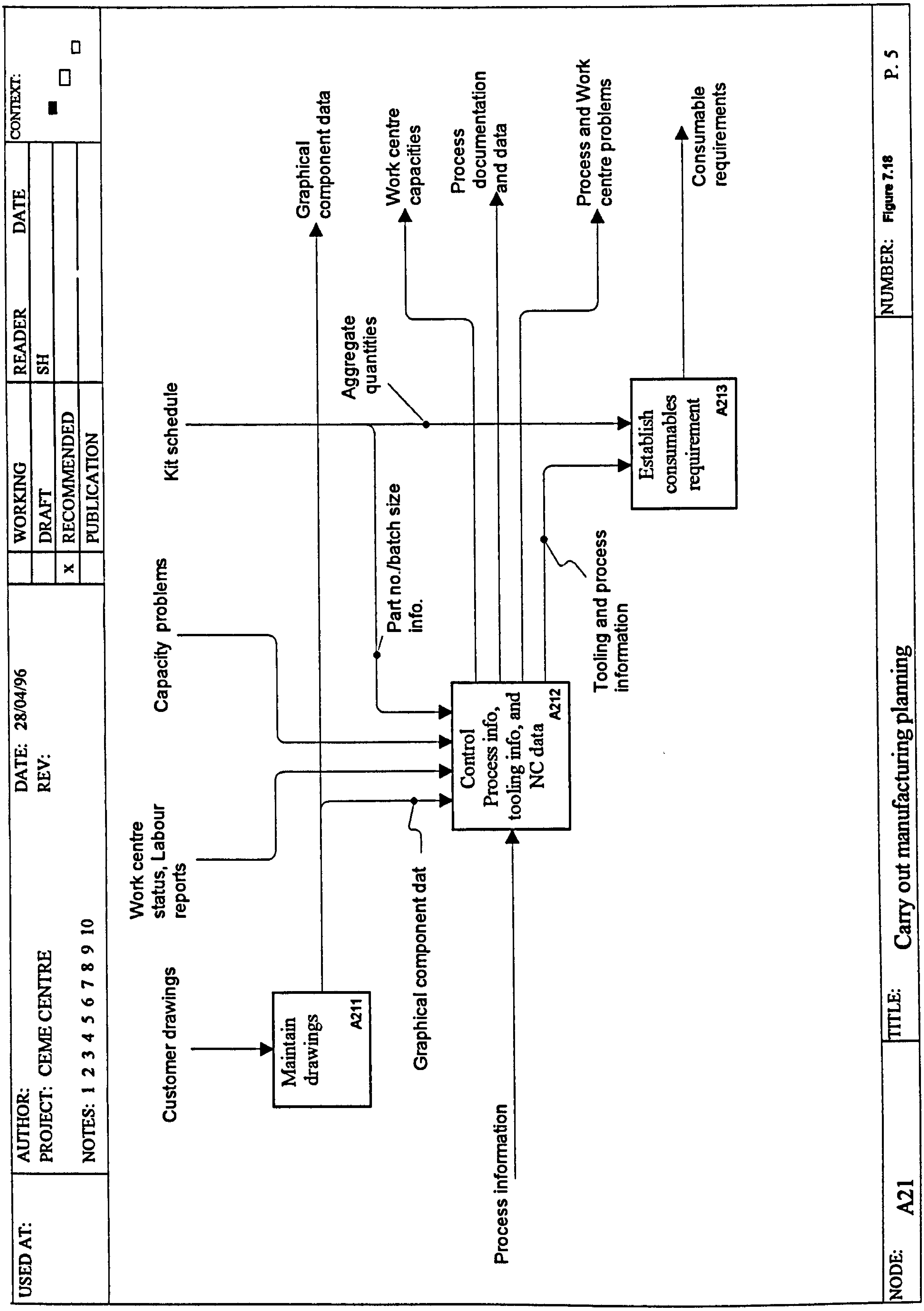


Figure 7.18 Node A21 Carry out manufacturing planning

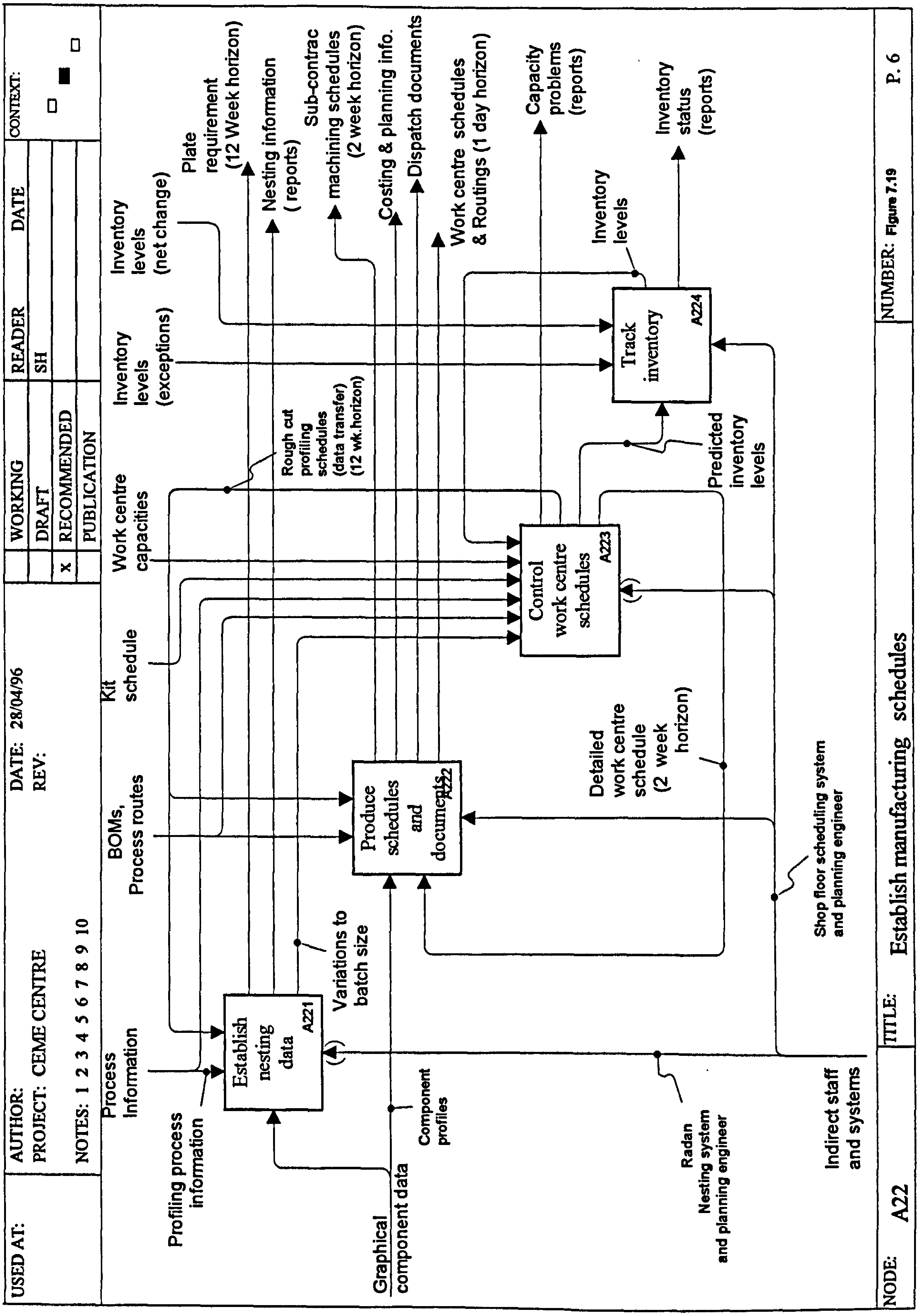


Figure 7.19 Node A22 Establish manufacturing schedules

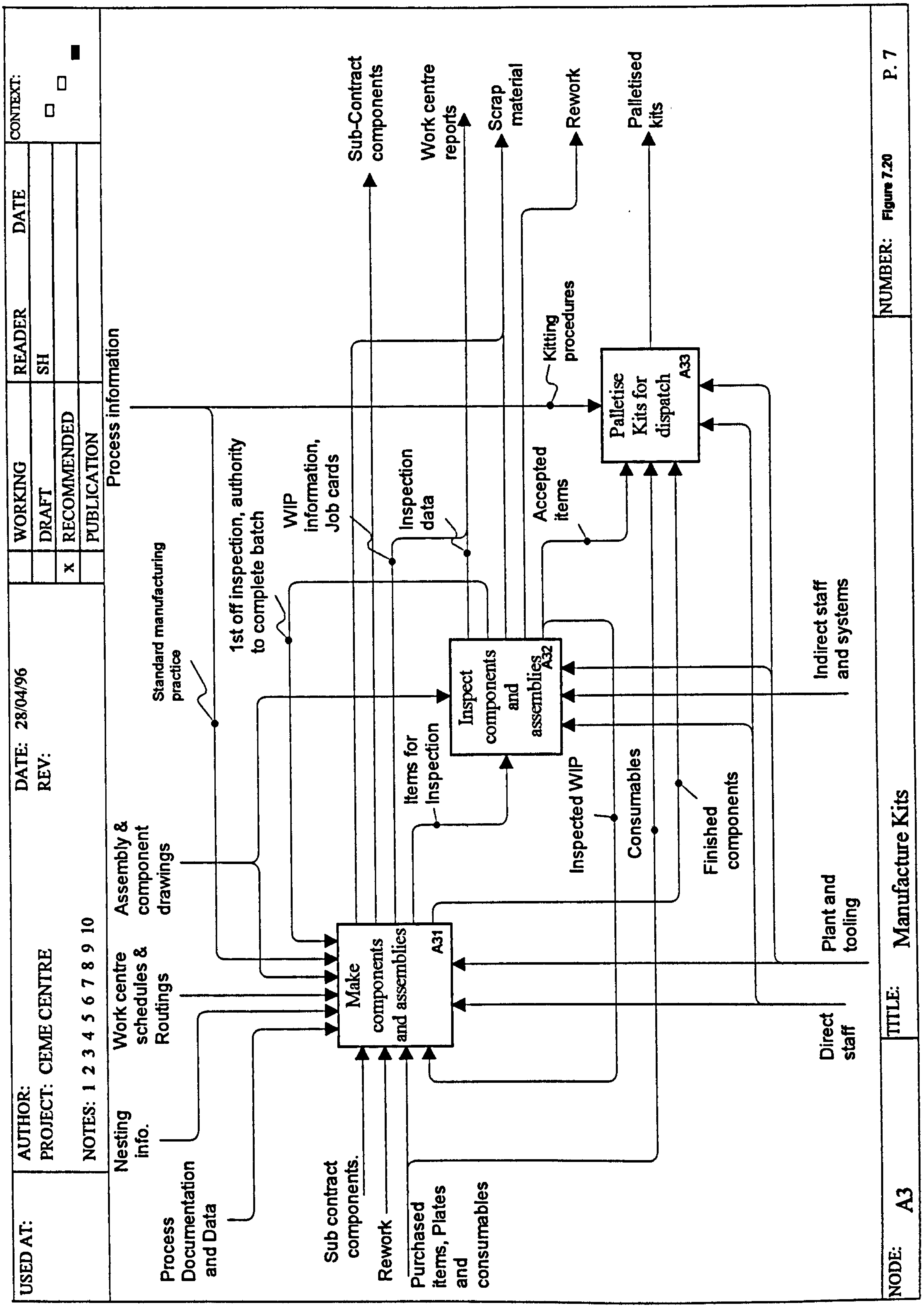


Figure 7.20 Node A3 Manufacture Kits

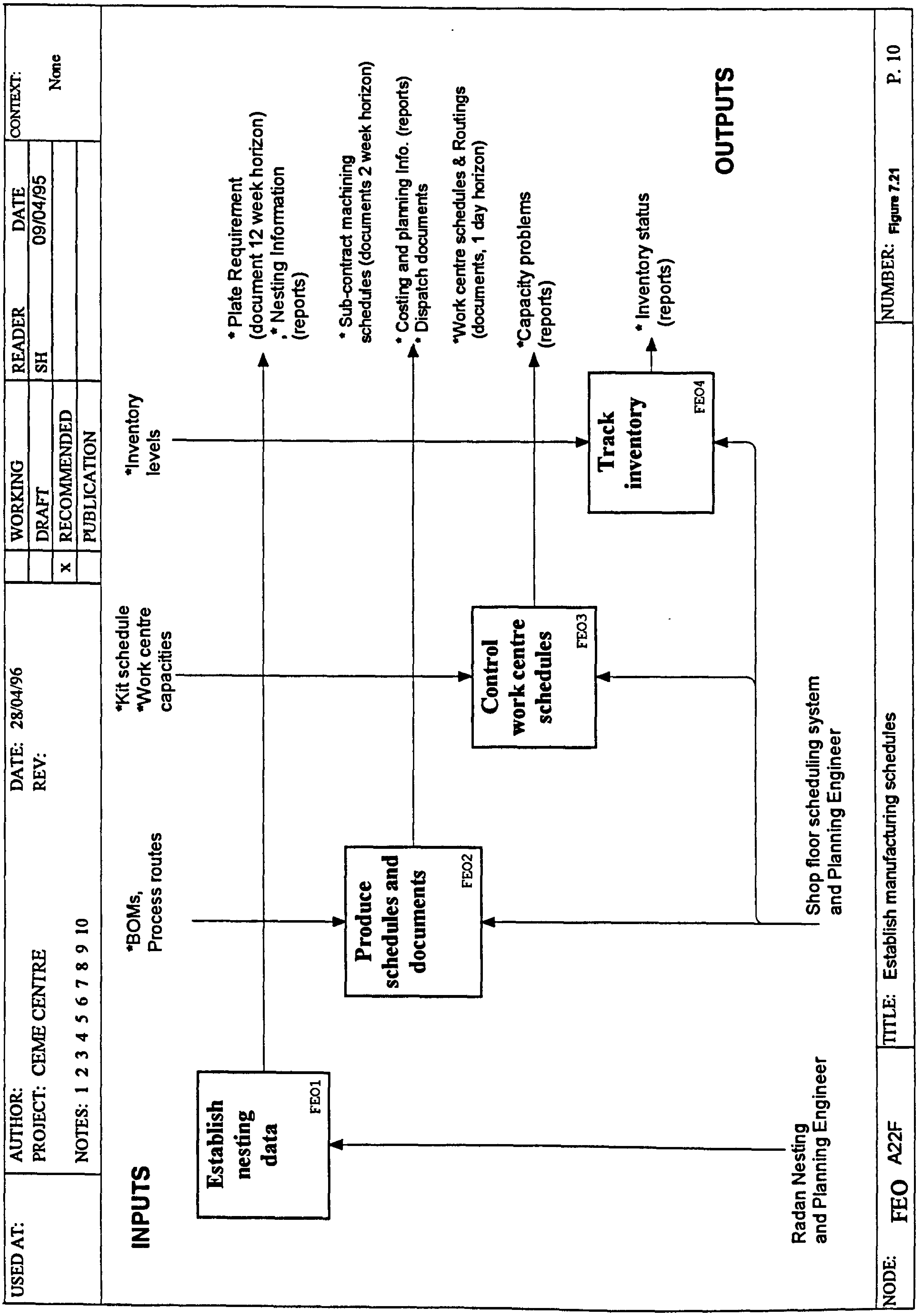


Figure 7.21 Node FEO A22F Establish manufacturing schedules

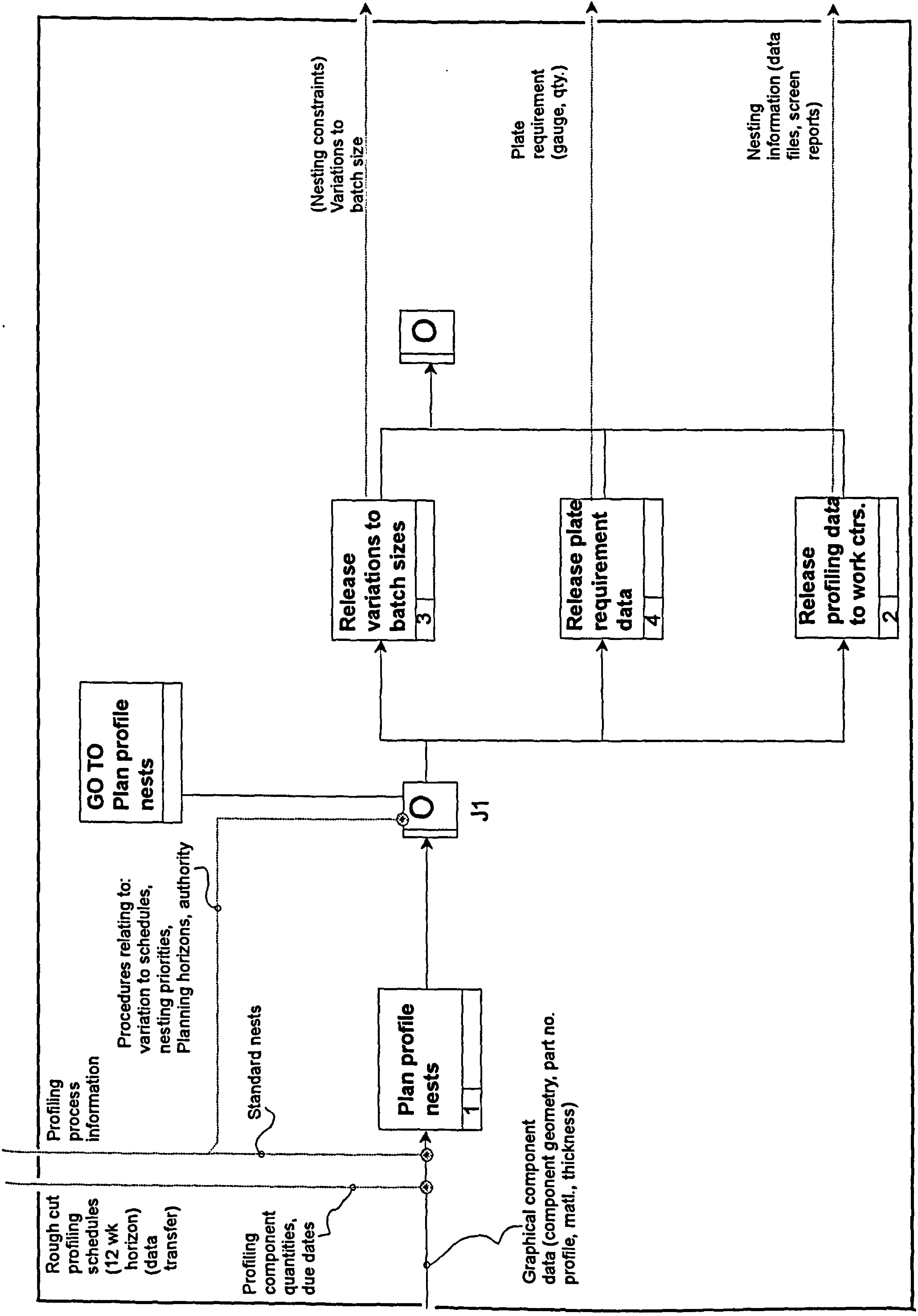


Figure 7.22 Node A03-221 Establish nesting data

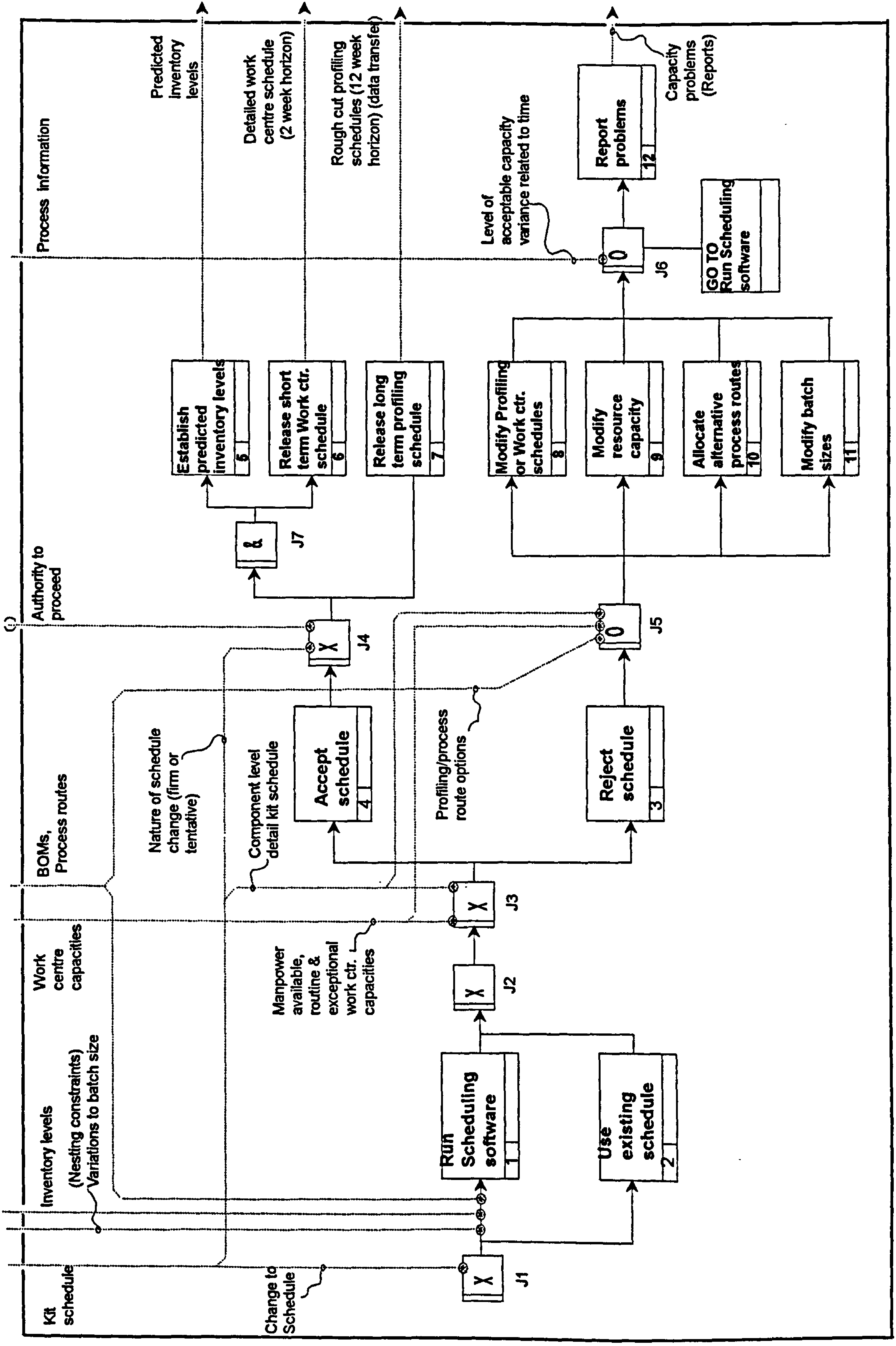


Figure 7.23 Node A03-223 Control work centre schedules

7.7 CONCLUSIONS

The final phase of the IDEF0-3 methodology involves implementation of the changes described by the TO BE model. Significant changes took place in the management of the BSD Leeds sites during 1995 and a decision to build the CEME centre at another location was taken in mid-1995. This was due in some measure to local objections to the additional noise and traffic that would result from three shift operation. Consequently system start up has been delayed. Implementation of many of the changes described by the model are currently underway (January 1996) The most significant is acceptance of the operating approach described by the TO BE model and the purchase of a shop floor control system (in November 1995) configured to support the model structure and defined in the BSD document (which is based on the TO BE model) shown in appendix 11.

The work of chapter seven has been analysed from two perspectives:

(i) The case study site.

Through the expansion of Spot and Contract manufacturing both the manufacturing staff at TIF and the BSD project team had considerable experience of plate handling plant and profiling and cutting equipment but limited experience of structured approaches to manufacturing control and of computer based approaches to shop floor control. The initial proposal to use modelling as a means of describing organisation, behaviour and information was treated with some scepticism. However as the project developed the AS IS model exposed the complexity of the existing situation and the design task ahead. Building the models, involving BSD staff as readers, and the discussions the diagrams provoked were recognised as significant to the success of the project. Two formal presentations of the case study findings and proposals were made by the author to shop floor supervisors and senior management at Leeds and one presentation was made to group management at BSD Stourbridge. Subsequently BSD adopted the proposals described by the TO BE model and incorporated them into their specification for shop floor management and scheduling. The company specification based on the IDEF0-3 model is shown in appendix 11. It relies on the IDEF0-3 model diagrams (listed in the final paragraph of appendix 11) figures 7.19, 7.21, 7.22, 7.23,) and uses figure 7.19 to describe three key activities necessary for shop floor control (defined in paragraph 1 of appendix 11). In addition a BSD produced overview diagram of 'CEME Scheduling' was used in the specification (appendix 11 sheet 5).

(ii) The application and development of the IDEF0-3 approach.

Application of IDEF0-3 relies on the proven modelling methods, $IDEF_0$ and IDEF3. It is the integration of the methods and the synergy ensuing from integration that is being tested by the case study. It was evident during modelling that the interface between the two methods revealed aspects of system behaviour in describing how $IDEF_0$ controls influenced processes and decisions and how $IDEF_0$ outputs were produced. The IDEF0-3 TO BE model, 'Run CEME centre', proved capable of incorporating and describing the recommendations from the AS IS model discussed in section 7.5.3. Using IDEF0-3 in the TO BE application, where diagram detail cannot be checked against existing systems, revealed its ability to validate the model by ensuring ICOMs in parent $IDEF_0$ diagrams and PFN structure correlate after decomposition.

It was found that all $IDEF_0$ controls are not necessarily directly related to decisions or Junctions. In such cases controls are linked to precedence arrows to indicate which aspect of process flow logic they constrain. An example is shown in the precedence logic preceding UOB 1 in figure 7.23 where the controls 'BOMs, process routes', 'Inventory levels' and 'Variations to batch size' are necessary for the UOB 'Run scheduling software' but do not influence the decision taken at the preceding Junction J1 or the alternative UOB 'Use existing schedule'.

The stage in modelling that an $IDEF_0$ function becomes a scenario for a PFN is key to the IDEF0-3 approach. For AS IS models it has proved to be, in the case studies to date, the stage in modelling where descriptions by domain experts rely on a logical narrative of events, i.e. a *sequence* rather than a description of aggregated functions. In an $IDEF_0$ diagram, at this stage, a description can become a 'waterfall' of functions indicating that functional modelling is turning into process modelling. In TO BE models the stage at which the logic of events is necessary to understand behaviour is the stage at which the interface between $IDEF_0$ ICOMs and PFNs must be described.

Decomposition of a UOB in an IDEF0-3 diagram was found to be necessary in one case shown in figure 7.9. Further decomposition of UOBs could, if necessary, be accomplished as in conventional IDEF3 modelling. Elaboration documents for UOBs and junctions were not found to necessary because the correlation of $IDEF_0$ ICOMs and PFNs gave the information necessary for model analysis and system design.

This case study gave an opportunity to refine the IDEF0-3 methodology user guide and the final version is presented in appendix 2.

CHAPTER 8

DISCUSSION, CONCLUSIONS AND FURTHER WORK

8.1 MODELLING IN MANUFACTURING ENTERPRISES

The aim of this research work has been to further the use of graphical modelling methods as a means of gaining insight, designing or improving performance in manufacturing enterprise systems. During its course it became evident that no single modelling method would be sufficient to capture the complexity of a manufacturing enterprise and that the selection and use of a method is subject to the purpose of the modelling exercise, the nature of the system being investigated and experience of the analyst. For manufacturing enterprises few methods have emerged to be generally accepted. To model the interaction of facilities, people, information and material is often so complex that a specifically designed modelling method, such as $IDEF_0$, is required. Although it only uses a simple graphical box and arrow construct with minimal model syntax its ability to model complexity is remarkable. Experience is necessary to build an effective model however, when used to communicate system descriptions, untrained users can quickly understand and interpret diagrams.

It is evident that continuous improvement and system change and development is the norm. The research concludes that the IDEF modelling methods significantly contribute to structure and guide the change process. $IDEF_0$ has advantages as a manufacturing enterprise modelling method in that it is in the public domain, it is widely understood, is well supported by software, and it has a proven record of success and has been adopted as a standard in US defence manufacturing.

Although $IDEF_0$ has been used extensively by the US defence industry its use outside is limited. The review of IDEF methods together with the survey in section 3.5 indicate that for UK manufacturing enterprises modelling is largely led by academics or consultants and that many aspects of manufacturing system design evolve from established practice. For many enterprises system models consist of disparate methods and diagrams such as discrete event simulation, CPA, DFDs, flowcharts and company specific diagrams.

The graphical representation used in a model is an expression of knowledge about the system under review, building exhaustive IDEF models consumes time and staff resources resulting in decisions being made before a model can be completed, in addition systems can change during modelling and validation. A pragmatic view is that in today's competitive, manufacturing environment it is unrealistic to expect UK manufacturing enterprises to have the time for protracted modelling programmes as a precursor to change or system design. This can be countered by using IDEF methods in a rapid, rough-cut way, diagrams can be produced quickly, in manual form if necessary, and the same model syntax can be used at a strategic or operational detail level. In this way it can be used just as effectively as for example CPA and in due course, become as universally accepted.

The use of a generic or reference model was demonstrated in section 5.3 this approach significantly speeded the modelling process but of course relies on sufficient reference models of the elements of manufacturing systems being available in the public domain. To be fully effective a standard methodology, CASE tool using standard data formats and a library of models would be necessary. Other engineering disciplines have extended the practice of using the standard library approach routinely (such as NAG library routines and retrieval (variant) process planning systems). It seems unlikely that extensive use will be made of reference models but since this aspect of the research was first published (Colquhoun and Baines, 1991) several other authors have advocated the use of reference models.

It is evident from this research that there is seldom a clear distinction between different modelling methods and there is little clear guidance or common understanding on what aspect of an enterprise particular methods are best applied. The lack of conventions and common practice for enterprise, system, or process design is in sharp contrast to product description and design where the range of modelling formats is well defined (for example graphical product descriptions are used for kinematic models, finite element models and tool path models) and the roles, scope and interfaces for the various models are commonly accepted. The manufacturing enterprise framework detailed in section 5.4 has contributed to a rational perspective of modelling methods for manufacturing methods and can contribute to their routine use.

8.2 APPARENT LIMITATIONS OF USING IDEF$_0$

The focus of the IDEF$_0$ method is on activities that transform inputs into outputs under the influence of their controls and mechanisms. Its limitations lie in its limited ability to describe the effects of controls and the timing of system behaviour. It is capable of depicting the *information* or *objects* necessary for control. The content and nature of information can be described using labels, however it cannot be used to describe how controls can affect functions or give information on their use. It does not attempt to describe the logical or consequential aspects of systems or the interaction of controls with activities or processes.

Much of the criticism levelled at IDEF$_0$ is related to its inability to represent time. However research suggests that there are three viewpoints of 'time' in manufacturing systems modelling terms.

1. The first is the passive representation where time is described by a label attached to a graphical modelling symbol as in CPA or the GRAI grid.

2. The second is where time is an integral part of the graphical representation as in discrete event simulation, where the graphical description can change over time, where, over a

time period, events (that change the state of a system) are predicted and where waiting, queuing and processing durations are considered.

3. The third is a more relaxed viewpoint (in modelling terms) where a modelling method represents the temporal aspects of a system behaviour and can capture concepts such as; after, before, during, when and until.

Fundamental to all the above viewpoints is the need to understand and describe the sequence of events processes or activities. However consideration of sequence can act as a constraint in isolating and understanding functional relationships. One of the strengths of $IDEF_0$ is that an analyst can in fact ignore 'time' and sequence and concentrate on aggregated activities. Critics of $IDEF_0$ overlook this positive aspect of the method.

In the second viewpoint it could be argued that the clarity of an $IDEF_0$ diagram would be lost if it attempted to model time, as many system aspects neither change over time or have a time related significance. In any event simulation is well served by an extensive body of knowledge, the key to providing a time aspect for $IDEF_0$ models is best accomplished by providing integration paths between an $IDEF_0$ description and existing approaches to simulation and IDEF0-3 satisfies this criteria.

The IDEF0-3 approach incorporates the best of $IDEF_0$ and IDEF3 using $IDEF_0$ at a higher level to gather aggregated functional descriptions and then using those functional descriptions as a scenario for IDEF3 PFNs where the sequence and temporal aspects of system behaviour can be described.

In the survey reported in section 3.5 and the research reported in section 3.3 it is evident that DFDs are perceived to have a similar role to $IDEF_0$ and that they are used to model manufacturing systems. The perception is perhaps because DFD approaches are more widely used in software design and are therefore considered more mature and as a result more modelling practitioners have used DFDs. $IDEF_0$ has several advantages over DFDs for manufacturing enterprise applications. The structure of a DFD has no formal layout making it difficult to see where to start reading a diagram. The box used by $IDEF_0$ to represent functions provides four faces to structure connecting arrows using the formal syntax. The circles used by DFDs do not provide this feature and a confusing crossing arrow structure can be the result, feedback arrows for example can be difficult to recognise when no positional structure exists for the bubbles used to represent processes. No limits are set on the number of processes used in a single DFD and a large number of processes on a single diagram can be difficult to understand. In addition the file and data store symbols used in DFDs are not necessarily an important modelling characteristic for manufacturing enterprise modelling.

8.3 THE CASE FOR THE IDEF0-3 METHOD

As a modelling method for manufacturing enterprises IDEF0-3 extends IDEF_0 and enables the representation of additional manufacturing characteristics in a single model. IDEF0-3 is able to represent features of a system not represented by either IDEF_0 and IDEF3 as individual models. More precise meaning can be given to controls by assigning the controls identified as necessary for IDEF_0 functions, to stages in IDEF3 PFNs. Consistency checking and model validation is also inherently achieved through the need to allocate inputs and outputs precisely to a PFN structure.

In modelling a system the first step is to capture its significant activities, system elements and important information. System description becomes more complex at an operational level where the necessity to understand behaviour is essential. In practice detailed descriptions given by domain experts rely on describing a logical flow of processes or a flow of information rather than on abstracted descriptions to describe operational detail, this re-enforces the use of a sequence description such as a PFN. The IDEF0-3 notation provides a time line for IDEF_0 functions and permits the creation of a single model that is capable of describing a greater range and depth of manufacturing system behaviour.

The IDEF0-3 approach extends modelling capability by describing:

- The influence of information or objects on processes.
- The controls and conditions for activities to initiate, stop or proceed.

- The controls necessary for decisions to take place.
- The mechanisms (staff, facilities or systems) responsible for deciding on alternative process sequences and for carrying out processes.
- The consequences for objects, information or data processed on the sequences of processes.

In this way IDEF0-3 gives a means of gaining insight, designing and improving the performance of a manufacturing enterprise system hitherto not possible.

The method (appendix 2 contains the user guide) was validated through its trial in a complex, live case study (reported in chapter 7) that tested its syntax, methodology and modelling capability. A total of six days, over a two month period, were necessary at the case study company to gather information for the model and a further fifteen days to analyse, validate and present the model to the company. The research does not draw any conclusions over the time involved for the new approach until more applications are carried out.

To build the AS-IS model it was first necessary to collect relevant information from the various domain experts then to reconcile the information into a coherent picture of the way the manufacturing system operated. Preliminary modelling starts with an incomplete understanding of the overall system, at this stage $IDEF_0$ is particularly good at forcing an analyst to identify the important features, both activities and information, using a top-down approach to describe information in a functional context. In the case study none of the staff involved had previous knowledge of IDEF modelling. Despite this diagram validation was accomplished with few ambiguities and inconsistencies and the terminology used was quickly resolved without the need for a formal glossary.

$IDEF_0$ functions become scenarios for a PFNs at a key stage in the IDEF0-3 approach. In the case study it was clear when the knowledge of domain experts was expressed as a sequential description of processes, activities or events using their relative positions in the sequence as a framework for discussion.

At this level of detail in conventional IDEF$_0$ modelling an analyst would normally have to interpret the system description and extract a functional view.

The transition from an IDEF$_0$ functional diagram to an IDEF0-3 diagram provides a behavioural description using the correlation of ICOMs and PFNs. In the case study this made it possible to understand how manufacturing was carried out in the AS IS model and how a software system could be configured to support shopfloor scheduling and operations in the CEME centre (TO BE) model. It was also found that elaboration documents for junctions and links were not necessary because the information provided by correlation provided the appropriate information.

The case study demonstrated that IDEF0-3 was capable of capturing and representing the perceptions of domain experts. The IDEF0-3 approach significantly helped the analysis of the AS IS model, to identify differences between their perceptions and resolve the model into a commonly agreed system description. The AS IS had sufficient resolution to allow meaningful analysis and provided the basis for developing the TO BE model. The indications are that the model minimised distortion of the system description to fit the characteristics of the modelling syntax.

The arrow structure flowing from left to right in a PFN, is intuitive helping IDEF0-3 model diagrams to be used as the basis of communication between the system participants and the analyst without the need for an extensive knowledge of the modelling method. It has been evident in all the modelling undertaken throughout the research that it is important to minimise the number of diagrams for a model to be accepted and deemed credible by non-modelling staff. The IDEF0-3 approach does minimise model size.

8.4 FURTHER WORK

This research is being extended in two areas:

(i) Using EPSRC-CDP funding (grant Reference GR/K39400) the research described in chapter three and four is being extended to distil current best practice approaches in modelling methods for manufacturing enterprises. The research aims to:

- Establish the extent of the UK user base for graphical modelling methods applied to the analysis and design of manufacturing systems .
- Categorise the type and nature of application and industry and to capture best practice.
- Report on the effectiveness, benefits, resource implications, application time span and training necessary.
- Disseminate findings and produce a video and manual for exploiting the methods to their full potential.

The first phase of the project, started in 1995, was a national survey of manufacturing companies to primarily identify a group of manufacturers using modelling methods and to provide an indication of which methods are being used, the types of manufacturing system being modelled, the characteristics of industrial users, the barriers to use and to establish measures of success for application. Following the survey a series of longitudinal and snapshot case studies will be used to monitor the way that UK manufacturers use modelling methods in the change process in their organisation. In parallel similar case studies in companies not using modelling methods will provide a basis for comparison. The final phase of the work will disseminate the findings through a manual and video based on a methodology, application guide and best practice case studies. Preliminary results are being published (Small, Baines, and Colquhoun, 1996, Baines, Small, and Colquhoun, 1996).

(ii) It is necessary to build a number of models using the IDEF0-3 method. To this end, again using EPSRC-CDP funding, another case study site is being considered where the method will be used in an automotive body blanking plant currently under construction. The plant has no established procedures or working practices and the method will be used by personnel having no previous involvement in its development.

In more general terms the following further work has been identified or has arisen from this research:

The development of a software tool to support IDEF0-3, to reduce the time involved in diagram production, to provide syntax checking and for the method to be more acceptable to industry. Integration with existing $IDEF_0$ and IDEF3 software tools would be a requirement to allow import and export of existing models and to be compatible with modelling standardisation (Cauthorn, 1993).

The author / reader validation, control and management of models generally has not been extensively researched yet this aspect of modelling was found to be of critical importance. For manufacturers to gain confidence in the validity and effectiveness of models and to contribute to the success of manufacturing enterprises, model validation will need further attention.

Similarly little attention is given to the analysis of complete models. No evidence was found of structured methodologies being extended to incorporate analysis and interpretation, phases which often rely on value judgements being made. The structured nature of finished models has the potential to lend itself to the development of a set of generic rules or guidelines related to the characteristics of diagrams that could flag potential system problems or solutions.

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APPENDIX 1

PAPERS PUBLISHED IN THE COURSE OF THE RESEARCH

Publications directly related to the research (abstracts are presented in appendix 12):

Colquhoun, G. J., Gamble, J. D., and Baines, R. W., 1989, The Use of IDEF$_0$ to Link Design and Manufacture in a CIM Environment, *International Journal of Operations and Production Management*, 9 (4), 48-65.

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APPENDIX 2

THE IDEF0-3 METHODOLOGY USER GUIDE

CONTENTS

A2.1 INTRODUCTION

In developing IDEF0-3 to contribute to enterprise improvement, to gain acceptance as a routine management tool and to promote the use of modelling in manufacturing, certain features were considered desirable:

- *It must describe an aspect or aspects of an enterprise in a way suitable for managing change in manufacturing where a knowledge of functional structure and process behaviour are desirable prior to a change or enhancement.*

- *It must be capable of capturing and representing the perceptions of participants in a system in a way that makes it possible to identify qualitative or quantitative differences between those perceptions. This ability is necessary if a method is to have sufficient resolution to allow meaningful analysis and to provide the potential for optimisation. The method should also be capable of aggregation and decomposition but should not encourage the distortion of a system description to fit the characteristics of the method.*

- *The model and its diagrams should be simple enough to be used as a basis of communication between system participants and the analyst. The method needs, in its* *initial form, to be graphical, capable of being produced with or without a CASE tool and use a minimal number of diagrams to complete a model. For intuitive use simple graphical constructs are required negating the need for an extensive knowledge of the modelling technique.*

- *The method should require minimal time to gather the information necessary to construct diagrams, to build models and to validate and analyse them.*

- *It should be useful in the change process in allowing decision making to take place using more complete and realistic information. The model must facilitate analysis and evaluation to assist in predicting the performance and behaviour after a change has been implemented.*

The IDEF0-3 approach provides these features by using the strengths of the $IDEF_0$ and IDEF3 methods and by correlating $IDEF_0$ and IDEF3 diagrams. In the IDEF0-3 methodology no changes are made to the established techniques or syntax used by $IDEF_0$ and IDEF3 diagrams (those documented in US Air Force, 1981a, and Mayer, et al, 1992a respectively). This user guide is concerned only with defining the concepts and rules for the correlation of $IDEF_0$ and IDEF3.

A2.2 IDEF0-3 MODELLING CONCEPTS

The IDEF0-3 method can be used to model systems in manufacturing enterprises that can include combinations of software, hardware, machines, facilities, objects and people. For existing systems IDEF0-3 can be used to investigate and understand functional structure and aspects of behaviour. For new system design it can be used as a common understanding or blueprint for organisational or system implementation.

By applying the method a model consisting of a set of diagrams is produced. The model comprises $IDEF_0$ diagrams and IDEF3 Process Flow Networks (PFNs) cross-referenced (correlated) using IDEF0-3 diagrams. If necessary a model can also include text descriptions such as the 'page pair' for $IDEF_0$ diagrams and 'Elaboration Documents' for IDEF3 diagrams. In addition a node index or node tree can be used to describe model structure.

An IDEF0-3 model separates a system into its constituent parts using structured decomposition to ensure relationships between all the parts are maintained and traceable. The initial diagrams in a model are the most general, aggregated (i.e. most abstract) description of the system. $IDEF_0$ diagrams are used for the higher level diagrams to describe functional detail and the relationships of the information or objects that functions use, need or produce. The analyst applying the method must decide at what stage in the $IDEF_0$ decomposition process it is necessary to understand behavioural aspects of the system. It is at this stage that the correlation of $IDEF_0$ and IDEF3 PFNs using IDEF0-3 diagrams takes place.

At this stage, functions (boxes) in $IDEF_0$ diagrams can become 'scenarios' for PFNs. In $IDEF_0$ a function is characterised by an active verb phrase, in general terms - 'do something' as shown in figure A2.1. The verb can be specific, such as, measure, assemble, select, or conceptual such as, evaluate, develop, resolve.

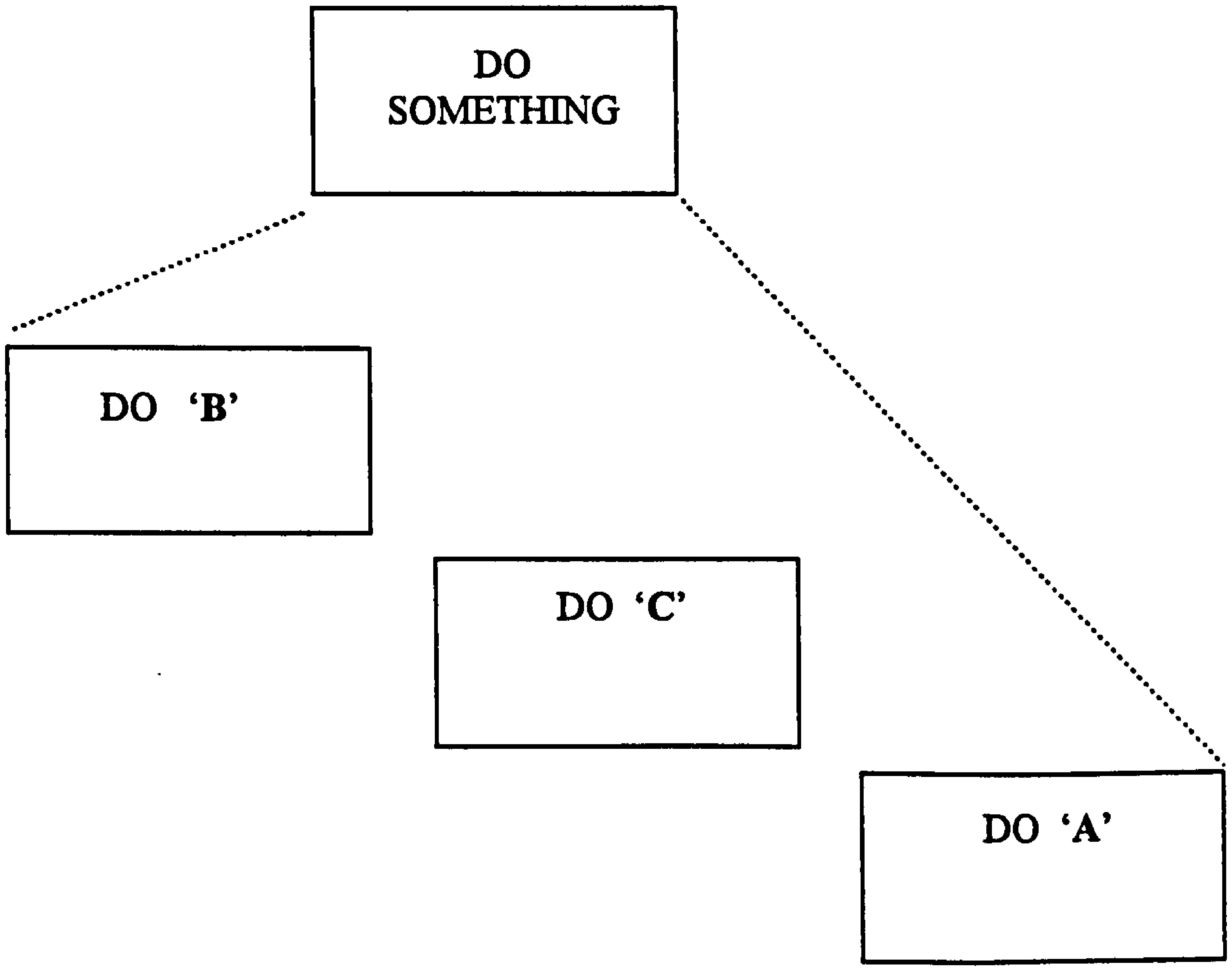


Figure A2.1 $IDEF_0$ decomposition

Figure A2.1 shows conventional IDEF$_0$ functional decomposition where the functions **B, C** and **A** are shown as the constituent functions of 'do something'. No sequence is inferred by their relative position, the diagram simply describes the situation that 'do something' involves functions **B, C** and **A**.

If it is necessary to understand not just the functional relationships but also the behaviour of 'do something', decomposition of the function to a PFN is necessary to describe *how* 'do something' is carried out, figure A2.2 shows the decomposition. In this case **A** and **C** are carried out concurrently and start at the same time. They must be completed, but not necessarily at the same time, before **B** can be started. In this decomposition the aggregated function 'do something' has been described as a set of sub-processes related by a sequence.

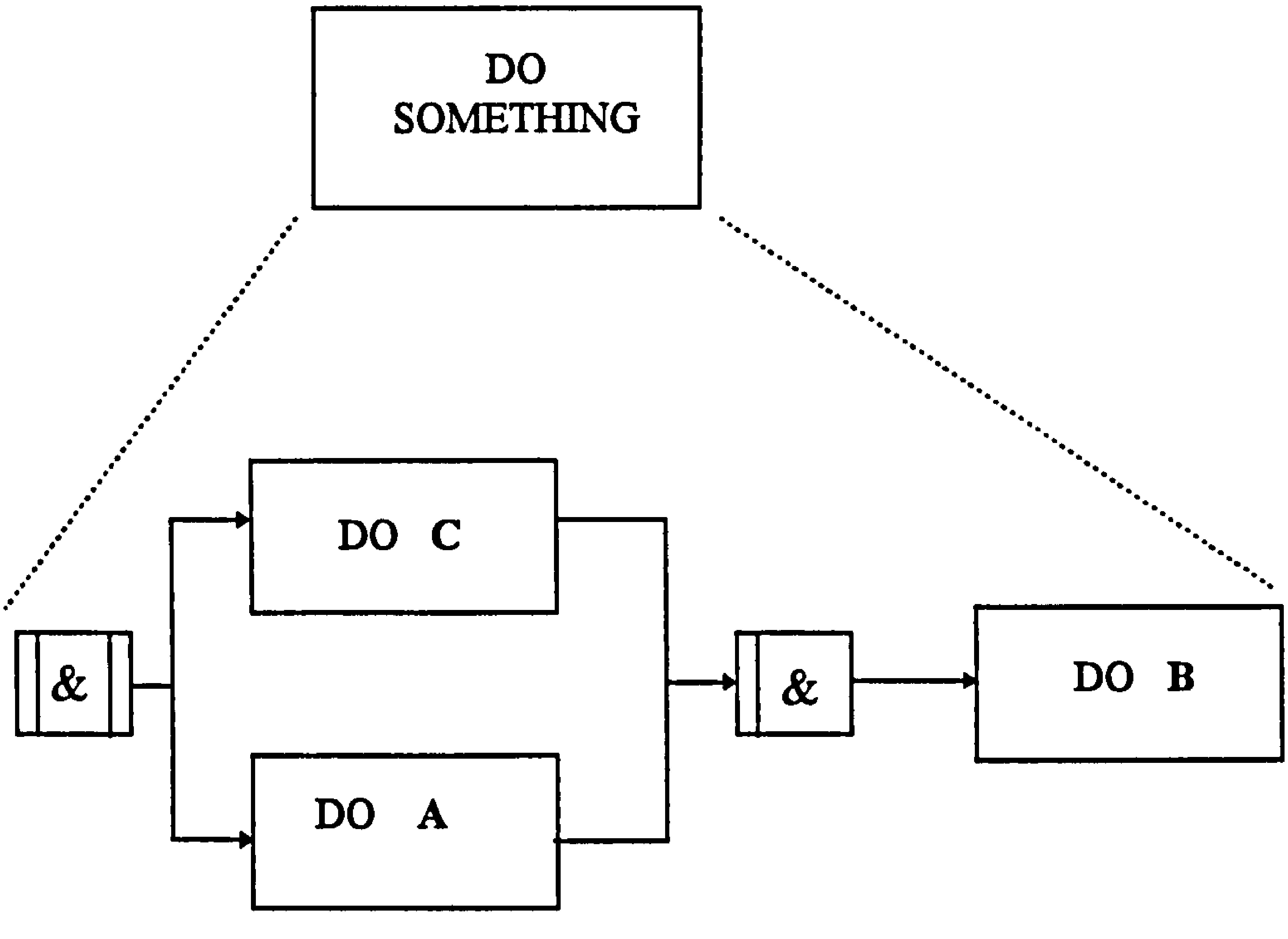


Figure A2.2 IDEF$_0$ to PFN decomposition

A2.3 BUILDING IDEF0-3 MODELS

An IDEF0-3 model is a set of diagrams together with any necessary supporting documentation. A model begins with a viewpoint and purpose declaration and a conventional $IDEF_0$ context diagram. The single box context diagram is then decomposed successively into more detailed $IDEF_0$ diagrams until the stage where it is necessary to understand or describe behavioural aspects of the system under review.

This stage could be after one $IDEF_0$ decomposition level or after many levels. Experience with the method to date has shown that this stage is characterised by: (i) a domain experts description moves away from aggregated descriptions to become a sequential narrative (i.e. first we do this, then we wait for A, then X arrives), (ii) the use of $IDEF_0$ to describe the system is becoming difficult because of the need to force aggregation on a real situation in order to describe it with $IDEF_0$ syntax or (iii) simply that a detailed understanding of behaviour is required.

At this stage IDEF0-3 syntax and rules are used to correlate $IDEF_0$ and IDEF3 diagramming conventions.

A2.3.1 ICOM DECOMPOSITION IN AN IDEF0-3 MODEL

$IDEF_0$ functions (boxes) represent related sub-functions. The sub-functions can perform various aspects of the larger aggregated function under different circumstances, using different combinations of inputs and controls and producing different outputs. Using correlation rules and syntax IDEF0-3 describes the different activations of the higher level box using an IDEF0-3 diagram.

- **INPUTS and OUTPUTS**

INPUT arrows shown entering the side of an IDEF$_0$ box are symbols representing data, information, objects or anything that can be described by a noun phrase. INPUTS are necessary to carry out the function and when the function is performed the INPUT is converted (or processed) into an OUTPUT shown by an outgoing arrow on the right hand side of a box. Figure A2.3 shows a parent IDEF$_0$ box with a detailed PFN which can be considered to fit inside the parent box.

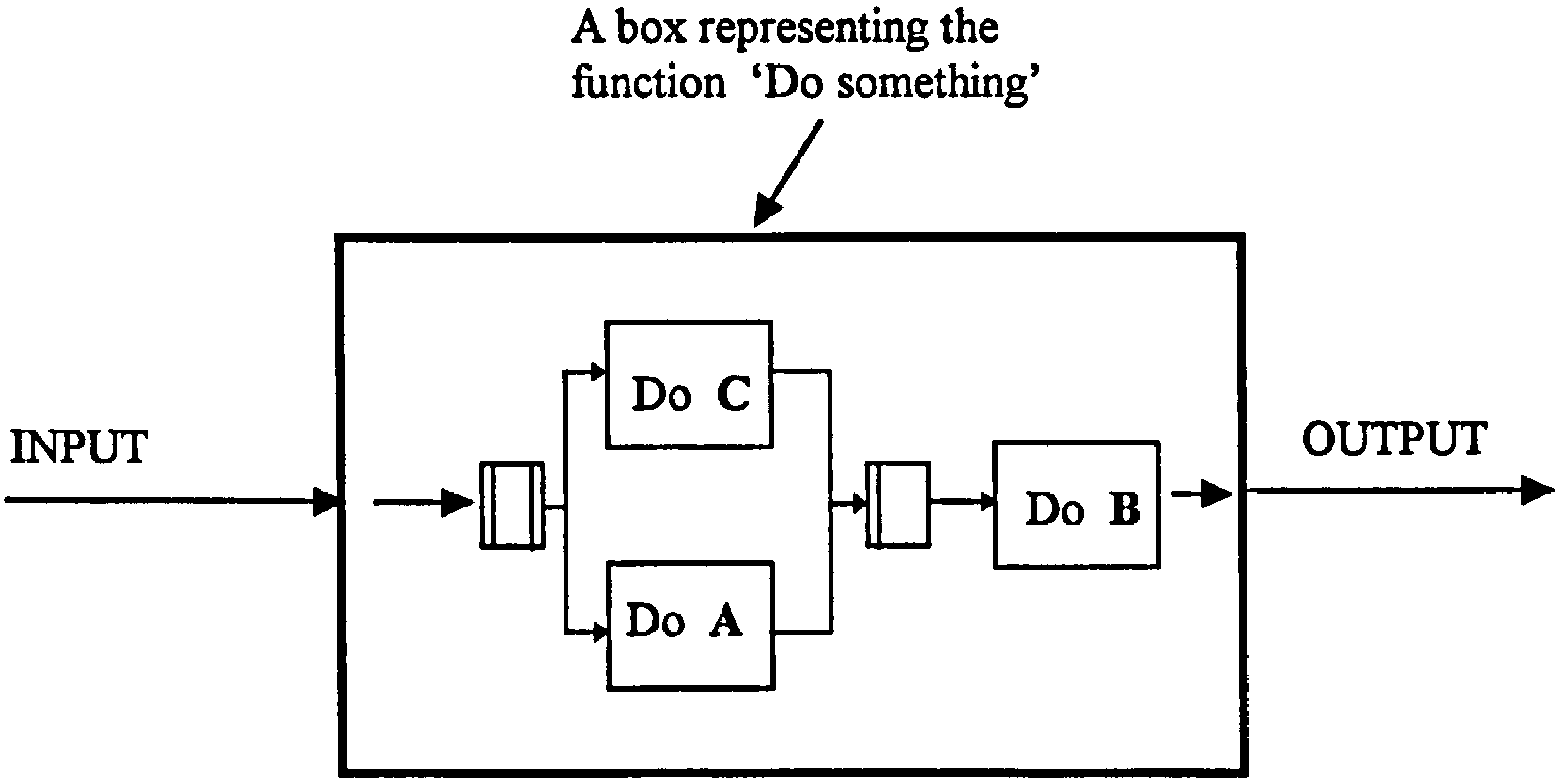
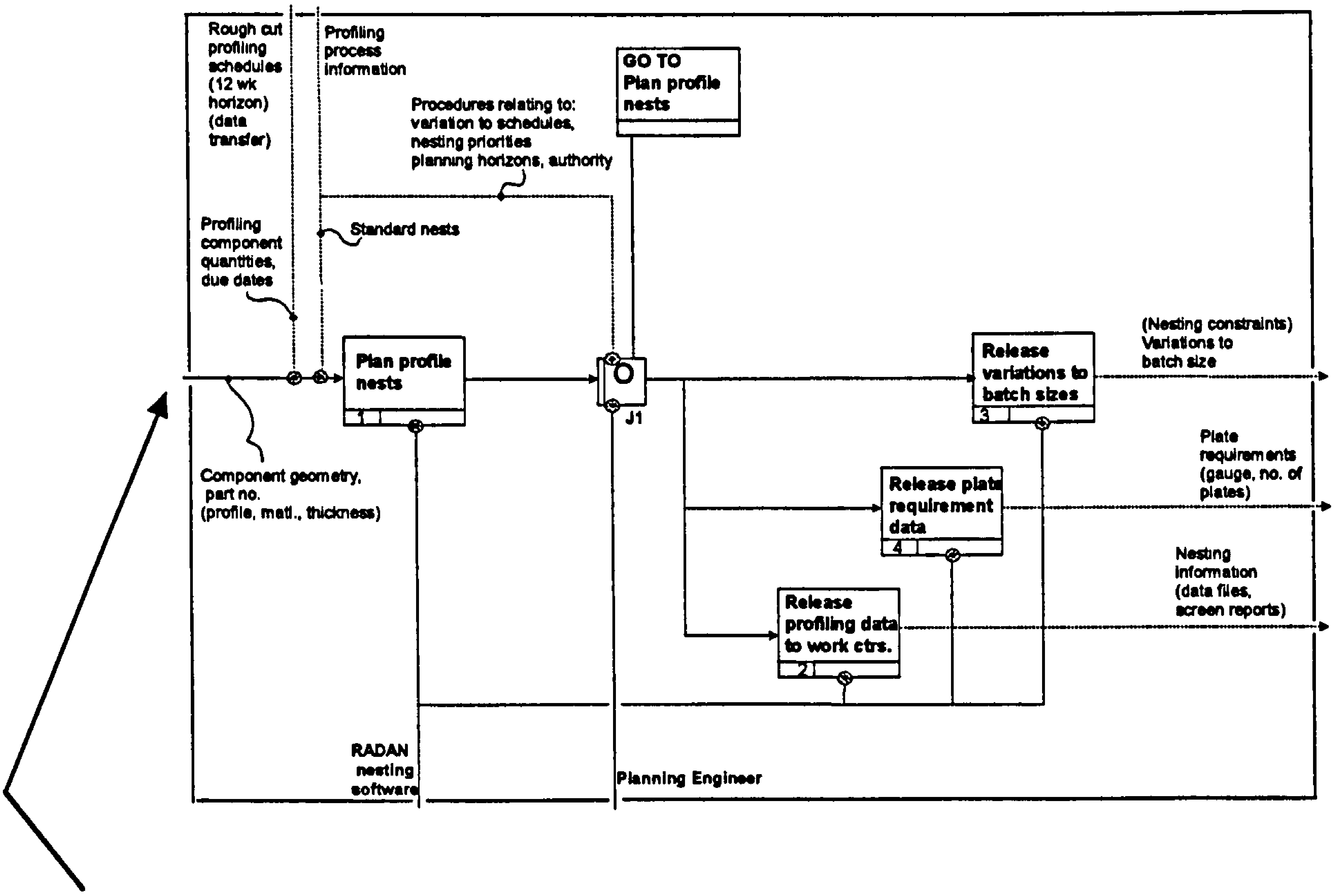


Figure A2.3 IDEF$_0$ parent and PFN child

In figure A2.3 C and A are processes or UOBs that take part in the transformation of INPUT to OUTPUT they are therefore necessary for the processes to be initiated. To describe this the input is shown on an IDEF0-3 diagram as a labelled arrow entering the junction horizontally. The arrow enters or leaves through a 'gate' on the border of an IDEF0-3 diagram to indicate a correlation with a higher level IDEF$_0$ diagram. An example of an IDEF0-3 diagram is used to illustrate this feature in figure A2.4. In an IDEF3 model a

PFN starts with a single junction or process and no separate PFNs are described in a single diagram.



An input 'gate' used to indicate the correlation of the higher level IDEF$_0$ input 'Component geometry, part no.' with the process 'Plan profile nests'

Figure A2.4 An IDEF0-3 diagram

Similarly OUTPUTS in a parent IDEF$_0$ diagram are produced by a process or sequence of processes, so any sequence of processes can be correlated with an output in the parent IDEF$_0$ diagram. This is shown in figure A2.3 where the output from the 'Do something' box is correlated with the sequence of processes culminating in process B. Figure A2.4 shows an IDEF0-3 diagram and the use of output 'gates' to indicate the correlation. In this case there are three terminating processes, each one has an output which has been described by the parent IDEF$_0$ diagram. Terminating processes are the last process in sequences, figure A2.5 shows three types of terminating processes. The absence of an output from a terminating process would flag either a correlation problem (such as; is there an output in the parent IDEF$_0$ diagram? is the process description valid?) or a potential anomaly in the system under investigation.

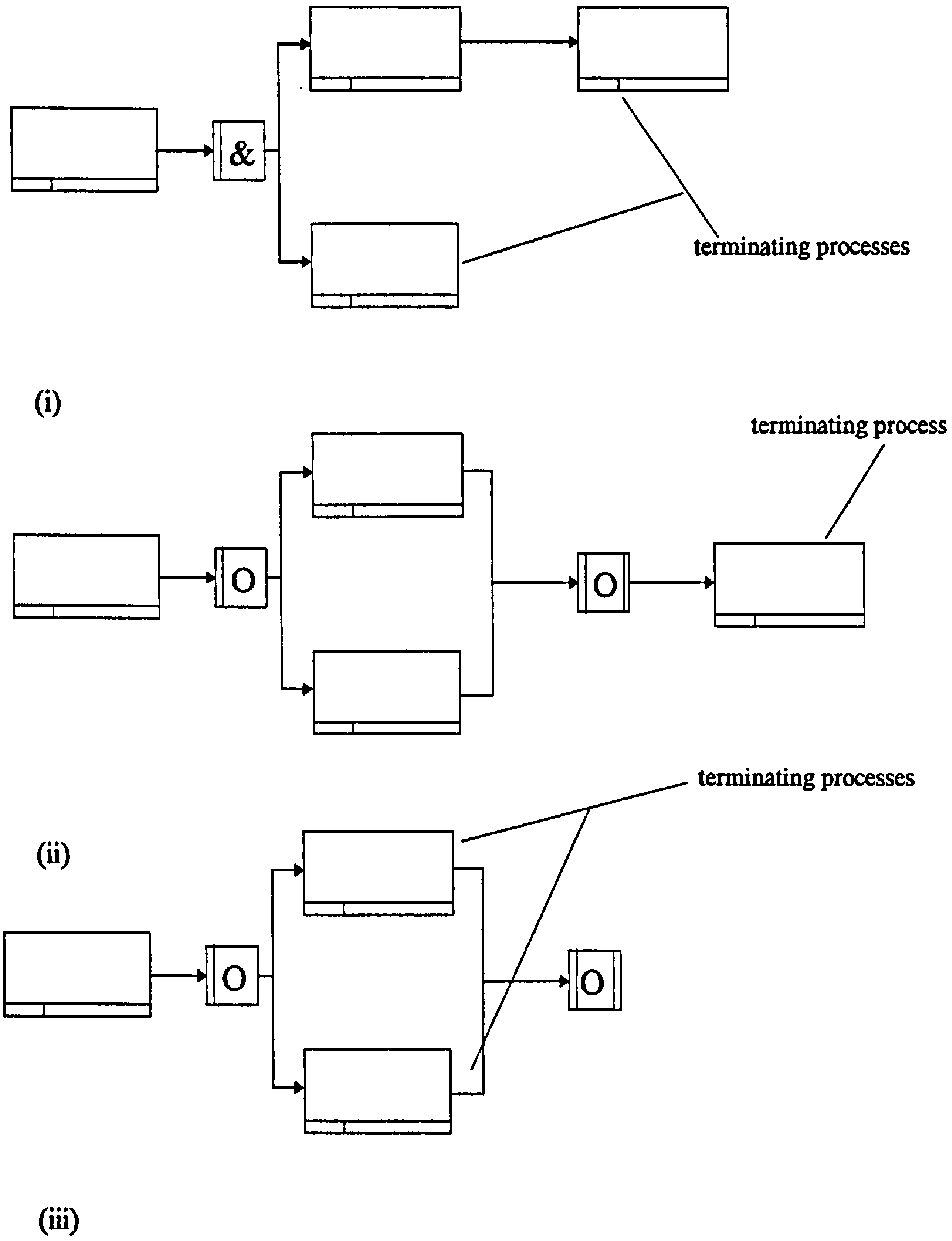


Figure A2.5 Types of terminating processes

- **CONTROLS**

In an IDEF$_0$ diagram a control is distinguished from an INPUT by the assumption that *an arrow is a control unless it obviously serves only as an input*, any function must have at least one control. To correlate control arrows between a parent IDEF$_0$ diagram (or scenario) and IDEF0-3 diagrams the controls are examined in terms of their influence on junctions (decisions) and processes.

In an IDEF3 diagram junctions describe the logic of process branching which can be either, a process that splits into two or more process paths (fan out junctions), or two or more process paths converging into a single path (fan in junctions). Junctions can be AND (&), OR (O) or Exclusive OR (X) and synchronous or asynchronous process actuation and completion is represented by the junction symbol. For example in figure A2.5 (i) the fan out junction is an asynchronous AND junction describing the situation where the two following Processes do not start simultaneously. In figure A2.5 (iii) the asynchronous OR fan out junction describes the situation where one or both of the processes will start, and the synchronous OR fan in junction indicates that the processes will complete simultaneously.

To correlate IDEF$_0$ and IDEF3 PFNs in an IDEF0-3 diagram it is necessary to connect IDEF$_0$ controls with processes or junctions in the IDEF3 PFN. The syntax used is shown in figure A2.6. The IDEF0-3 diagram controls (dotted lines) are shown entering through 'gates' in the border that connect with either a fan out junction or a link. The diagram describes a situation where:

- When the process 'W' is completed, the information, objects or data summarised by control 'A' must be available for the process 'X' to proceed.

  and
- before either process 'Y' or 'Z' (or both processes) can proceed the information, objects or data in the control 'B' must be available and will influence the logic described by the OR junction, i.e. will influence whether either or both processes occur.

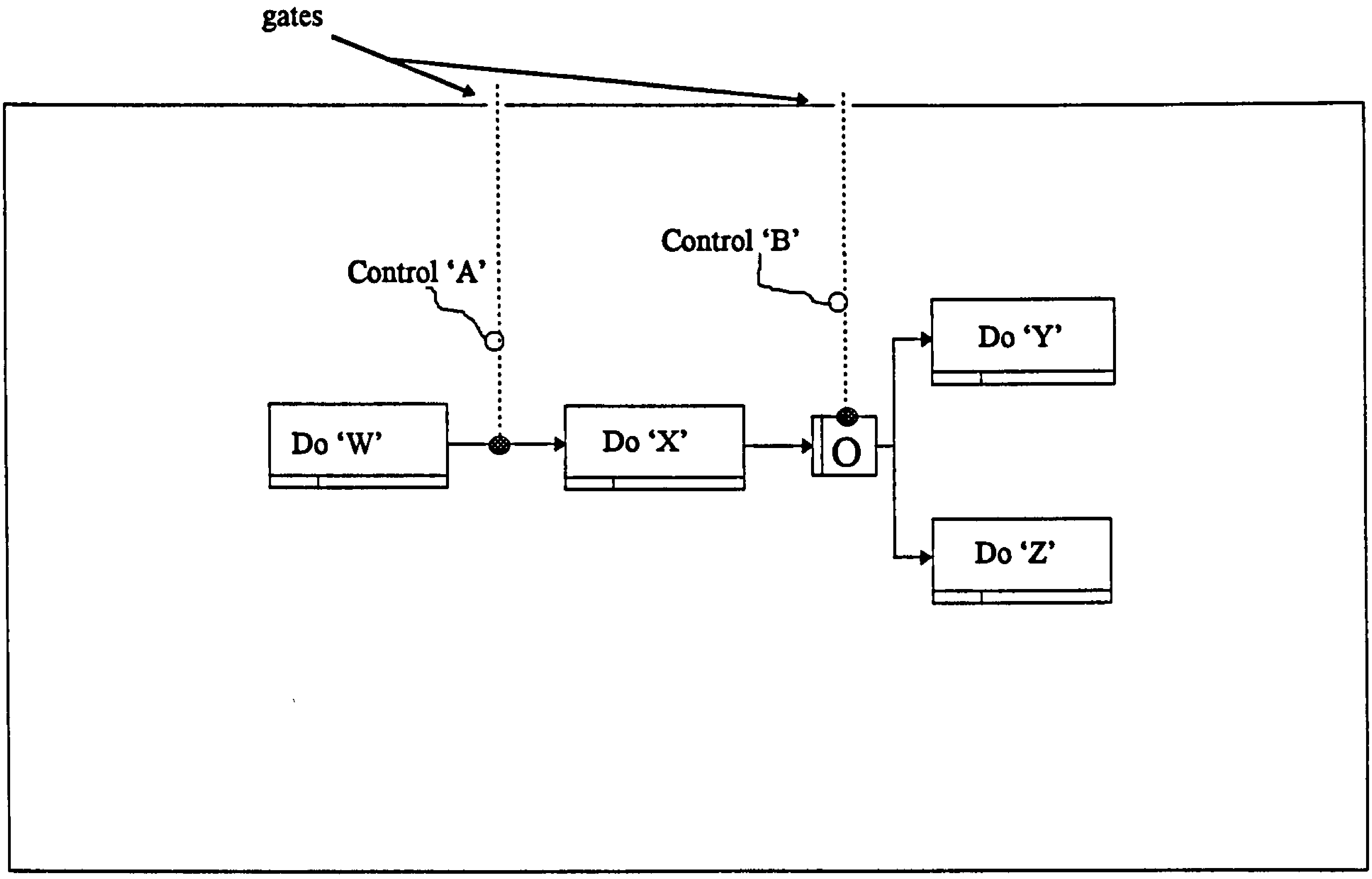
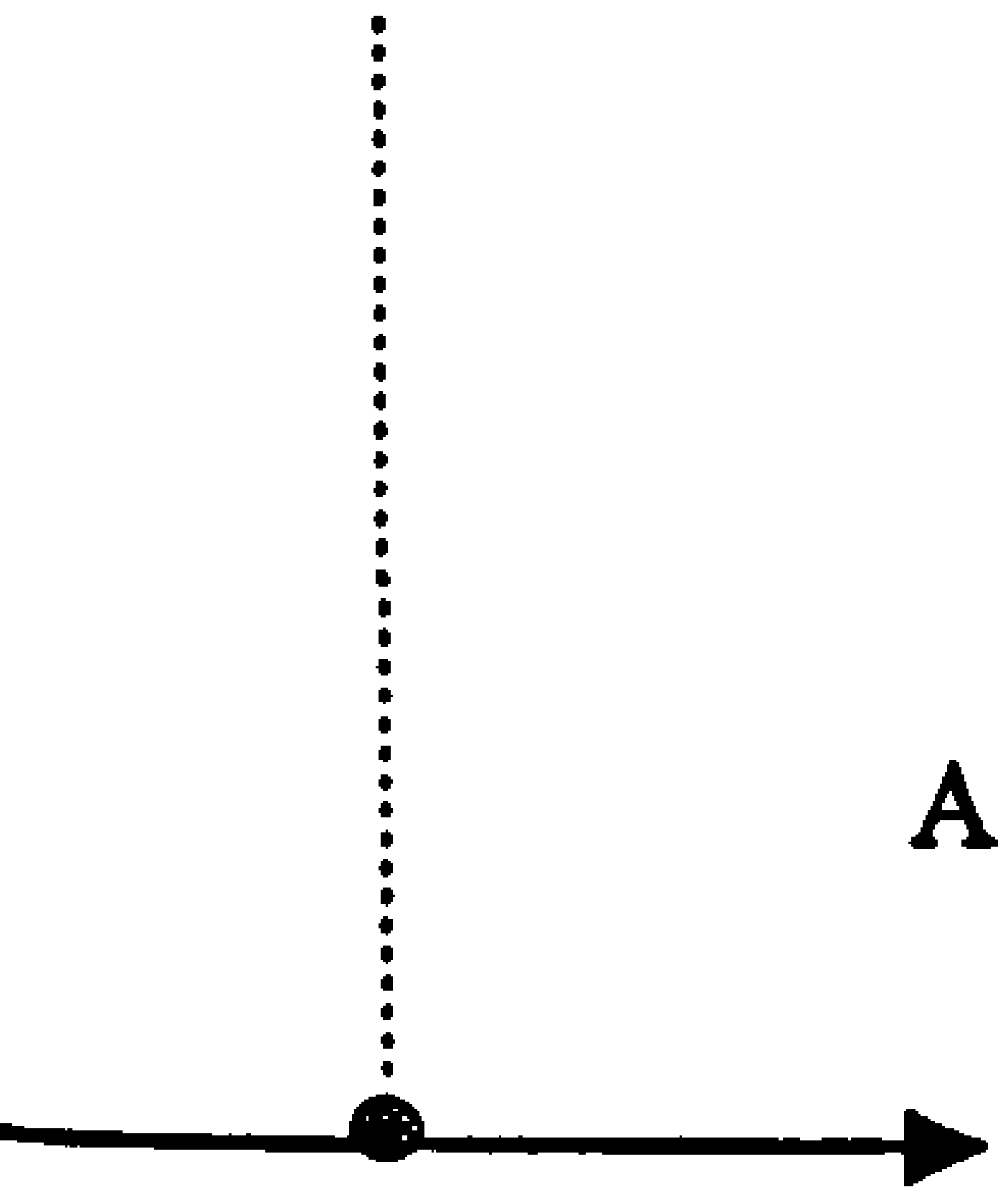
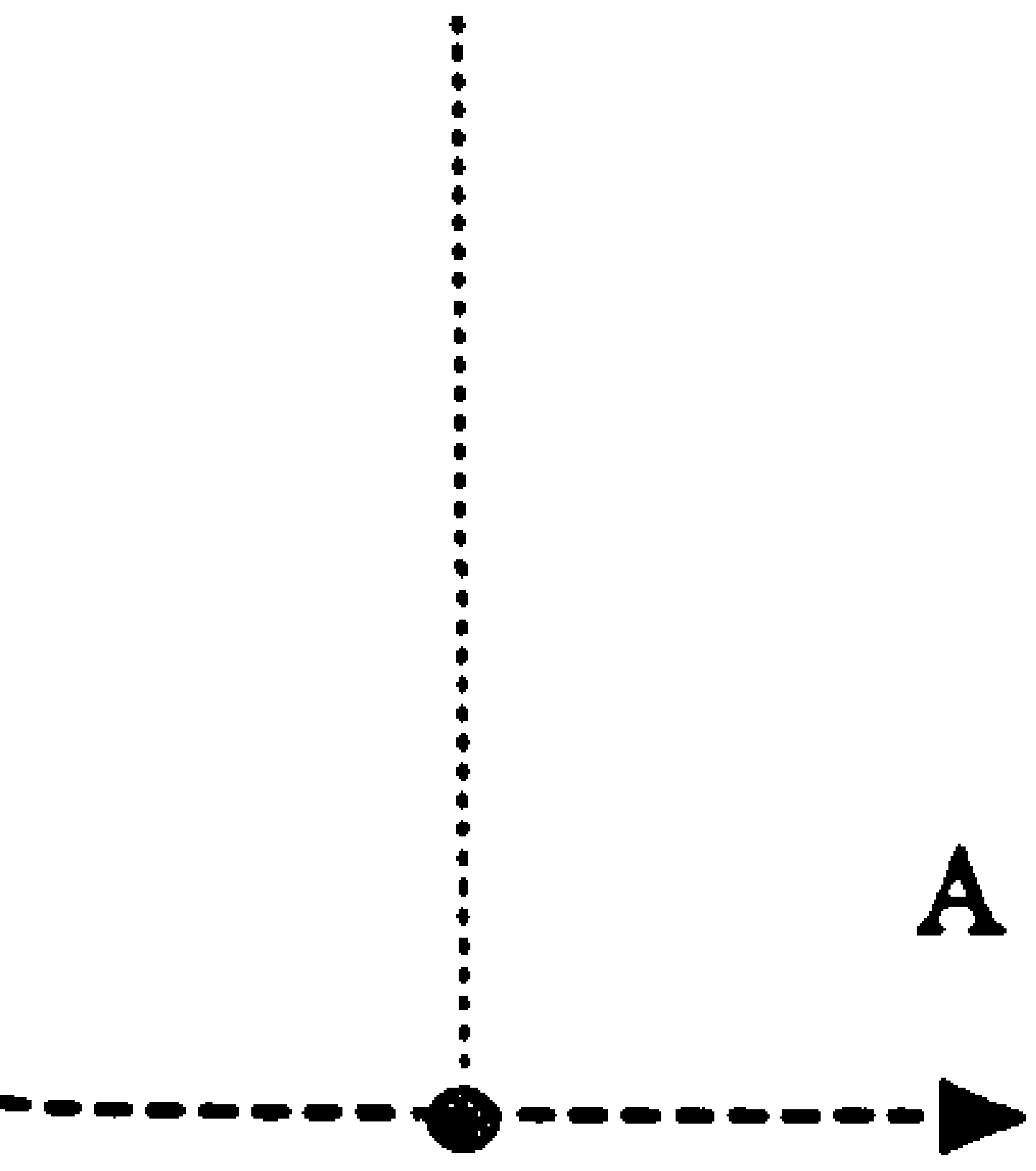


Figure A2.6 IDEF0-3 syntax.

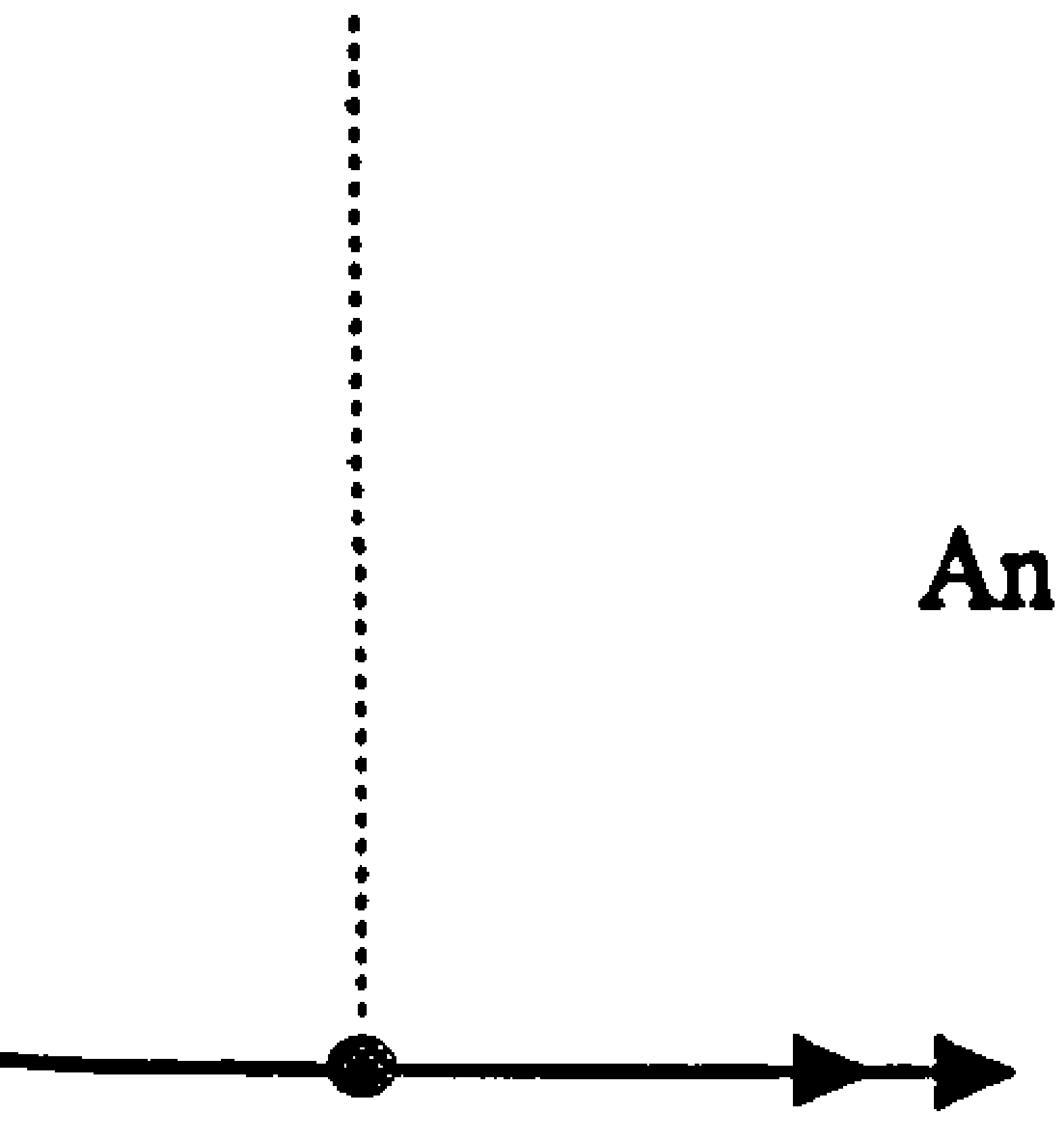
Controls are correlated with links using dotted lines and a connector and they can constrain the following types of IDEF3 links;



A 'precedence link' representing temporal precedence (the most common link) is shown constrained by a control. This describes the situation that the next process is only enabled when the information, objects or data described by the control are available.



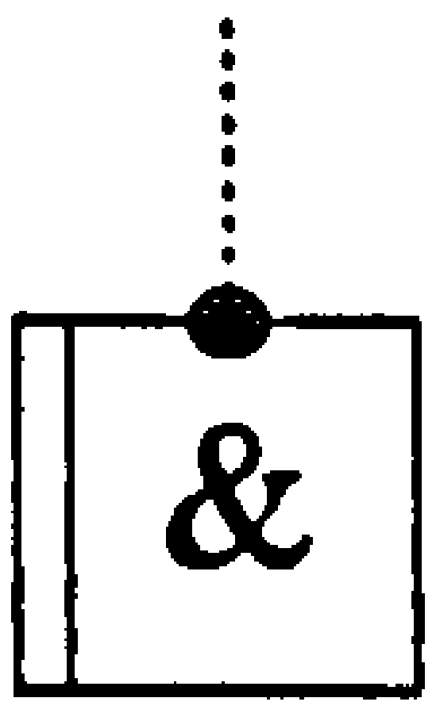
A 'relational link' (or user defined link) carries no pre-defined semantics and is shown constrained by a control. This describes the situation where a control influences the user defined link.



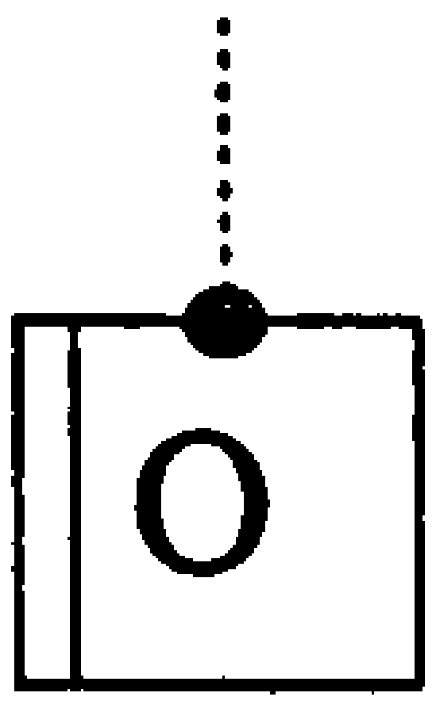
An 'object flow link' describes the same temporal semantics as a precedence link and also highlights a significant object flow between two Processes. As in the case of a precedence link the use of a control describes the situation that the next process is only enabled when the information, objects or data described by the control are available.

Controls can influence the following junction types;

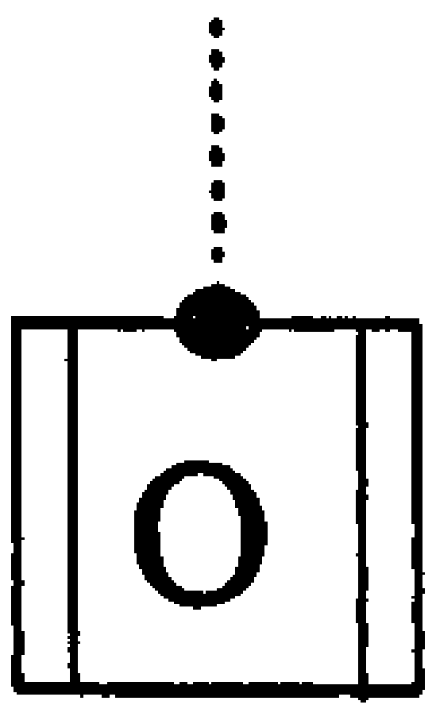
Fan out junctions



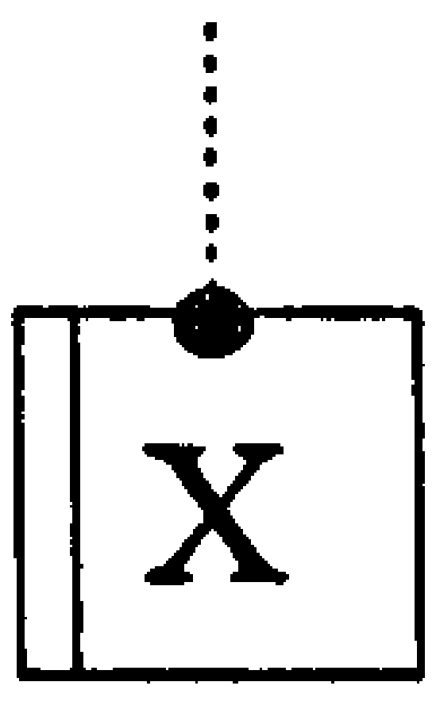
Asynchronous AND - All the following processes start, but not start simultaneously, The conditions for start are influenced by the control.



Asynchronous OR - One or more of the following processes will start, but will not start simultaneously. The decision or constraint effecting which processes start is influenced by the control.

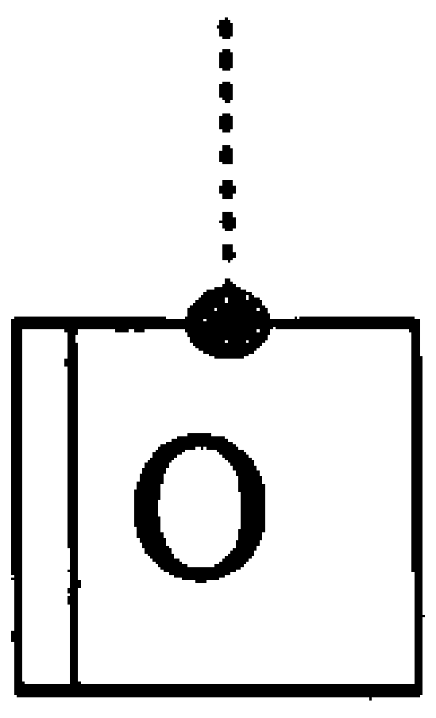


Synchronous OR - One or more of the following processes will start simultaneously. The decision or constraint effecting which processes start is influenced by the control.

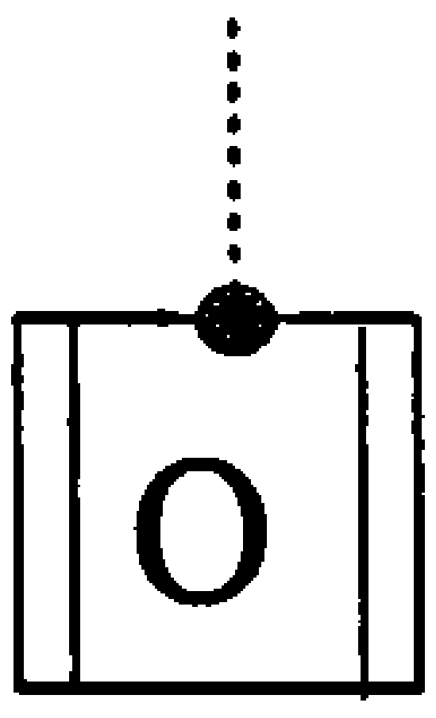


Exclusive OR - Exactly one of the following processes will start. The decision or constraint effecting which process starts is influenced by the control.

Fan in junctions



Asynchronous OR - One or more of the preceding processes complete, but not simultaneously. The conditions for completion are influenced by the control.



Asynchronous OR - One or more of the preceding processes will complete simultaneously. The conditions for completion are influenced by the control.

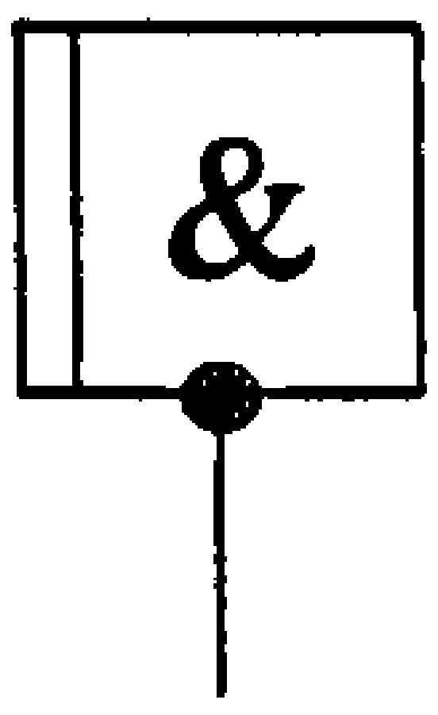
- **MECHANISMS**

Mechanisms in IDEF$_0$ diagrams indicate the means by which a function is performed for example, a machine, computer, software or person instrumental in completing the function. To correlate IDEF$_0$ and IDEF3 diagrams in an IDEF0-3 diagram it is necessary to connect mechanisms identified in the IDEF$_0$ diagram with processes or junctions in the IDEF3 PFN. An example of the representation of mechanisms is shown in figure A2.4. In an IDEF0-3 diagram mechanisms (solid lines) are shown entering through 'gates' in the bottom edge of the diagram to connect with either a fan out junction or a link. The diagram describes a situation where:

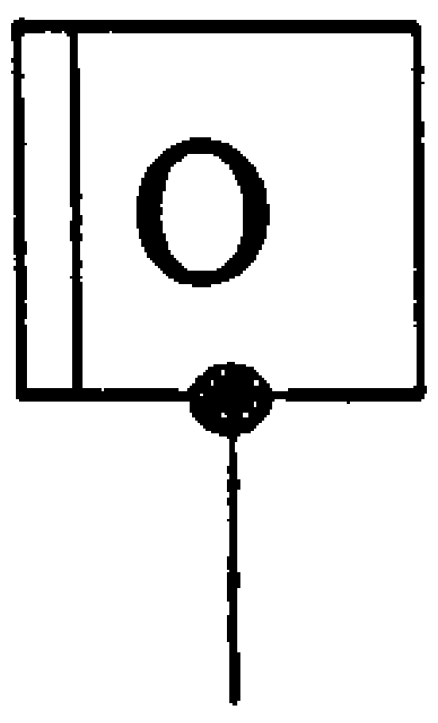
RADAN nesting software is used to carry out the processes 'Plan profile nests', 'Release profiling data to work centres', 'Release plate requirement data' and 'Release variations to batch size'. The decision on which process or processes will follow 'Plan profile nests' is taken at the asynchronous fan out junction by the mechanism - 'Planning engineer'.

Mechanisms can connect to the following junction types:

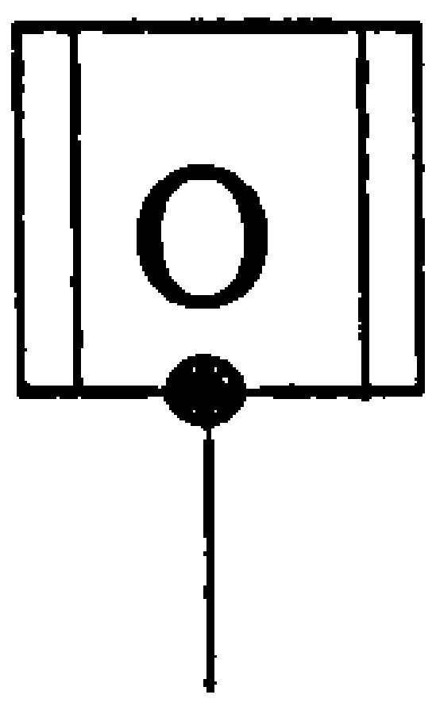
Fan out junctions



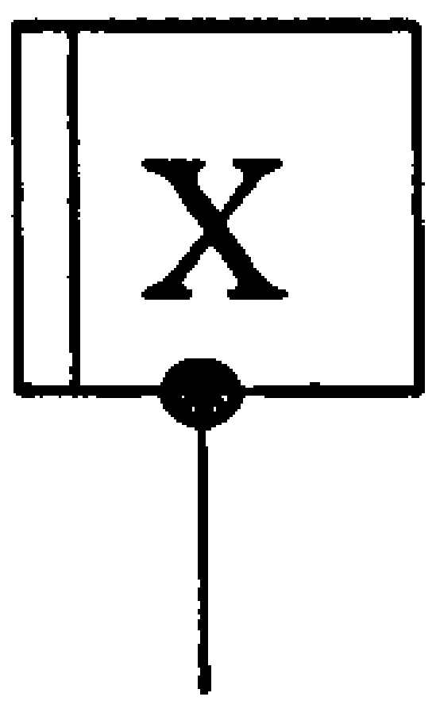
Asynchronous AND - All the following processes will start, but not simultaneously, The conditions for start are influenced by the mechanism



Asynchronous OR - One or more of the following processes will start, but not simultaneously. The decision effecting which processes start is taken by the mechanism.

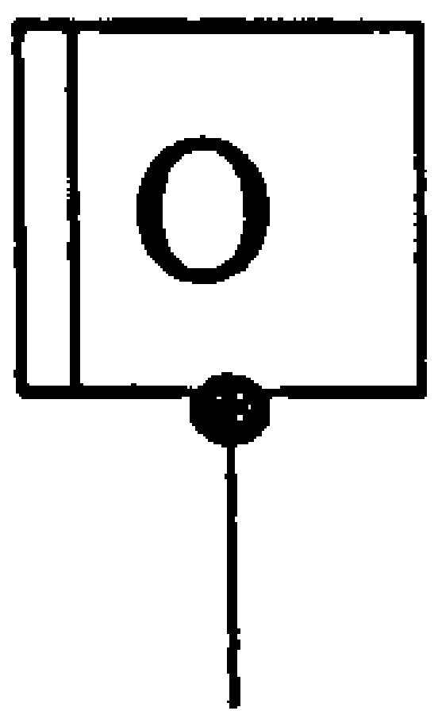


Synchronous OR - One or more of the following processes will start simultaneously. The decision effecting which processes start is taken by the mechanism.

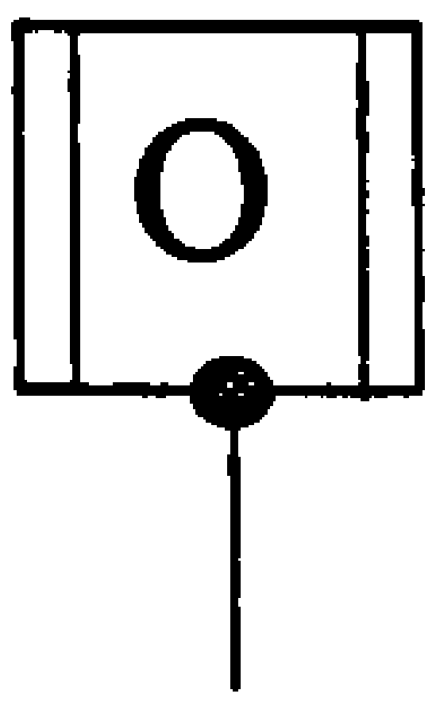


Exclusive OR - Exactly one of the following processes will start. The decision effecting which process starts is taken by the mechanism.

Fan in junctions



Asynchronous OR - One or more of the preceding processes will complete, but not simultaneously. The conditions for completion are influenced by the mechanism.



Asynchronous OR - One or more of the preceding processes will complete simultaneously. The conditions for completion are influenced by the mechanism.

A2.4 CONSTRUCTING IDEF0-3 DIAGRAMS

The following steps are used to construct an IDEF0-3 diagram:

1. Establish the level in IDEF$_0$ decomposition appropriate for correlation with a process flow network.

2. In the context of the *purpose* of the model select appropriate IDEF$_0$ functions as scenarios for process flow networks.

3. Identify the processes (UOBs) associated with each selected scenario. Limit the number of UOBs to between 3 (to make the decomposition meaningful) and 20 (to limit the complexity of the diagram). If the number of UOBs is excessive consider either aggregating UOBs or further IDEF$_0$ decomposition before correlation. Diagram complexity can reach a point where too many relations detract from the clarity of the description

4. Develop a sequence of processes

5. Develop the logical structure of process flow using junctions.

6. Correlate IDEF$_0$ inputs and outputs with the start and terminating processes in the PFN. Validate the correlation by identifying the sources of IDEF$_0$ outputs in terminating processes.

7. Correlate $IDEF_0$ controls with junctions and processes. Validate the correlation by identifying all $IDEF_0$ control connections.

8. If information concerning the influence of 'mechanisms' is necessary for the model purpose and viewpoint, correlate $IDEF_0$ mechanisms with junctions and processes.

9. If additional detail is required for the elements of a PFN develop elaboration documents for UOBs, links and junctions in the conventional way.

Diagram numbering:

IDEF0-3 diagram numbers are all suffixed A03 followed by the $IDEF_0$ node (or scenario) number from which the IDEF0-3 diagram was decomposed. For example, an IDEF0-3 diagram numbered **A03-223** indicates that 223 is the number of the node on the parent $IDEF_0$ diagram (diagram number A22) from which **A03-223** was decomposed.

The diagram development procedure is inevitably iterative involving an analyst, a domain expert and others and typically several interview sessions to develop common agreement on diagram detail that matches the analysts description with the domain experts knowledge.

With a complete IDEF0-3 diagram a model can be developed by decomposing UOBs into greater levels of detail, if this is considered necessary the conventional IDEF3 approach to decomposition described by Mayer et al (1992a) is used.

A2.5 USING THE IDEF0-3 METHODOLOGY

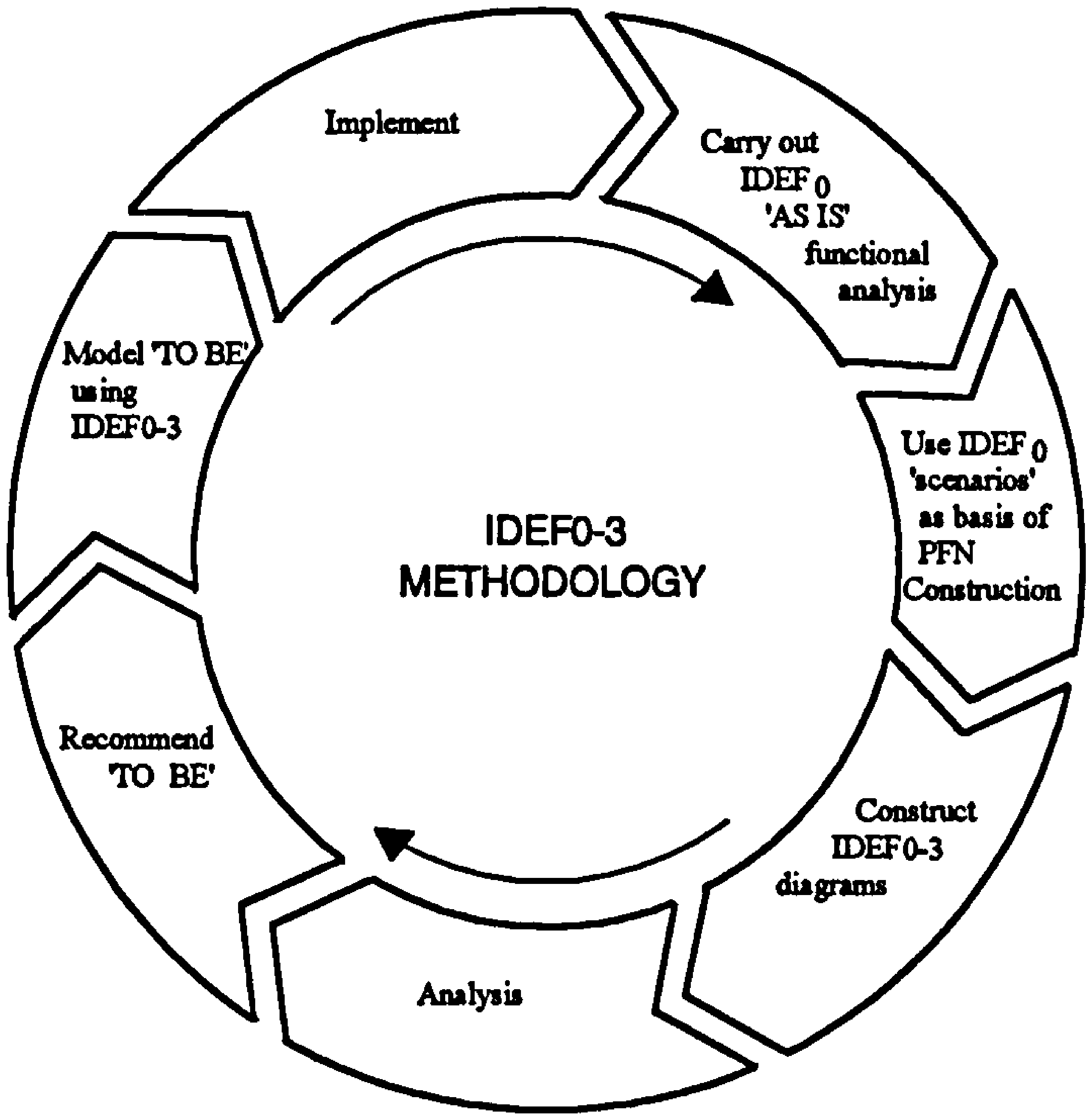
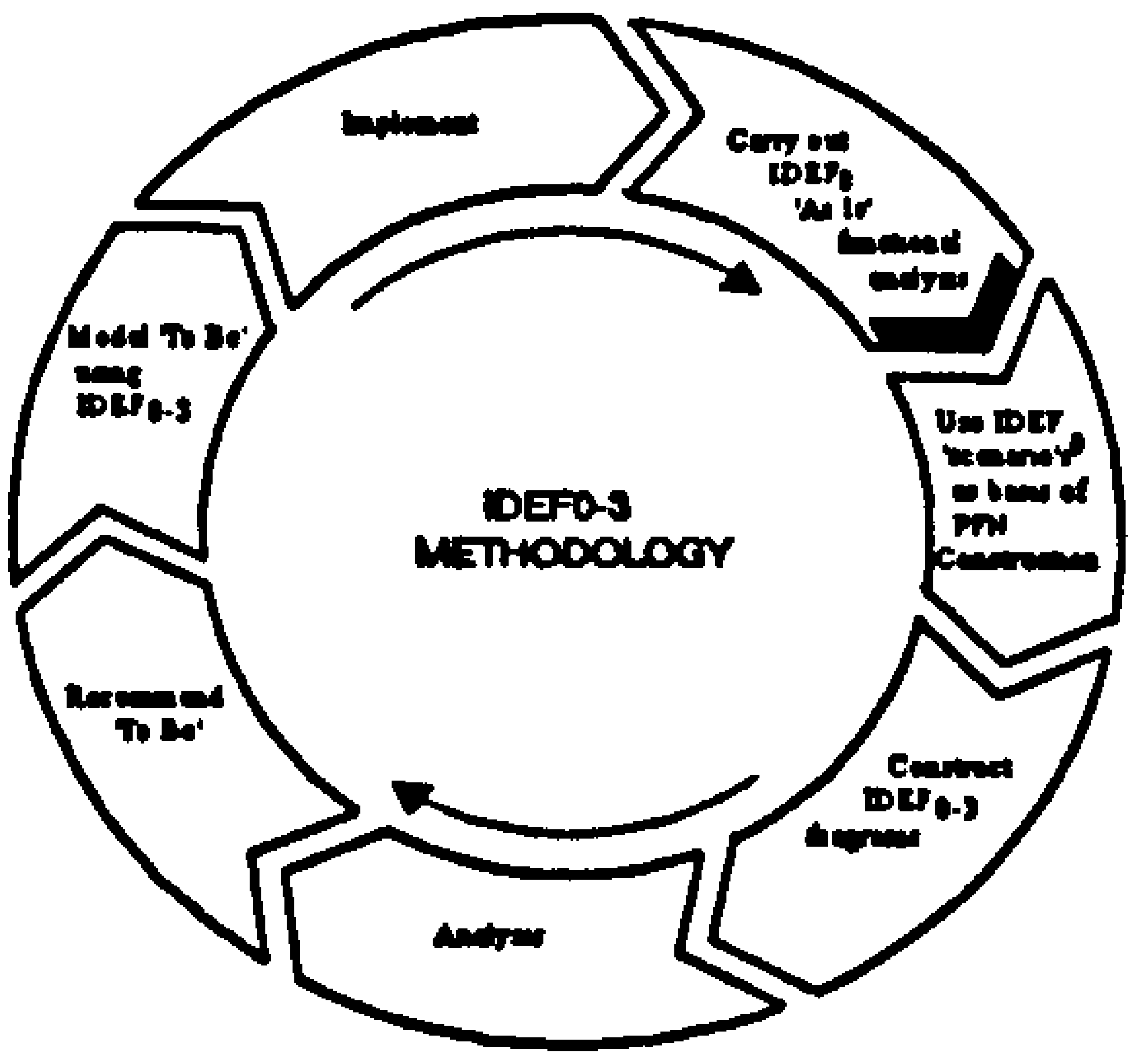


Figure A2.7 The IDEF0-3 methodology

The IDEF0-3 methodology is shown in figure A2.7. It consists of seven consecutive phases.

Phase 1



In phase 1 in the methodology establish a functional AS IS $IDEF_0$ model of the situation under review.

In this phase an analyst must establish the purpose for the modelling effort as a commonly agreed text definition on the $IDEF_0$ context diagram.

The text definition along with the $IDEF_0$ 'Context' and 'Viewpoint' diagrams are the top level of an IDEF0-3 model.

For the modelling effort to be effective the purpose and context for the intended model must map onto the manufacturing enterprise modelling framework shown in figure A2.8 ensuring the purpose of modelling is compatible with cells 10, 20, 30 ,50, 60, 70 and is within the capability and scope of the IDEF0-3 method. To achieve this the top level of a model must expose the focus and perspective of the modelling effort.

FOCUS PERSPECTIVE	a *CONFIGURATION* What, Where, Who	b *BEHAVIOURAL* How, When	c *QUANTITATIVE* How Much, How Quickly, How Many
1 ENTERPRISE Values, Goals, Scope	10 IDEF$_0$ IDEF0-3	50 IDEF0-3	90
2 STRUCTURAL Functional Relationships, Interfaces	20 IDEF$_0$ IDEF0-3	60 IDEF0-3	100
3 PROCESS The stages involved in information and material flow	30 IDEF$_0$ IDEF3 IDEF0-3	70 IDEF3 IDEF0-3	110
4 DYNAMIC The activation of information or object flow	40	80	120
ENTERPRISE OPERATION	Product, Material, Resources, Locations, Information.	Constraints, Material flow, Schedules and timing.	Resource consumption, Output, Performance

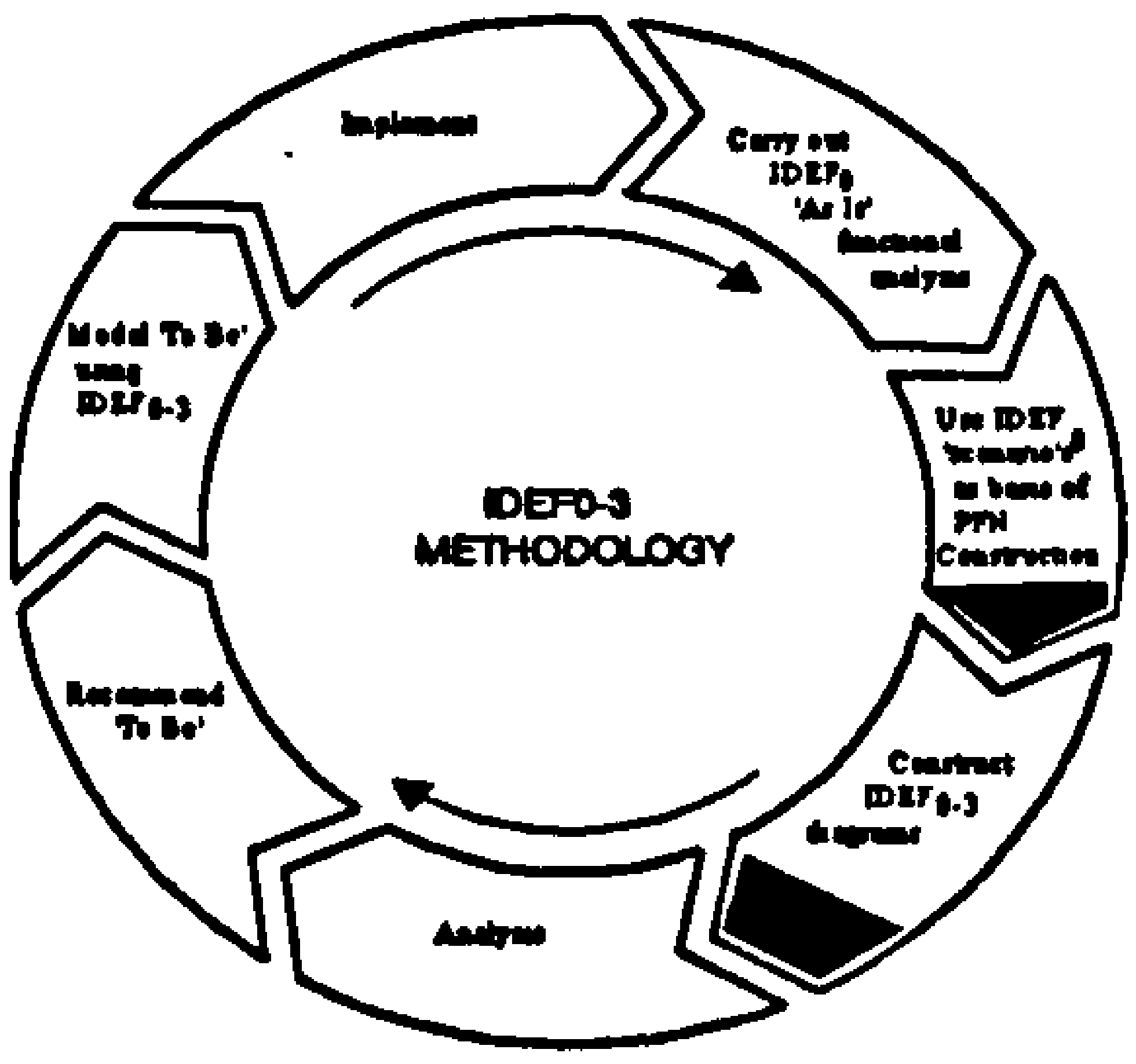
Figure A2.8 The manufacturing enterprise modelling framework

The framework indicates that IDEF0-3 can model; *Configuration* to answer interrogatives such as what?, who? where?, i.e. the objects, material, products, information, data and resources used by an enterprise together with their relationships. *Behaviour* to describe how manufacturing is conducted, for example to represent the relative timing of events, the logic of processes, what initiates, enables, constrains and inhibits manufacture.

It also indicates that IDEF0-3 can represent: An *Enterprise perspective*, a high level view that considers the manufacturing scope of an enterprise, the products, its overall goals, operation and values and the manufacturing strategy that it uses to achieve its goals. A *Structural perspective* that examines the relationships between the elements of an enterprise in a static functional view to describes the interfaces, links and relationships that exist. A *Process* perspective that looks at the actions that take place to change the state of material or information and the sequence of events and the cause and effect of events.

Phase one is completed by developing an AS-IS IDEF$_0$ model using the model building techniques described by the IDEF$_0$ manual (US Air Force, 1981a).

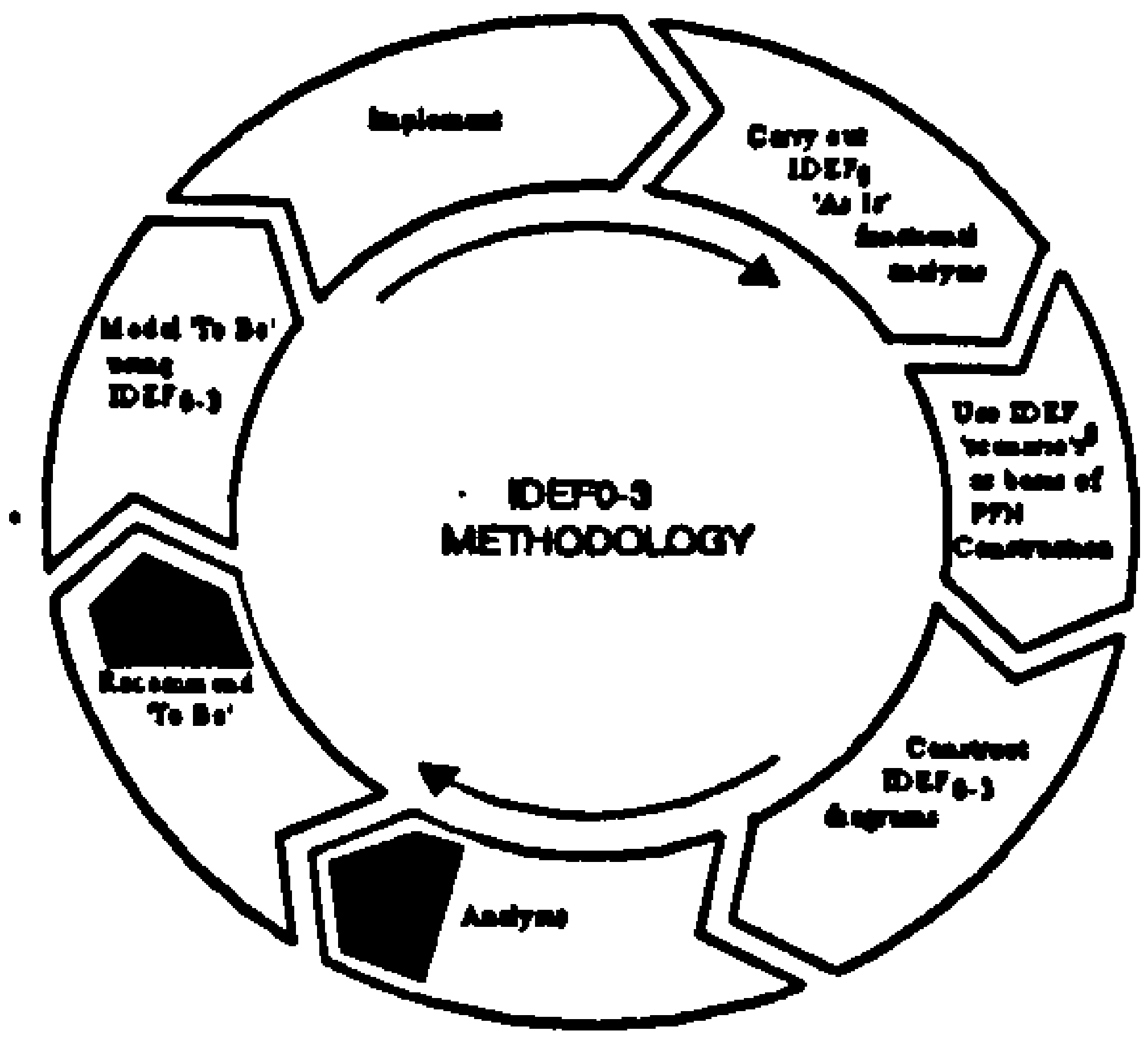
Phase 2 and 3



In phase 2 selected IDEF$_0$ functions become scenarios for decomposition into IDEF0-3 diagrams. This stage is reached when functional descriptions become sequential narratives or when knowledge of aspects of the systems behaviour is necessary to achieve the modelling objectives'.

In phase 3 IDEF0-3 diagrams are completed using the rules and techniques described in sections A2.3 of this user guide and validated through the 'Author Reader Cycle' in the usual way (US Air Force, 1981a).

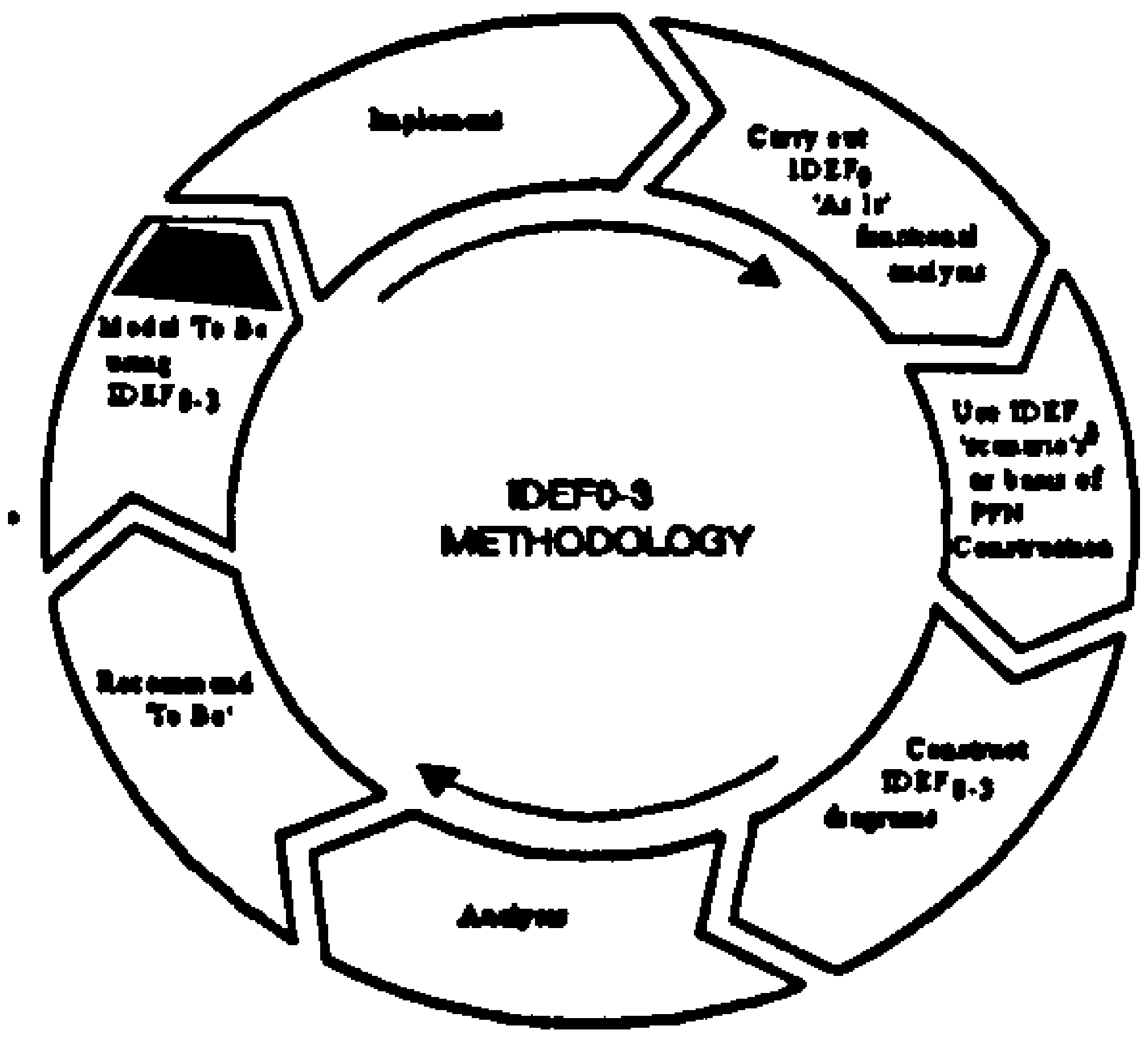
Phase 4 and 5



In phase 4 the AS IS IDEF0-3 model is analysed by all those involved in the modelling effort. Gaps and inconsistencies between the perceptions of those involved are resolved. An outcome of this phase is agreement on the AS IS model as a common understanding by both domain experts and analysts.

Phase five involves recommending the changes necessary to achieve the modelling goals this becomes the context and viewpoint of the TO BE IDEF0-3 model to be reviewed and changed in light of the problems, inconsistencies or general findings from analysis of the AS IS model.

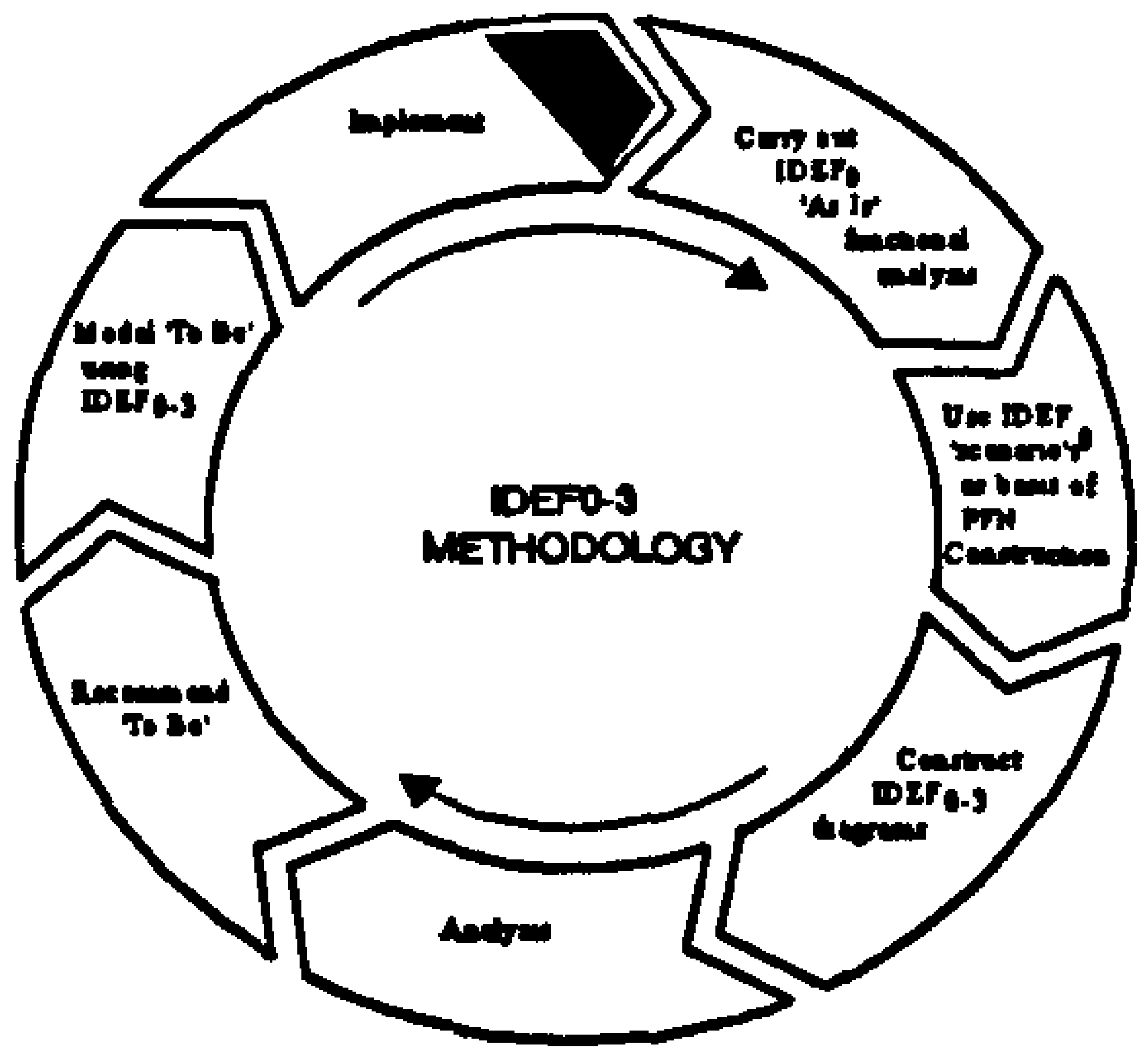
Phase 6



In phase 6 the TO BE IDEF0-3 model is developed, firstly defining a purpose context and viewpoint and IDEF$_0$ diagrams to describe the planned state of system incorporating the recommendations agreed in phase 5.

The TO BE IDEF0-3 model is created and correlated using scenarios identified as important in the higher level IDEF$_0$ diagrams. The model is then validated through the author reader cycle.

Phase 7



Implementation takes place in phase 7. The nature of this phase is wholly dependent on the project and on the implementation procedures of the enterprise involved.

APPENDIX 3

A BRIEF REVIEW OF THE IDEF METHODS

CONTENTS

A3.1 $IDEF_0$

The complete $IDEF_0$ method is defined by the 'Architects Manual' (SofTech Inc., 1980) it includes guidance for modelling, together with rules for model syntax, diagram and model format, text presentation as well as a structured model validation, document control procedures and interview techniques. A key concept of $IDEF_0$ modelling is the definition of a 'Context' and the modeller's 'Viewpoint' to establish an explicit common understanding of the boundary and aspect of the system being modelled. The first step in $IDEF_0$ modelling is thus concerned with establishing the objectives of the modelling effort from which a context and viewpoint can evolve.

An $IDEF_0$ model consists of a hierarchy of related diagrams that represents an aspect of a manufacturing system (the method is also widely used outside manufacturing, the focus of this work is however manufacturing enterprises). Each diagram is based on a diagonal row of boxes (normally between three and six boxes on each diagram) connected by a network of arrows. Boxes represent activities or functions of a system and a text block inside a box is an active verb phrase describing an activity. Arrows represent the relationship between activities in terms of the information or objects used, produced or required by activities. Arrows entering the left side of a box are inputs (I) to the activity, arrows entering the top of a box are controls (C) on the activity and arrows leaving the right side of a box are outputs (O) as a result of the activity. Finally a mechanism (M) is a person, system or device associated with carrying out the activity and is shown as an arrow entering the base of a box. This arrow structure is termed the ICOM structure. Each diagram is referred to by its 'node number' that defines where it lies in the hierarchy of a model. An example of IDEF_0 activity diagram format is shown in figures 5.7 to 5.13. A node index and node tree can provide a convenient way of showing the relationship between all the diagrams in a model, examples are shown in figures 7.12 and 7.13, and a data dictionary can be used to summarise all sources and destinations of objects, information or data (Colquhoun et al, 1989).

An IDEF_0 model comprises of a set of related activity diagrams presented in node number order that represent the subject under scrutiny. The perspective taken by the author of the subject and the scope of the model is defined by the 'context' (node A-0) and 'viewpoint' (node A0) diagrams at the apex of the hierarchy. The depth of the model hierarchy (the number of diagrams below the viewpoint) is determined by the amount of detail required by the analyst.

Supporting the basic principles of the method is the IDEF_0 forms and procedures guide (Ross *et al.* 1980) and the ICAM library maintenance and distribution procedures (US Air Force, 1981e) The procedures, based on the 'Author/Reader cycle' provide a structured means of controlling, documenting and validating the model building process. The final model is thus the shared understanding of a team of people producing a common representation of the subject under review.

A3.2 IDEF3

A complete guide to the IDEF3 method is provided by Mayer et al (1992a), what follows is a brief description of the main characteristics of the method. IDEF3 is used to describe a system by capturing a representation of what a system does, rather than to predict what a system will do. It uses Process Flow Network (PFN) diagrams and Object State Transition Network (OSTN) diagrams. The PFN diagram represents Units Of Behaviour (UOBs) (where a UOB could be: a process, a function, an activity, an operation, a decision, an action, or an event) connected by their temporal, causal and logical relationships. An OSTN diagram describes the various states of objects used in processes and relates those states in terms of the processes that cause objects to change state.

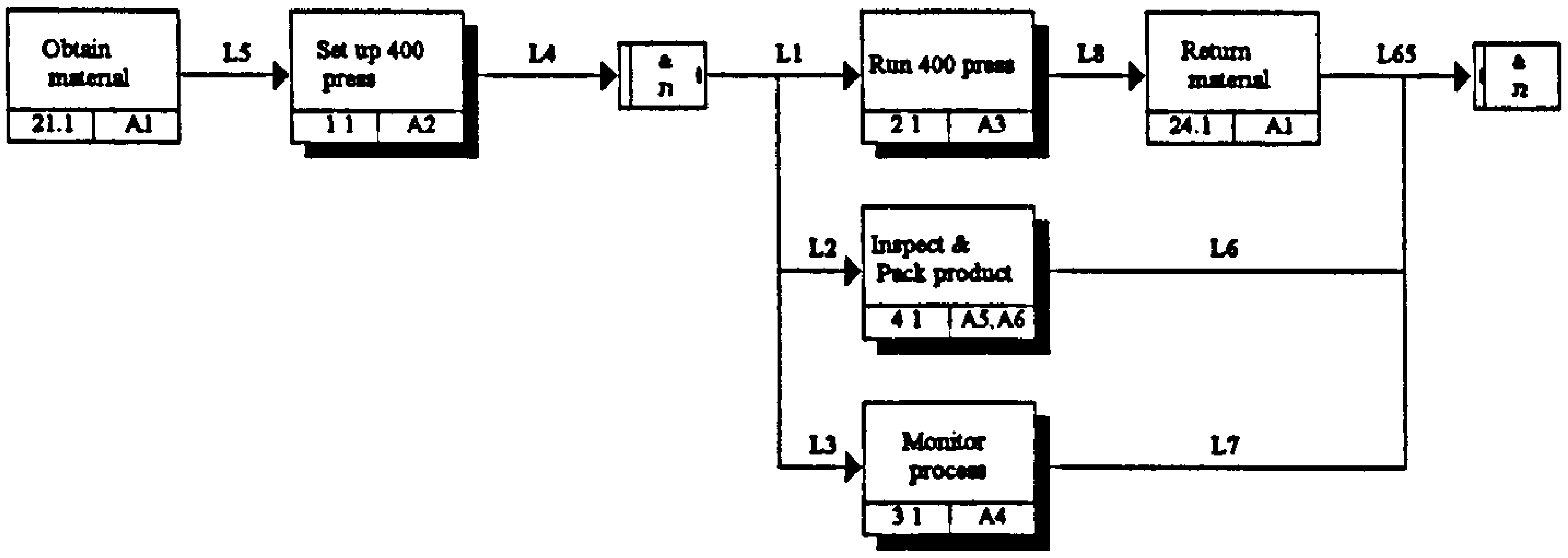


Figure A3.1 A Process Flow Network - Run Cell.

The IDEF3 method is focused on capturing the knowledge of the experts involved in the system and uses graphics and text to describe the observations, beliefs and statements of participants in the system

Figure A3.1 is an example of a PFN that describes the operation of a manufacturing cell. The large rectangles labelled in the bottom left hand corner are UOBs describing the processes involved in the 'scenario' of 'Run Cell' for example 'Obtain material (21.1) and 'Set up 400 press' (1.1) are processes that occur sequentially (indicated by the precedence

Link L5). Smaller rectangles labelled with a 'J' are Junctions representing the divergence or convergence of sequence logic. The box labelled J1 in figure A3.1, for instance, represents an 'asynchronous AND' situation using a fan out junction, where the processes 'Run 400 press and Return material', 'Inspect & pack product', and 'Monitor process' all occur concurrently. 'Asynchronous' indicates that they do not necessarily start at the same time and 'AND' indicates that they all do occur.

In common with other modelling methods the principle of decomposition can be applied to 'explode' a UOB into lower levels of detail using formal syntax to structure the process. In Figure A3.1 those UOBs depicted with a shadowed rectangle have been decomposed to a lower level. Junctions and UOB's are connected by 'Links' depicted by arrows. Links can represent precedence, object flow or a user defined relationship. Each UOB, Junction and Link can have a structured 'Elaboration document' to describe the element in more detail.

A3.3 IDEF$_0$ and IDEF$_{1X}$ MODELLING TOOLS

Since the IDEF$_{0}$, $_{1}$ and $_{1X}$ methods have been in the public domain a range of software tools have been developed, many of which are marketed as integrated software suites:

Wisdom Systems Inc. (1300 Iroquois Avenue, Naperville, Illinois) was founded by Dennis Wisnosky in 1986 (Jenks, 1993). Wisnosky was program manager for the ICAM project and is credited along with Ross with coining the IDEF acronym, (Wisnosky, 1979). The company began by marketing the first commercially available IDEF tools - IDEFine-0 and IDEFine-1[1]. Using their current product Wisdom systems claim to have established the term Computer-Aided Process Re-engineering (Wisdom Systems, 1995) based on an 'integrated set of tools' consisting of five modules.

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[1] IDEFine-0 and IDEFine-1 were a product of Sophides International, Churchillstraat 35, Barnaveld, Netherlands

1.Minerva - A BPR methodology to integrate the modules

2. Process Works - $IDEF_0$ modelling

3. Data Works - $IDEF_{1X}$ modelling

4. Wisdom model repository - A database for model management

5. Other Wisdom analysis tools provide a means of analysing $IDEF_0$ models:

- TimeWIZard, time line analysis (Gantt chart)
- CostWIZard, Activity Based Costing
- QualWIZard, Quality Function Deployment
- SimWizard, for export of functional models to ProModel or CACI SIMprocess discrete event simulation tools.

Triune Software Inc. (2900 Presidential Drive, suite 240, Fairborn, Ohio), founded in 1988 produce the Automated Business Logic Engineering Process Modeller (ABLE PM) tool, it is an $IDEF_0$ modelling tool that claims to 'help manufacturers retailers or service providers re-engineer their way toward enhanced productivity' (Triune Software, 1993). No links with other tools are claimed and no $IDEF_{1X}$ modelling capability is provided.

Coe-Trueman Technologies Inc., (1321 Duke Street, Suite 301, Alexandria, Virginia) formed in 1985 produce COSMO an 'Interactive Enterprise engineering and CASE tool' consisting of five modules.

1. COSMO-SP- a strategic planning and model management facility
2. COSMO-0 - an $IDEF_0$ modelling tool
3. COSMO- ABC Activity Based Costing using $IDEF_0$ models
4. COSMO-1X - $IDEF_{1X}$ modelling
5. COSMO-PRO a 'User view' generator using SQL to produce database queries and reports. The module uses COSMO-1X $IDEF_{1X}$ models to construct normalised databases.

Knowledge Based Systems Inc. (KBSI), (1500 University Drive East, College Station, Texas) founded in 1988 by Richard J Mayer (Mayer 1993a) produce an 'intelligent workbench' consisting of six modules.

1. AI0 WIN - IDEF$_0$ modelling
2. Pro ABC - Activity based costing using AI0 WIN IDEF$_0$ models
3. ProCap - Process modelling using IDEF3
4. ProSim - Process modelling (IDEF3) with an interface to AT&T ISTEL's WITNESS discrete event simulation software tool.
5. ProCost - Activity based costing using ProSim IDEF3 models
6. SmartER - Information and Data modelling using IDEF1 and IDEF$_{1X}$

LogicWorks Inc. (214 Carnegie Centre, Princeton, New Jersey) is described by Frank (1993) as 'a relatively inexpensive CASE tool' consisting of four modules.

1. BPwin - IDEF$_0$ modelling
2. ERwin/ERX - IDEF$_{1X}$ modelling
3. ERwin/DBF - design and reverse-engineering for databases (dBASE, FoxPro and Clipper) from/to ERwin/ERX IDEF$_{1X}$ models.
4. ERwin/SQL - Generates SQL schema's and indexes from ERwin/ERX IDEF$_{1X}$ models for SQL database applications.

Texas Instruments (AIM Division, 6550 Chase Oaks Boulevard, Plano, Texas) produce the Business Design Facility (BDF) which is a unified CASE tool that incorporates several diagramming methods, Process outline diagrams, Process maps, Process chains and IDEF$_0$ diagrams together with IDEF$_{1X}$ diagrams.

MetaSoftware (125 Cambridge Park Drive, Cambridge, Massachusetts) founded in 1985 produce a combined $IDEF_0$/$IDEF_{1X}$ tool called Design/IDEF. The company claim that it is the only $IDEF_0$ tool that has an integral Activity Based Costing facility. In 1988 the company began development of Design/CPN (Coloured Petri-Net) claimed by its designers (Albrecht et al, 1992) to be the first software package to support hierarchical coloured Petri-nets. The tool is linked to a Design/IDEF $IDEF_0$ model to build a CP Net graph.

IDEF software tools from the various vendors are not integrated although some work is being carried out to provide a common software tools environment. In the USA the National Centre for Manufacturing Science (NCMS), for example, have established an IDEF Model Repository System designed to facilitate access to all the various modelling tools (Cauthorn, 1993).

All the modelling tools discussed originated in the USA in the mid to late 1980s and the advertising literature relating to the various systems emphasises the strong influence of US government requirements (see section 2.3) and indicates that the major market in companies involved in US government contracts. In the UK the only tool actively promoted is MetaSoftware's Design/IDEF and approximately one hundred and twenty five copies have been sold in the UK over the last five years (see section 3.5). Logic Works have (in 1994) appointed Admiral Software (Camberley, Surrey) as their UK agent, sales of this tool are unknown. The approach adopted by most tool vendors has been to provide $IDEF_0$ modelling as part of a CASE tool environment and reflects the emphasis on IS application of the method. The recent rise of Business Process Re-engineering (BPR) in the USA as a paradigm for the management of change (Drucker, 1991, Hammer, 1990) has provided fresh emphasis on the need to understand and design *processes* as the basis of commercial, service and manufacturing enterprises. Which in turn has provided a new marketing impetus for IDEF tools under the banner of BPR tools.

This is to some extent reflected in the change of name of the US IDEF User Group[2] which was formerly a forum for IDEF practitioners and tool vendors, to The Society for Enterprise Engineering in 1995 to 'promote and expand the practice of analytical techniques, specifically IDEF, in BPR' (Preston, 1995).

This research in connection with IDEF tools led to a working relationship with the UK vendor for MetaSoftware's Design/IDEF and to the company's support for the survey of users discussed in section 3.5.

3.4 IDEF$_1$

The need for the IDEF$_1$ method 'became clear as the difficulty in designing integrated manufacturing systems became more and more apparent' (US Air Force, 1981b). The method was designed to produce an information requirements model before designing and building an information system. It is capable of capturing and graphically representing what information is necessary to manage and operate an enterprise and can include, not only the information necessary for computer systems, but also physical entities such as material, products, and equipment. It was designed to analyse and describe information resource management requirements rather than to design database structure. A model can describe the logical relationships in information flow and the rules controlling the management and storage of information and can be used to provide the knowledge and insight necessary to identify problems and build a strategy for information management.

IDEF$_1$ modelling principles:

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[2] IDEF Users Group, Kettering, Ohio, USA, founded 1989 (Preston, 1990)

The graphical conventions used can represent; objects, the physical or abstract relationships between objects, information concerning objects and the data structure used to deal with information. The basic building blocks of an IDEF$_1$ model are 'entity classes' comprised of groups of entities. An 'entity' for example could be real, such as a 'design manager', a 'solenoid valve' or a concept such as 'manufacturing problem'. An entity has properties or attributes, for the solenoid valve, 'part number', 'description', 'cost' and 'supplier name' could be the information or attributes associated with a particular solenoid valve to identify it uniquely and differentiate it from another entities.

Each entity is an individual member of an 'entity class' which represents the information that a group of entities have in common. In the case of a solenoid valve for example several could be used by an enterprise, single acting, spring to centre, three position etc.. An entity class represents the information known about the similar properties of the collection of entities, for example, 'supplier', 'port size', 'pressure range' etc.. The first stage in building an IDEF$_1$ model is to build an entity class glossary or pool in the form of a list or table. Each entity class is an entry in a table and each entry has an associated entity class definition on a separate form.

The second stage is to establish the 'relation classes' between entity classes. A relation class describes the manner in which members of an entity class relate to members of another entity class (or entity classes). For example the entity class 'solenoid valves' are 'used on' (the relation class) another entity class 'hydraulic power pack'. IDEF$_1$ uses a relational matrix simply to indicate if there is a relationship between entity classes.

To describe the cardinality and dependency between entity classes the graphical conventions shown in figures A3.2. and A3.3 are used. Figure A3.3 describes the following relationship: Any 'solenoid valve' entity may be used on zero, one or many (0, 1, N integer values) 'Hydraulic power pack' entities. Each 'Hydraulic power pack' entity uses precisely one solenoid valve. The diagram also defines that no other entity classes relate to 'solenoid valve' or 'Hydraulic power pack' entity classes and that no other relation class exists between the two entity classes.

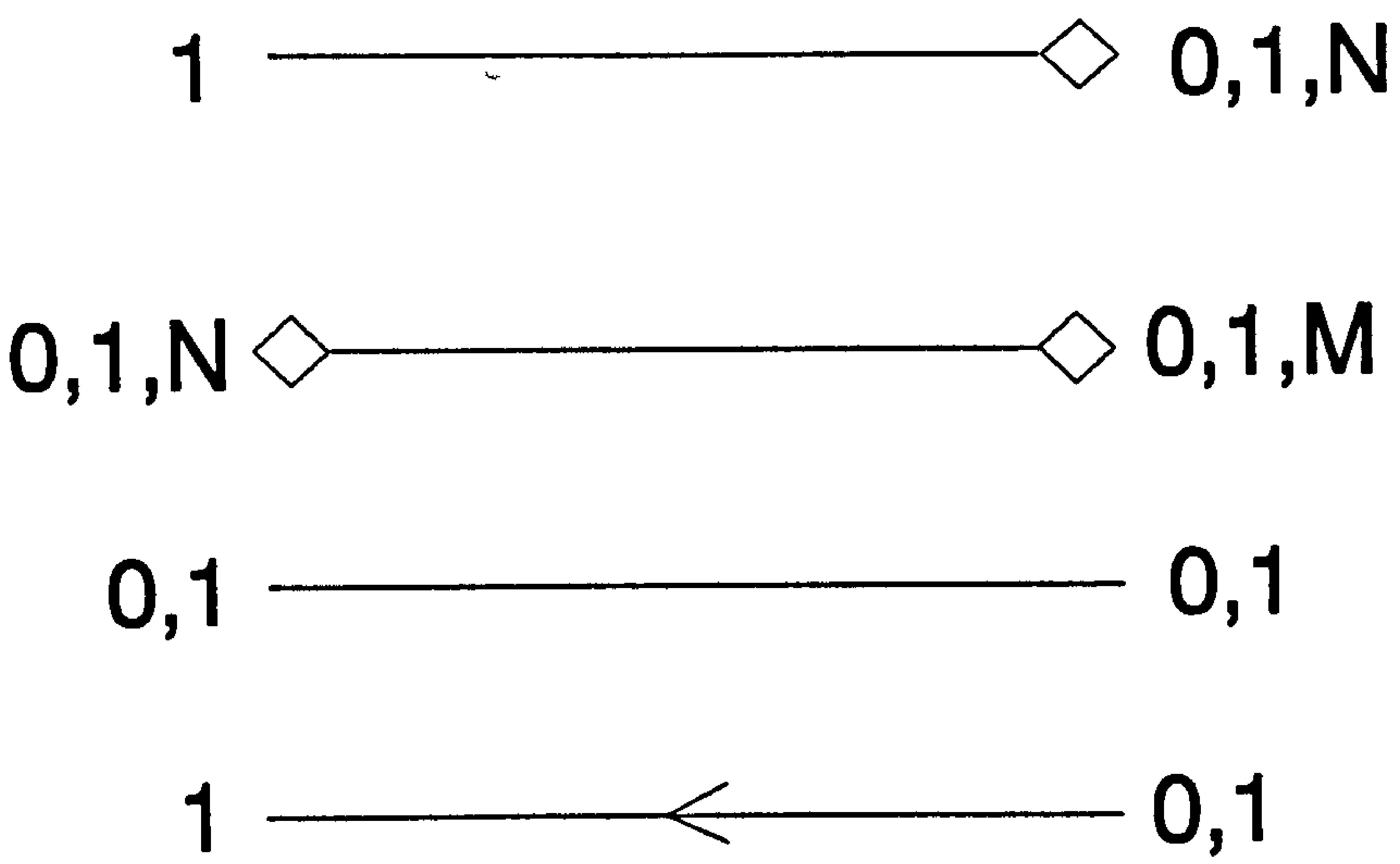


Figure A3.2 IDEF$_1$ graphic notations to specify relation classes

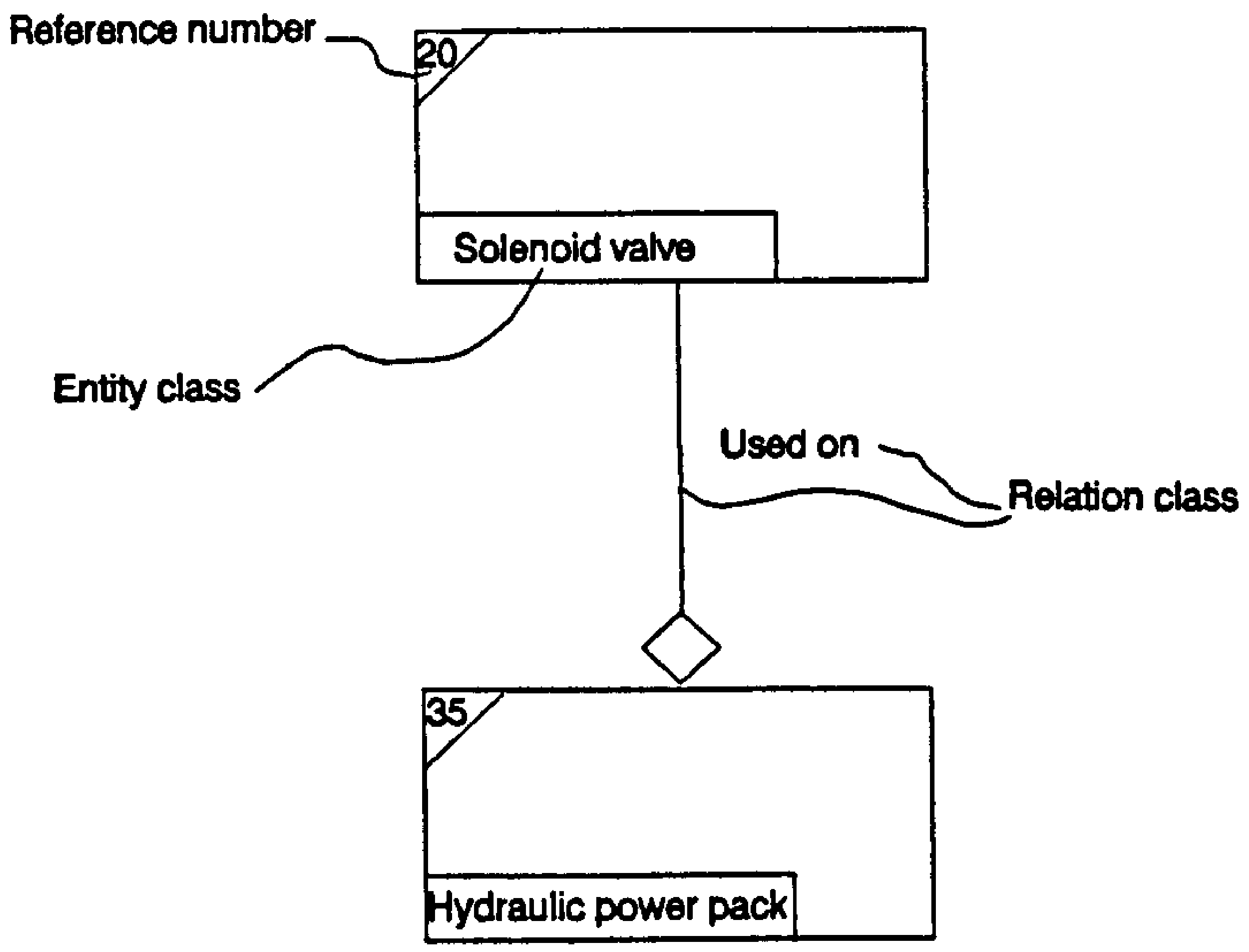


Figure A3.3 A simple IDEF$_1$ entity class diagram

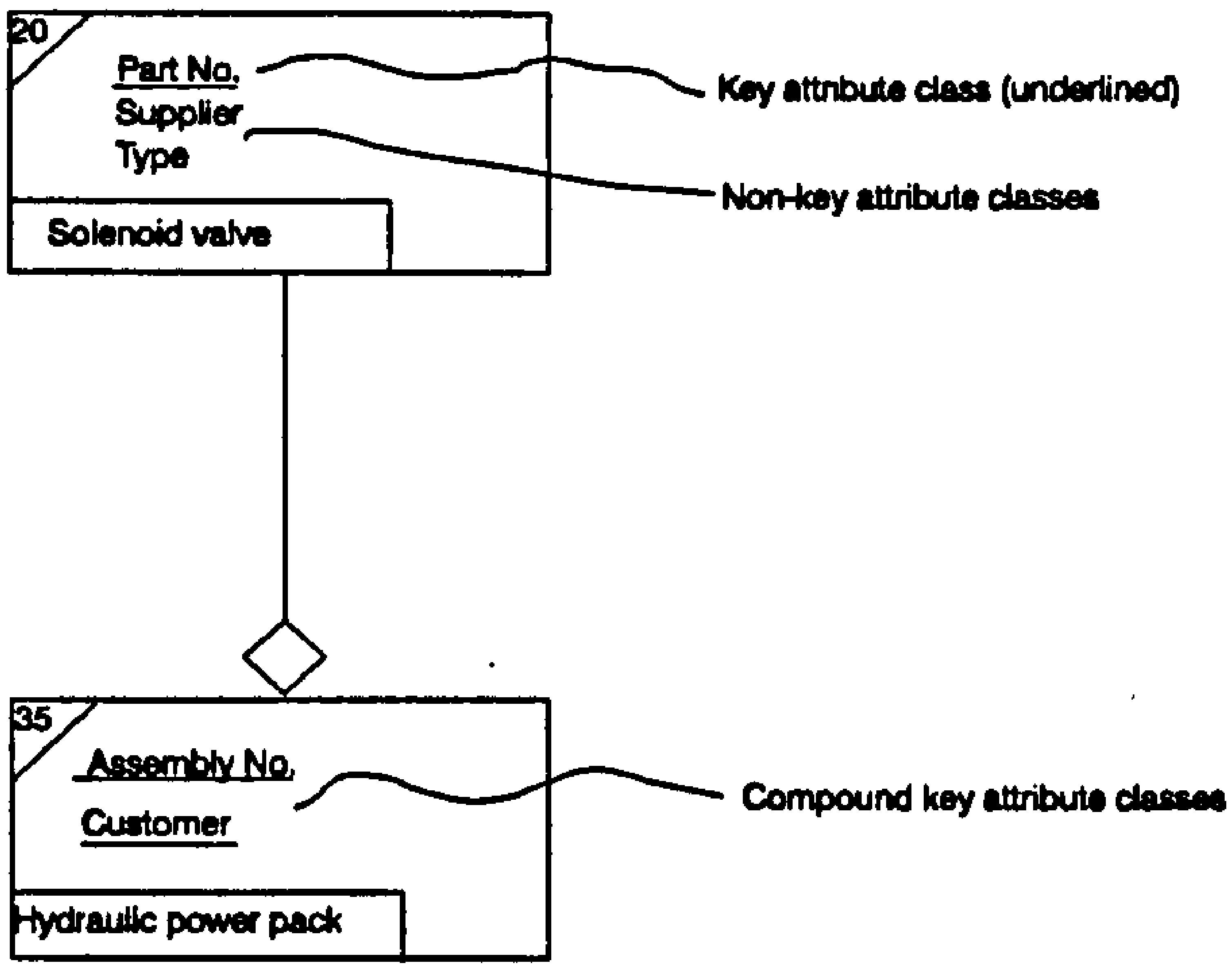


Figure A3.4 A simple IDEF$_1$ entity class diagram showing attribute classes

The third stage of the method involves defining the attributes of entity classes in order to be able to distinguish individual members of the same entity class. 'Key' and 'non-key attribute' classes are used. Key attribute classes can be single or compound (two or more attribute classes). Figure A3.4 illustrates single and compound key attributes.

Finally phase four involves the assignment of non-key attribute classes to entity classes to complete the description of entity classes.

Alongside the principles of the method the IDEF$_1$ methodology uses the Author/Reader cycle for model building and validation in common with IDEF$_0$ (US Air Force, 1981a, b). IDEF$_1$ is a method for documenting information requirements and structure as a foundation for database design it is a knowledge gathering method designed as an 'AS IS' method rather that database design method. For the task of database design the IDEF$_{1X}$ method was developed using the experience gained in the development of IDEF$_1$.

A3.5 IDEF$_{1X}$

IDEF$_{1X}$ is a database design method that is independent of data storage (i.e. the target database) and the user interface and is one of many data modelling approaches based on the work of Chen (1976). It was designed as a method to design relational databases and is 'not particularly suited to serve as an AS IS analysis tool' (Mayer, 1990b) and is not considered useful for object-oriented systems. The method is used to develop a conceptual schema, that is, the logical structure of data independent of the application of the data (the external schema) and how it is accessed and stored (the internal schema).

IDEF1X modelling syntax and semantics:

An outline of the key IDEF$_{1X}$ modelling concepts; entities, relationships and attributes, is given in this section. The details are based on the original US Air Force (1986) IDEF$_{1X}$ report, Mayer (1990b) and the work of Bruce (1992).

(i) Entities.

IDEF$_1$ and $_{1X}$ terminology is similar however there are fundamental differences in the concepts employed. In IDEF$_{1X}$ an 'entity' is a set of real or abstract items of interest such as components, staff, concepts or events sharing common attributes. Individual members of sets (single occurrences of an entity) are 'entity instances'.

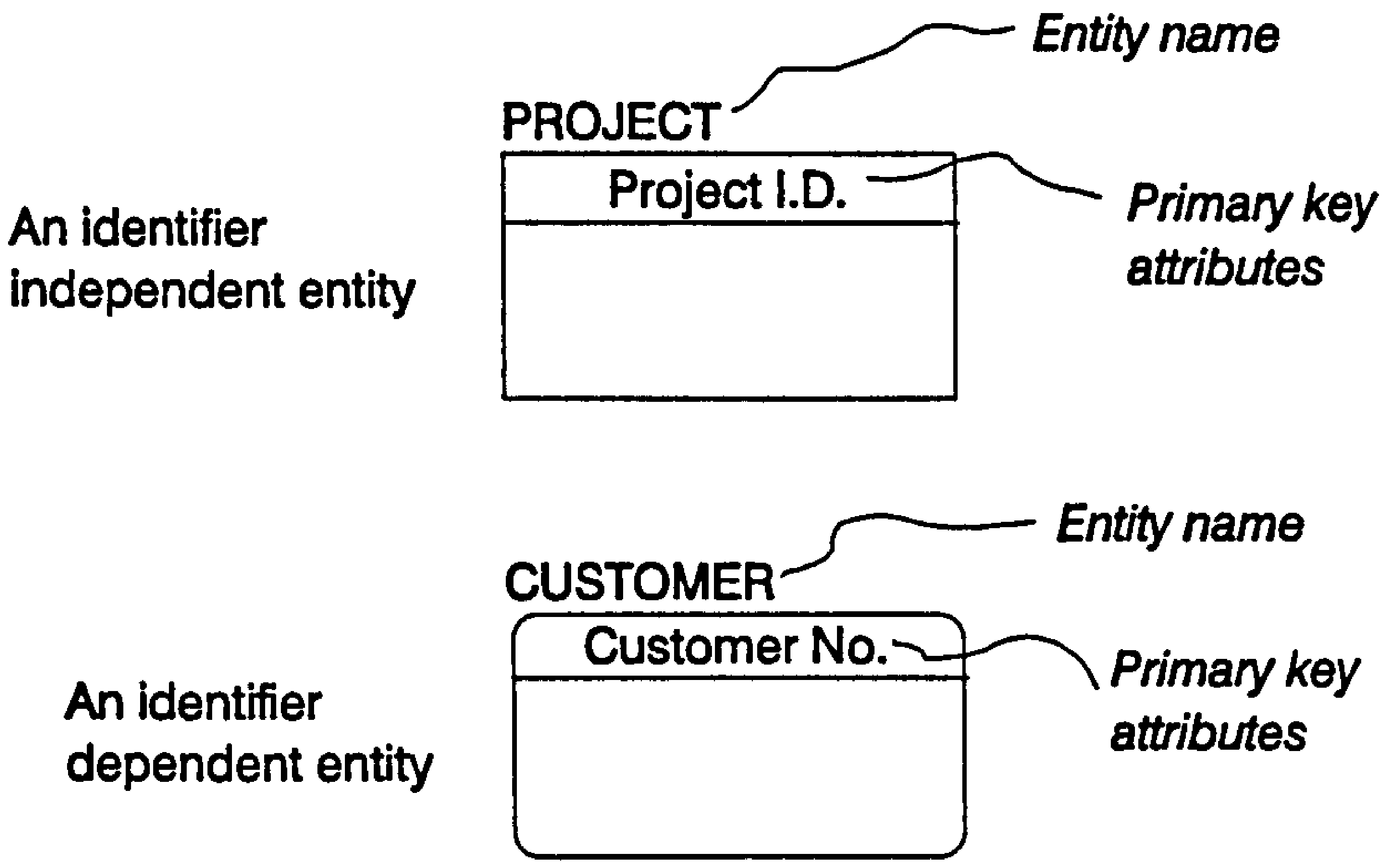
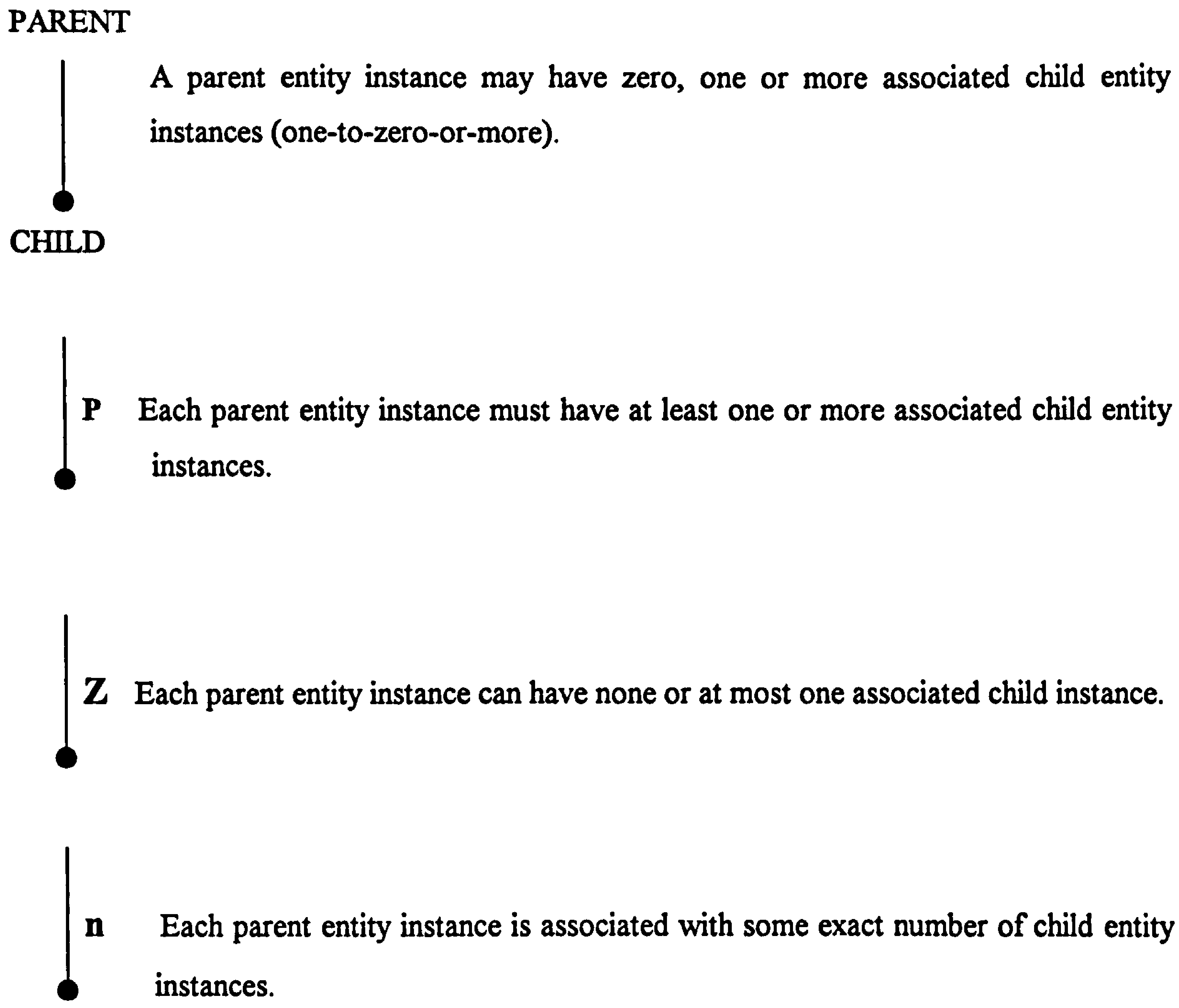


Figure A3.5 Graphical representation of IDEF$_{1X}$ entities

An entity is termed 'independent' if each entity instance can be uniquely identified without knowing its relationship with other entities. An entity is 'dependent' if its relationship with other entities needs to be known to uniquely identify its entity instances.

(ii) Relationships.

Relationships between entities are based on the parent-child concept where each instance of an entity, referred to as the 'parent entity' is related to zero, one or more instances of a second entity called the 'child entity' and each instance of the child entity is related to one specific instance of the parent entity. The instance of the child entity can only exist if its associated parent entity instance exists.



A parent entity instance may have zero, one or more associated child entity instances (one-to-zero-or-more).

Each parent entity instance must have at least one or more associated child entity instances.

Each parent entity instance can have none or at most one associated child instance.

Each parent entity instance is associated with some exact number of child entity instances.

Figure A3.6 IDEF_{1X} relationship cardinality

The relationship cardinalities detailed in figure A3.6 can be described using IDEF_{1X}. In figure A3.6 the solid line represents the identifying relationship between parent and child entities, when a relationship exists the child entity is always identifier-dependent and represented by a box with rounded corners. In such a case the primary key attributes of the parent entity are also inherited primary key attributes of the child entity.

In an identifying relationship a parent entity is identifier-independent unless it is also a child entity in a relationship with other entities, in which case parent and child entities are identifier-dependent.

A non-identifying relationship is described by a dashed line. In which case both parent and child entities are identifier-independent unless they are in some other relationship which is an identifying relationship.

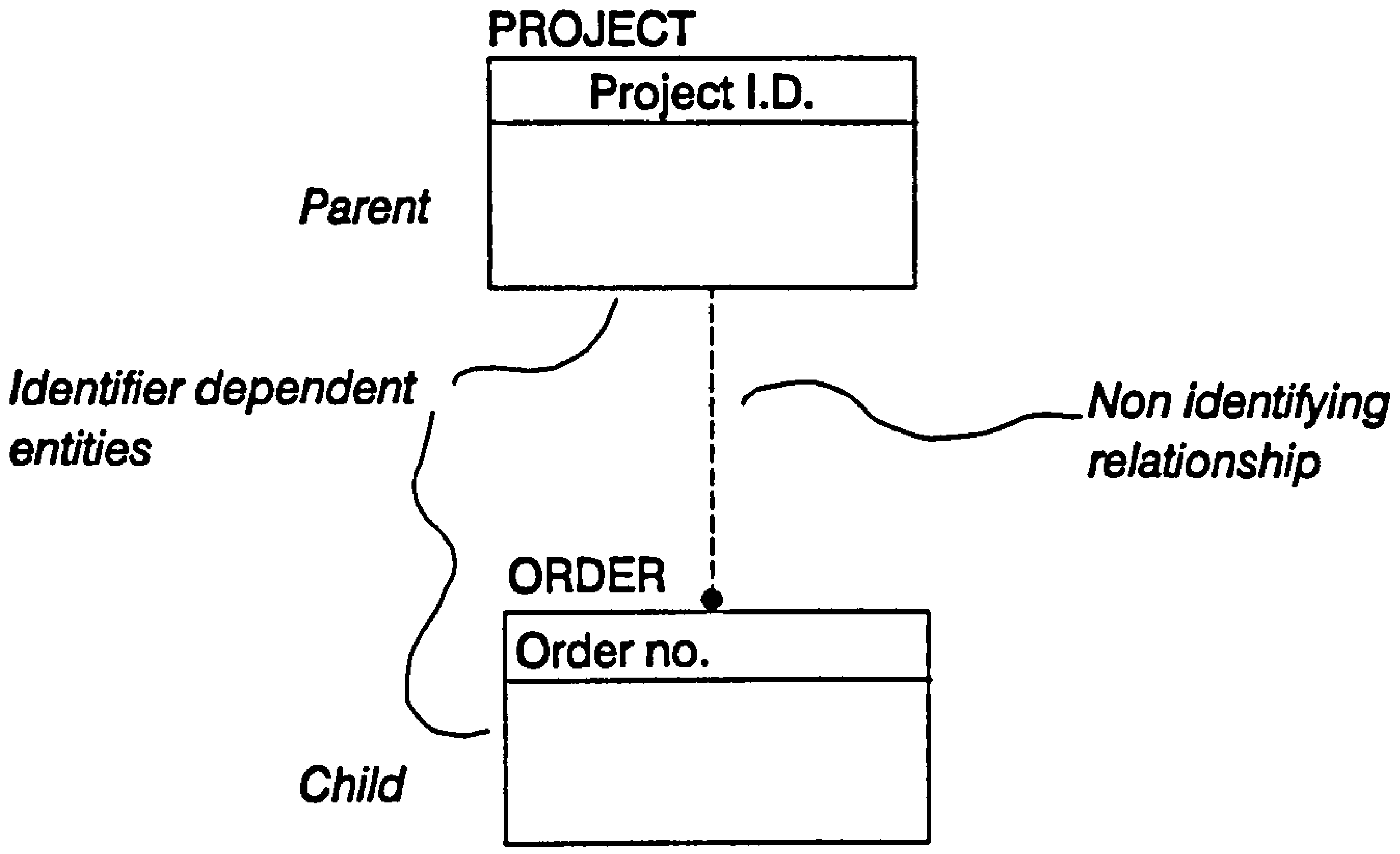


Figure A3.7 An $\mathrm{IDEF}_{\mathrm{IX}}$ non-identifying relationship

In non-identifying relationships an additional discriminator is used in the presence or absence of a diamond at the end of a relationship symbol. A one-to-something relationship is denoted without the diamond as the examples in figure A3.6. With the diamond it becomes *zero-or-one*-to-something, an example is shown in figure A3.8.

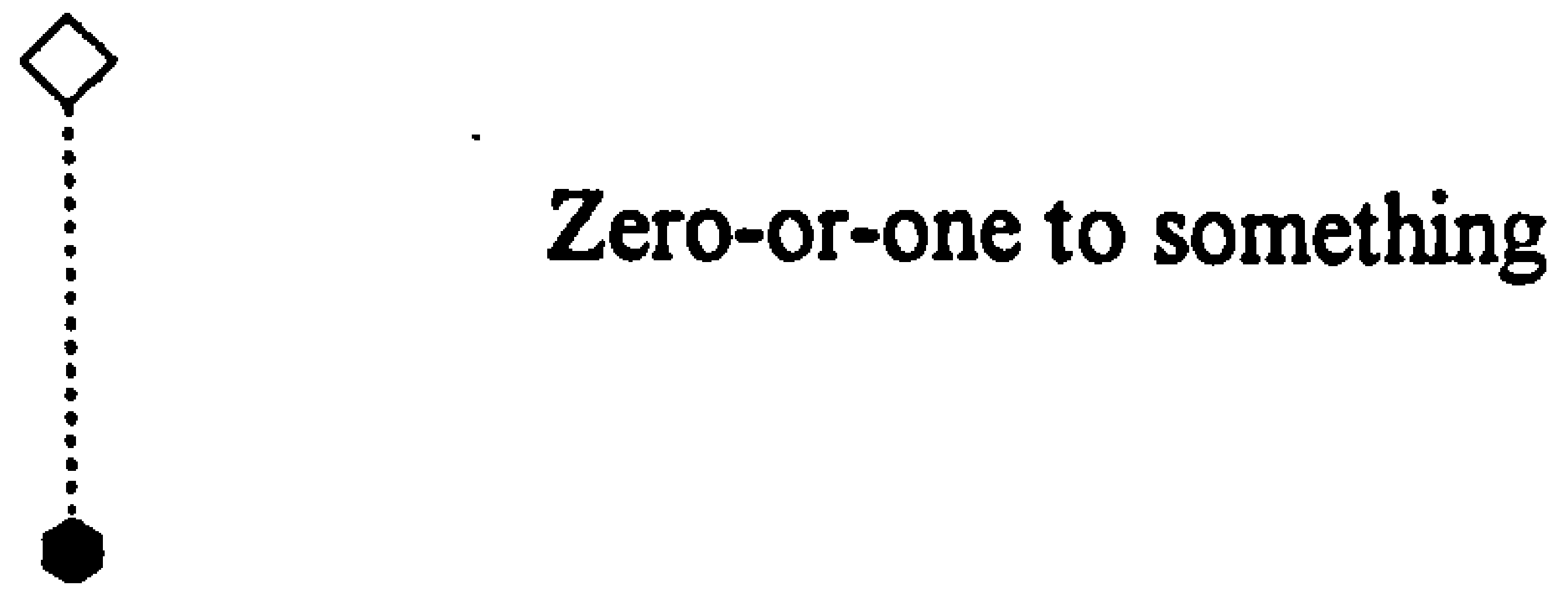


Figure A3.8 A zero-or-one to something $\mathrm{IDEF}_{\mathrm{IX}}$ non-identifying relationship

Categorisation is used in IDEF_{1X} to group entities hierarchically when they share common characteristics. An example of the graphical symbols used is given in figure A3.8. A discriminator, *Valve type*, is used in the example, each instance of the parent entity *Valve* is associated with one instance of one of the child entities, *Manual valve*, *Pneumatic valve* or *Solenoid valve.*

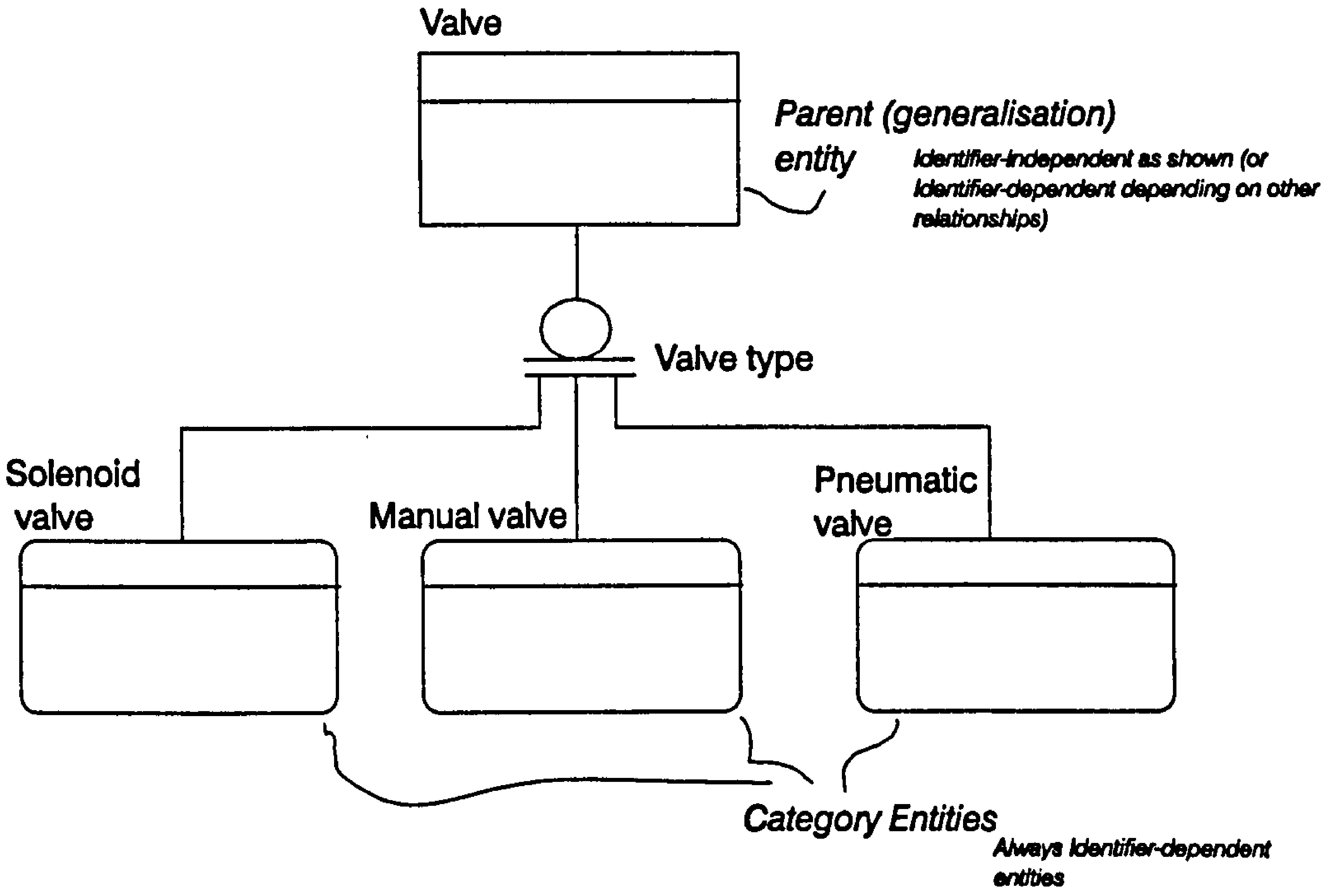


Figure A3.9 IDEF_{1X} categorisation relationships

(iii) Attributes.

An attribute is a set of certain properties of an entity, and an attribute instance is a specific characteristic of an individual member of the set. Attributes can be: Primary key - an attribute that has been selected as a unique identifier for the entity. Non-primary - an attribute of an entity but not a primary key. Candidate key - An attribute (or group of attributes) that could be selected as a primary key. Alternate key - A candidate key not selected as the primary key. Foreign key - is an inherited attribute in a parent-child relationship, where the primary key attribute of the parent entity is also an attribute of a child entity. Figure A3.10 is an extract from a data model for Engineering Data Control (EDC) in capital plant manufacture illustrating the representation of attributes.

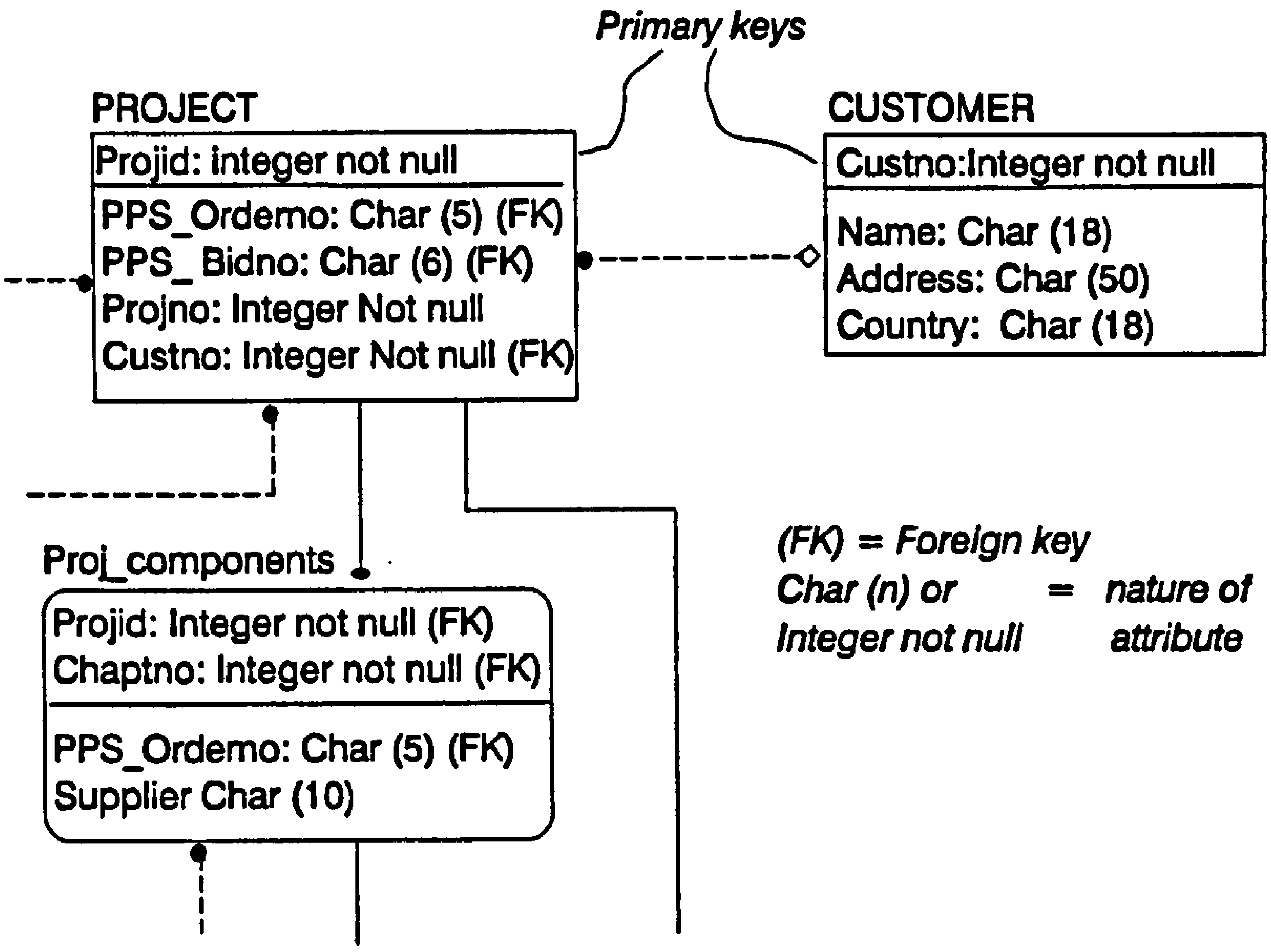


Figure A3.10 Extract from 'Engineering Data Control (EDC) in capital plant manufacture'
(source: Hubel and Colquhoun, 1996)

The syntax and semantics of IDEF$_{1X}$ provide a phased methodology to designing an information system. As part of the methodology the IDEF$_0$ forms and procedures guide (Ross *et al.* 1980) and the ICAM library maintenance and distribution procedures (US Air Force, 1981e) (in common with other IDEF methods) provides rigour to validation, documentation and model development.

The method is widely recognised in the USA, the National Institute of Standards and Technology (NIST) has funded efforts to establish IDEF$_{1X}$ as a Federal Information Processing Standard (FIPS) and section 2.6 indicates the level of software support available for the method. There is, however, no evidence that the method is widely used in the UK or Europe. In the context of this research the method serves as an example of entity-relationship IS modelling and as a complementary method to IDEF$_0$ and IDEF3. Much of the modelling effort in manufacturing enterprise systems is ultimately aimed at introducing modifying or implementing software solutions. Any functional or process modelling approaches must be compatible with the more exhaustive detail requirements if IS modelling which is an argument for using methods such as IDEF in preference to methods such as GRAI and Checkland.

A3.6 IDEF$_2$

IDEF$_2$ is the ICAM dynamics modelling methodology, 'designed to describe the time varying behaviour of manufacturing systems in such a way that the descriptions can be analysed using computer simulation to generate measures of manufacturing system performance' (US Air Force, 1981c). It was specifically designed to represent 'a wide class of manufacturing systems' production lines, group technology cells, software systems or procedural systems such as shop order release systems. The method is designed as a descriptive and an analysis tool and Pritsker and Associates[1] propose that an IDEF$_2$ model can be employed in five ways:

- As an explanatory device to define a system or problem
- As a documentation medium
- As a communications vehicle to determine system elements components or issues
- As a design assessor to synthesise and evaluate proposed solutions to problems
- As a predictor to forecast and aid in planning future developments

The rationale behind development of the method was that the ICAM methods under development in the late 1970's (IDEF$_0$ and IDEF$_1$) could not describe the dynamics of functions or information. In addition to the aspects of IDEF$_0$ and IDEF$_1$ models that could vary over time, there were other aspects of manufacturing such as queues and decisions which demanded a modelling method. The need to evaluate specific measures of manufacturing system performance such as; throughput, the ability to meet deadlines, resource utilisation, in-process inventory, was also considered an objective in the development of IDEF$_2$.

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[1] Pritsker and Associates, The company with responsibility for development of the method, Milner, R. J., Pritsker, A. A. B., and Ippolito, J. F. were specifically responsible for developing the syntax and semantics associated with IDEF2.

IDEF$_2$ modelling principles:

This section is a summary of the principles of IDEF$_2$ modelling, the major reference work is the Architects Manual (US Air Force, 1981c) which provides a detailed account of syntax, semantics and methodology.

An IDEF$_2$ model comprises four sub-models:

(i) An entity flow sub-model that describes entities, such as material or information, the sequence of processes they undergo and what alternative processes are possible. Arrows represent activities and nodes represent the start or end of activities where queues, decisions, and events occur. Figure A3.11 is a flow network showing the symbols used. Activities or processes are shown as arrows and labelled, Queue nodes are shown using 'accumulate' symbols and resource required and resource released states are shown using split box 'assign' and 'allocate' symbols together with labels. The 'boundary' of the system under investigation is shown using a split circle with a 'type' label in the upper half and a location number in the lower half. Boundary types can be START, STOP or GO TO (another location).

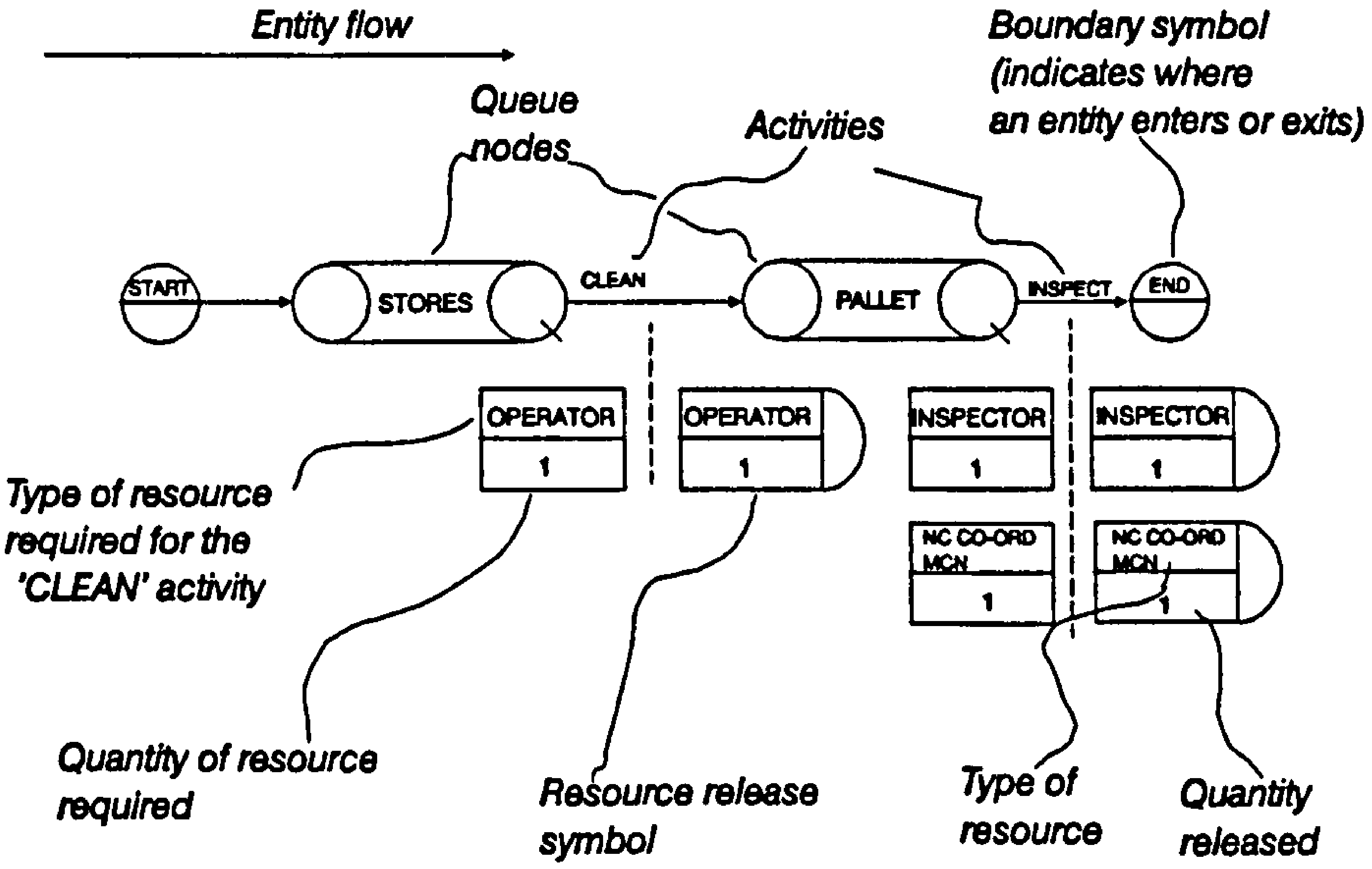


Figure A3.11 An IDEF$_2$ entity flow diagram

Entity flows in a network can have different routes and are shown by diverging arrows after 'selector' symbols, an example is shown in figure A3.12. A complete diagram or 'entity flow network' may contain several branches to represent routing decisions, entity selection, entity matching or branching based on probabilities or conditional logic for each flow path.

Other symbols used in $IDEF_2$ are the 'match node' used to describe a condition where entities in a queue are matched on the specific value of an attribute and the 'assembly node' to describe the situation where several entities from different queues are assembled into a single entity.

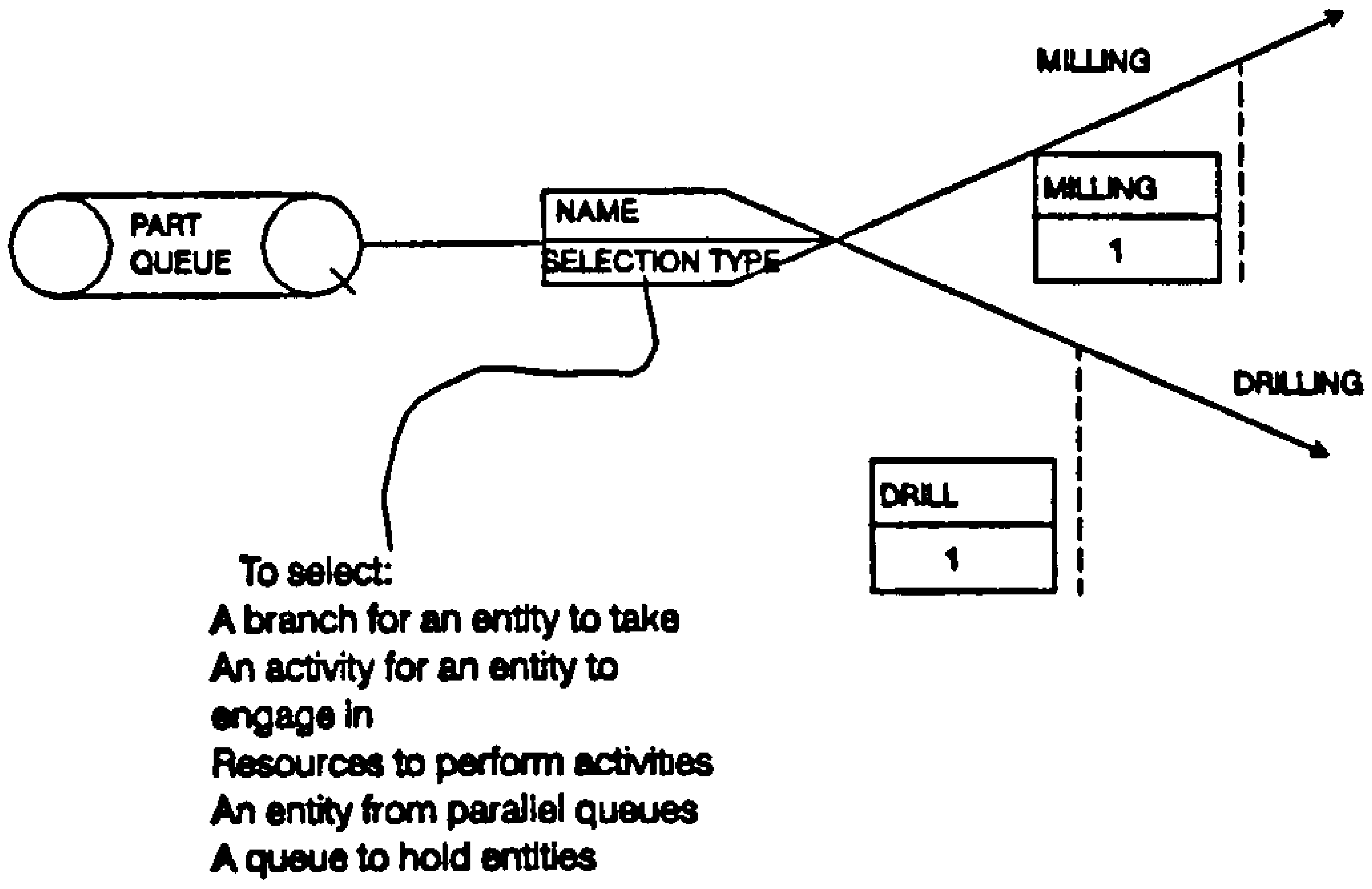


Figure A3.12 Alternative entity flows

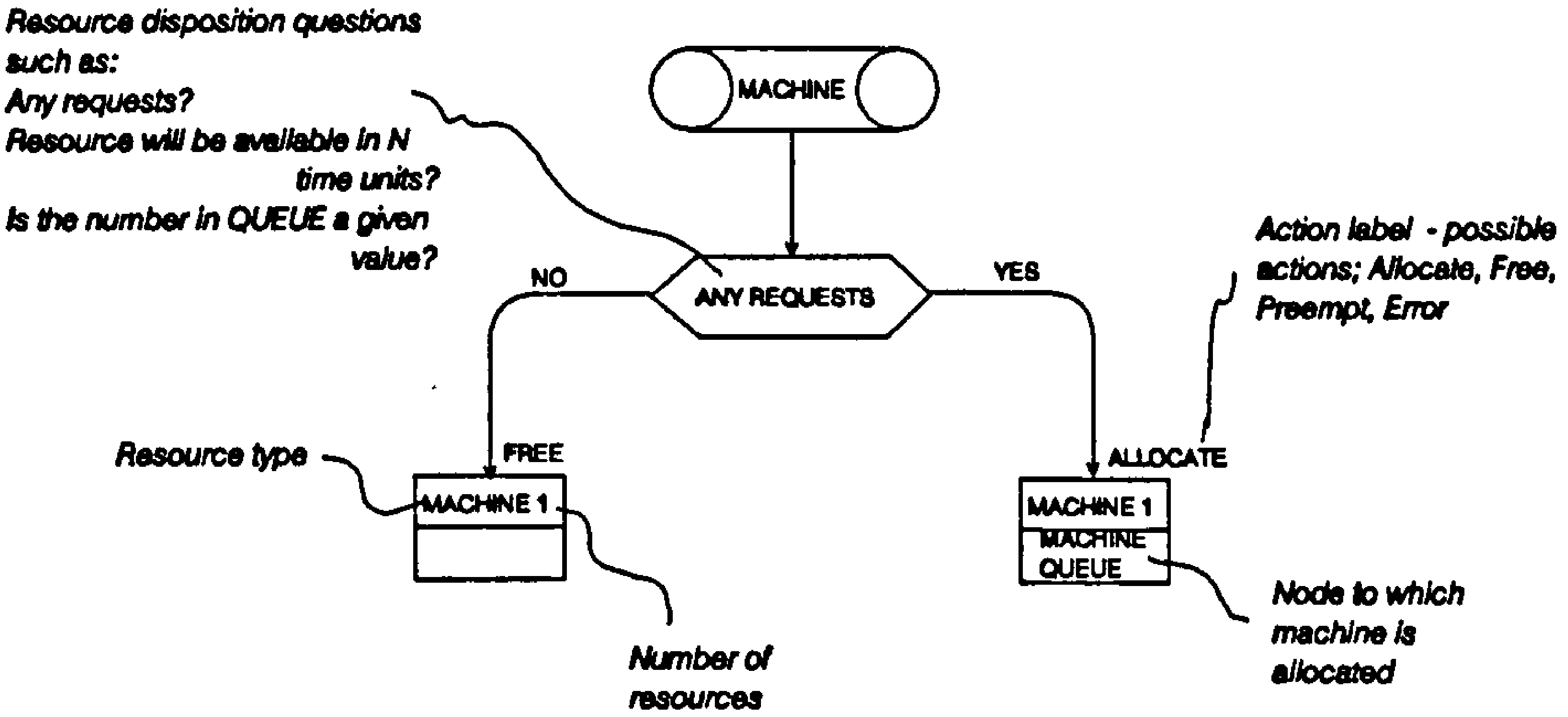


Figure A3.13 A resource disposition tree (Adapted from US Air Force, 1981c)

(ii) A resource disposition sub-model used to describe the state of resources. A hierarchical tree structure using QUESTIONS and ACTIONS describes the disposition of a resource when an activity is completed. Figure A3.13 shows a resource disposition tree for a 'machine' resource that processes parts from a queue, when a part is completed the disposition of the machine is established.

The 'any requests' box polls the machine to see if any parts require processing. If the answer is no the resource can be freed, if the answer is yes the resource 'machine' is allocated to the machine queue. Four possible actions can be initiated using a resource disposition tree; allocate, free, pre-empt and error.

(iii) A system control sub-model describing the actions of activities that control the flow of entities. The control described in a System Control Network is initiated by events, milestones or decisions where the status of the system may change. Figure A3.14 is a simple example of a System Control Network describing the arrival of entities into a system. The CREATE node describes the generation of entities, the SELECTOR node feeds entities to boundary nodes in entity flow networks. The control over which entity goes to which entity flow network is defined by the branch labels. In this case three controls are defined; that the number of entities is greater than 25, that the number of entities in QUEUE 1 is less than 12 and that the current time is less than 1000 units.

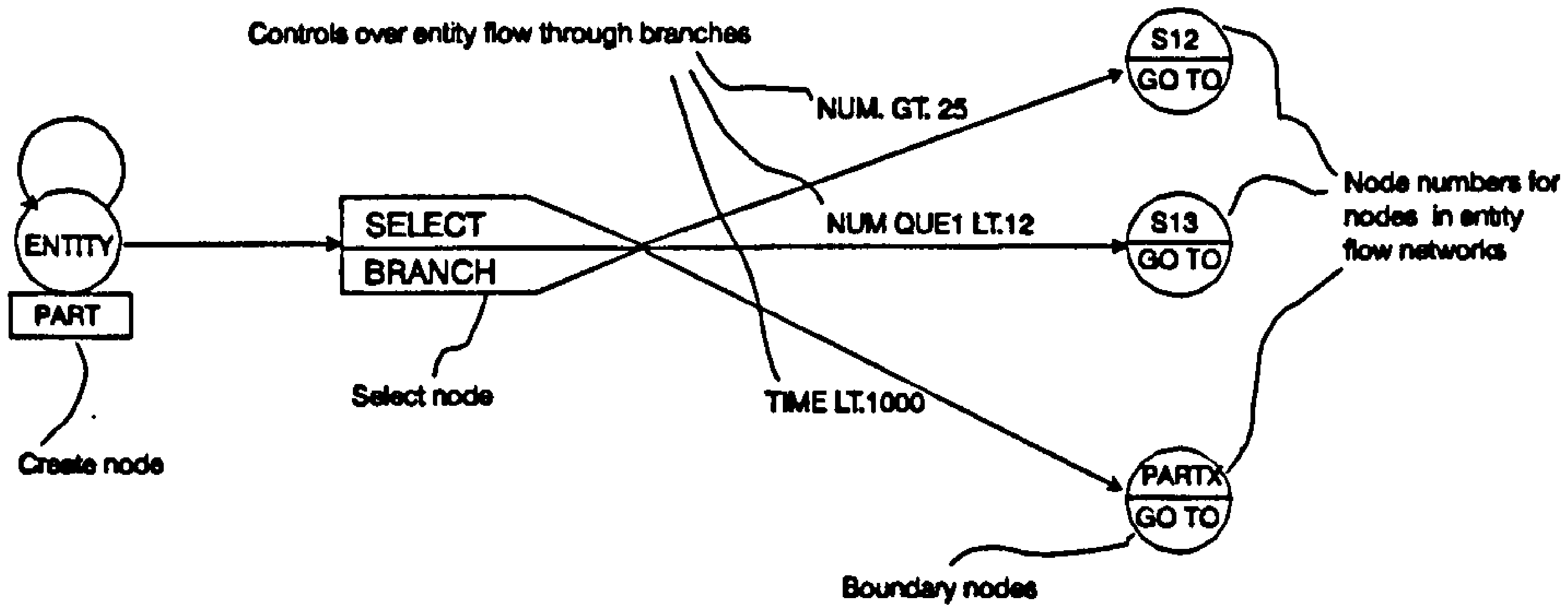


Figure A3.14 A System Control Network (Source: US Air Force, 1981c)

Other nodes that are used in System Control Networks include the ENTER node which is used to initiate an event occurrence and the ACTIVATE/DEACTIVATE node which is used to describe resources available or not available for use. In addition control network nodes include ALTER (resource capacity), DETECT(variable values) and PREEMPT (resource use).

(iv) A facility sub-model which describes the relationships between equipment or resources used by the system. The model could include physical, procedural or intellectual resources. This aspect of IDEF$_2$ modelling uses sketches of the relative locations of system elements in the initial modelling phase to provide a basic understanding of the system under review in terms of layout and production flow. The symbols used to describe elements have been adapted from conventional computer flow chart symbols because 'no standard methods are available, many plants use different layout techniques. However the emphasis when constructing a layout is usually on identifying the flow of materials through the facility' (US Air Force, 1981c). The sketches used in this phase of modelling are not considered to be formal aspects of a complete IDEF$_2$ model but as a structured means of gathering information.

In addition to the four diagramming techniques supporting documents are used to specify the characteristics of the elements in diagrams. A QUEUE for example could be characterised by; an identifier, a description, the ranking rule to extract from the queue, the maximum capacity, the initial number in the queue etc. The forms used to define attributes and values to diagram elements are:

- Facility Component Attribute Definition
- Entity Definition
- Entity Flow Node Definition
- Initial Entity Disposition (the initial states of queues and entities in activities)
- Initial Resource Disposition (the quantity and initial disposition of each resource)
- Initial Continuous System Definition
- System Control Node Attribute Definition

The IDEF$_2$ methodology also includes details of the control of 'Kits' (diagrams, text, glossaries and background information for review and comment) through the ICAM library maintenance and distribution procedures common to other IDEF methods.

During this research the only complete IDEF$_2$ model encountered is a detailed model (280 pages) of 'A Sheet Metal Centre Sub-system' produced by SofTech Inc. under USAF contract F33615-78-C-5158 (U S Air Force, 1981f) to demonstrate the usability of IDEF$_2$ on a real world problem and 'to build a model which can be analysed by IDEF$_2$ software when it becomes available'. It is clear that commercial IDEF$_2$ software did not become available, that the U S Air Force contract (Pritsker and Associates, see section 2.3.2) to develop the method stopped short of funding software development and the method has not been widely adopted. Bondi and Pritsker (1985), however, provide an account of a prototype system for the analysis of IDEF$_2$ networks called NET_TRANS (Net Translator). The system automatically determines the applicability of either the Graphical Evaluation and Review Technique (GERTE) (Pritsker, 1974) or queuing network theory for the analysis of an IDEF$_2$ models.

SLAMII is one of the four most widely used general purpose simulation languages in the USA (Law and Kelton, 1991), it was developed by Pritsker and Associates (Pritsker, 1986) from their earlier SLAM simulation software, Ross claims (1994) that $IDEF_2$ was the foundation of SLAMII although no acknowledgement of this is given by Pritsker in his work. SLAMII is one of a group of simulation languages that uses graphical networks as the basis of description (Yancey, 1985). The symbols used in a SLAMII network, nodes, queues, assignments, etc. are analogous to those in a $IDEF_2$ entity flow network although SLAMII carries more detailed parameter values in diagrams and the method is focused on 'statements models' (text statements of the sequence of entity flow through a network) for input to a computer.

Despite the lack of development of $IDEF_2$ it still played a part in the evolutionary development of simulation for manufacturing systems and more importantly for this research, had some influence on the development of IDEF3. The philosophy behind both methods is to provide a means of describing the behaviour of a system in such a way that the description can be analysed using a computer system to evaluate performance. Both methods emphasise the use of the graphical aspects of a model as a vehicle for communication and both methods recognise the need to represent the 'time' or temporal of manufacturing.

A3.7 IDEF4

IDEF4 (Mayer et al, 1992b) is a design method that supports an object-oriented approach to software design in contrast to $IDEF_{1X}$ which is based on structured analysis and functional decomposition. The object-oriented approach is an emerging philosophy now widely accepted as a means of thinking abstractly about software design problems independent of a software implementation language. Object-oriented modelling uses the concept of modelling real world 'objects' that combine data structure and behaviour in a single element and then utilising the model to design a system around the objects, independent of the language to be used for software implementation. Object-oriented approaches describe entities through data *abstraction encapsulation* and *inheritance.* Using the approach the system under review is seen as a collection of objects which are encapsulations of data whose functions are defined by the messages to which they respond. Through encapsulation, adding or deleting objects does not influence other objects. Objects also belong to classes or sub classes and they inherit the behaviour and structure of their super-class. New objects can be added easily by inheriting the characteristics of their class.

Many authors (Coad and Yourdon, 1990, 1991, Rumbaugh et al, 1991, Agresti, 1986, Somerville, 1992) advocate advantages for object oriented software design and analysis over traditional functional approaches;

- software re-use and flexibility due to modular design.
- software maintainability due to transparent system design, relative ease of program modification.
- the clear relationship between real world entities and system design. The real world tends to be perceived as physical entities rather than functions.

Several modelling methods (Booch, 1991, Rumbaugh et al, 1991, Firesmith, 1993, Shlaer and Mellor, 1988, Graham, 1991, Coad and Yourdon, 1990) have been developed to support the concept, amongst them the IDEF4 method. In the original version of IDEF4 (Mayer et al, 1992b) objects are modelled using a hierarchy of related diagrams, figure A3.15 shows the organisation of a complete model.

Revision two of the method was a substantial re-design using important features of successful object oriented designs and modelling conventions to 'leverage software components, client/server technology and successful object-oriented design technology' (Keen, and Schafrik 1995).

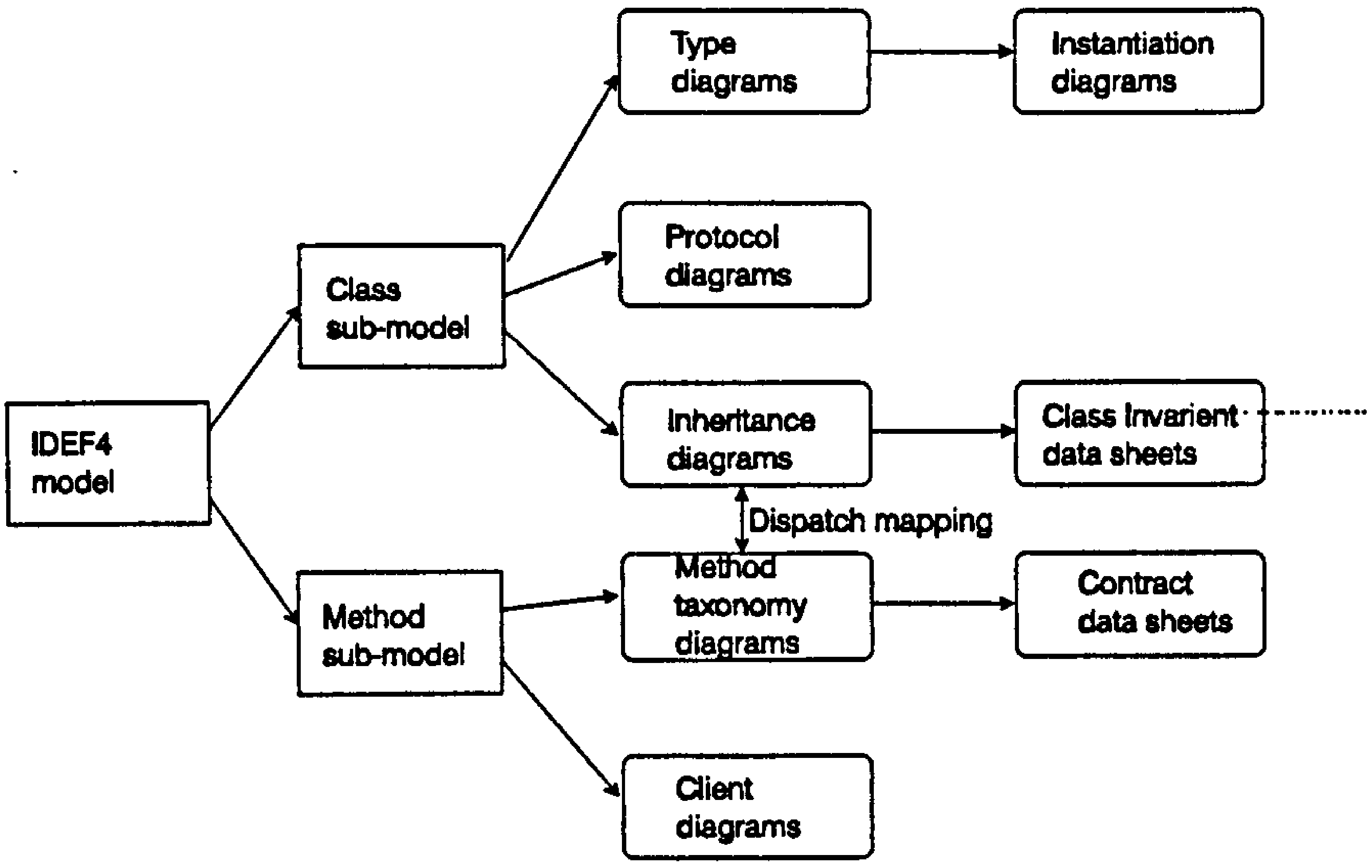


Figure A3.15 The structure of an IDEF4 model (Source: Mayer et al, 1992b)

Revision two-IDEF4 is very similar to Rumbaugh's Object Method Technique (OMT) and the Object Oriented Analysis and design technique (OOA/OOD) of Shlaer and Mellor with three crucial differences:

- It is specifically designed to interface and re-use information generated in $IDEF_0$, $IDEF_{1X}$ and $IDEF_3$ models.
- It allows tracking of the status of design artefacts from domain object through transition to design specification.
- It includes a design rationale component.

IDEF4 revision two (Keen, and Schafrik 1995) is based on three models: a Static model (SM), Dynamic Model (DM) and a Behaviour Model (BM) together with a design rationale component:

(Table A3.1 Gives examples of some of the terms used in IDEF4 revision two)

An SM defines time invariant relationships between *objects* such as inheritance, object classification, operations that can be performed on an object, *attributes* describing objects and structural *relations*.

A DM defines communications between objects using a graphical representation of the messages relayed between objects and the *events* which cause an object to implement a message.

A BM is a diagram that describes the implementation of messages by *methods*.

IDEF4 Term	IDEF4 symbol	Examples
Application domain		Bank
Feature		Aspects of the 'Bank' to be modelled
Object	O O	Account, Employee
Attributes	A A	Name, Address
Methods	M M	Open, Close
Relation	R	Emp/Acc
Event	E	Audit

Table A3.1 Examples of IDEF4 terms (Adapted from Keen, 1995)

Design rationale capture is accomplished by providing specifications for each IDEF4 *artefact* (figure A3.16 shows the evolution of IDEF4 *artefacts*). Figure A3.16 also illustrates the relationship between artefact evolution and design status. The essence of the IDEF4 methodology is that for each stage in design status SMs, DMs and BMs are produced.

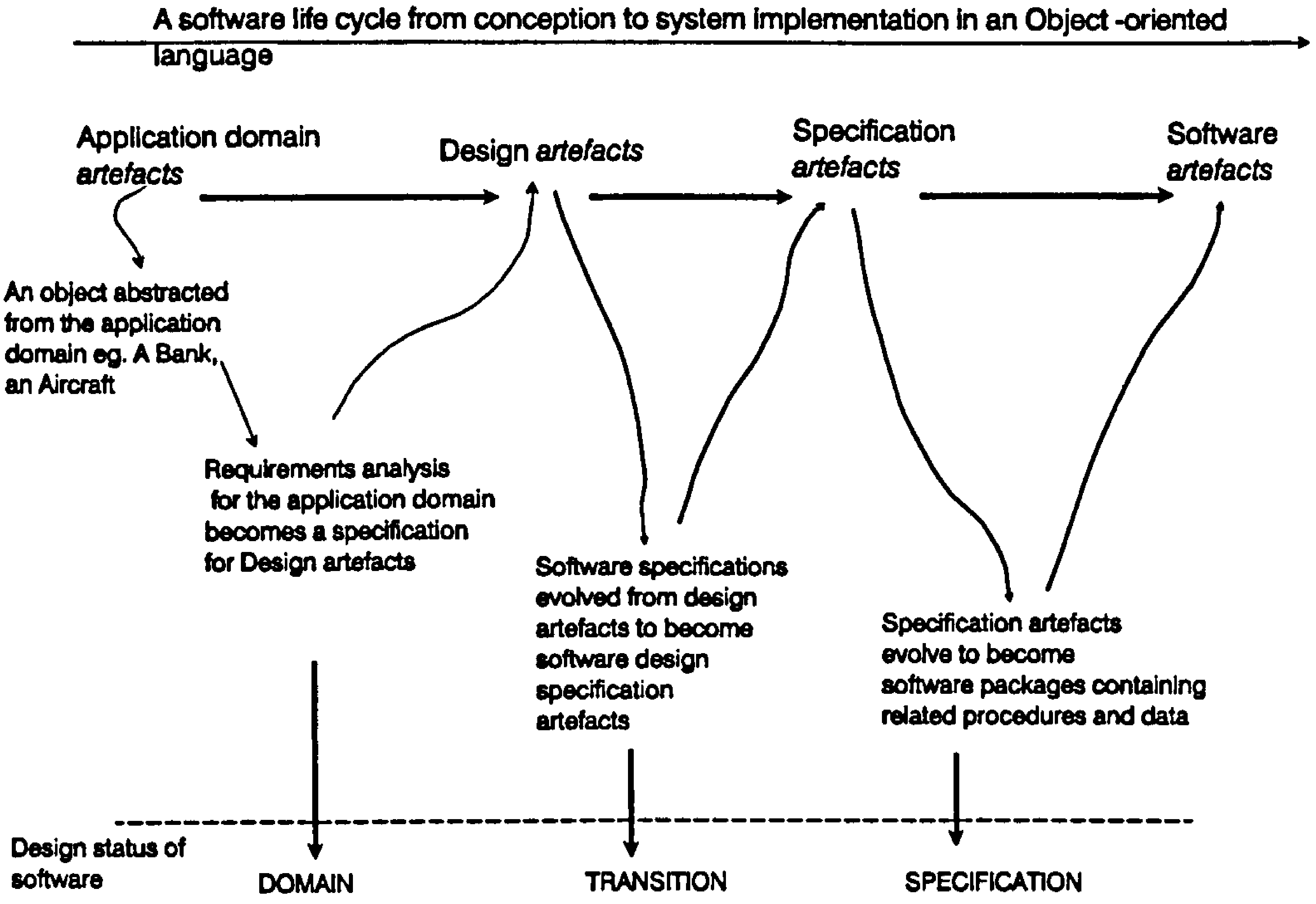


Figure A3.16 The evolution of IDEF4 artefacts

The links between IDEF4 version two and other IDEF methods are of particular interest to this research. Although no explicit indication is given of the potential interfaces it is evident that they are in the areas indicated in table A3.2.

IDEF4 version 2	IDEF0	IDEF3
Method	Activity	UOB
Features	Viewpoint	Scenario
Event		UOB & Junction
Object & Attributes	ICOM	

Table A3.2 Potential relationships between IDEF4 version 2 and other IDEF methods

IDEF4 version 2 is evidently in the development stage, little evidence (Zhao, Baines and Colquhoun, 1995) has been found of its application outside the work of the developers, KBSI, and no commercial IDEF4 software tool is available (KBSI are currently (1995) developing an IDEF4 tool called AI4^{TM}). There are many object-oriented methods in a more mature form than IDEF4, with CASE tools to support applications, unless the advantage gained through its links with other IDEF methods is significant widespread adoption of the method seems unlikely.

APPENDIX 4

MODELLING METHODS REVIEW

CONTENTS

A4.1 THE CHECKLAND SOFT SYSTEMS METHODOLOGY

At the clearly 'soft' end of the modelling spectrum shown in figure 4.1, the Checkland soft systems methodology (Checkland, 1981, Wilson, 1984, Checkland and Scholes, 1990) is proposed as a means of understanding situations by developing insight into how participants in a system view and interact with the system. 'From a soft systems perspective , the collective perceptions of the members of a system *are the system* for the people in that system' (Cavaleri and Obloj, 1993). The methodology provides an analyst with a means of structuring an investigation of systems problems. In brief the complete methodology comprises seven stages: 1. Recognition of the problem station. 2. Building a 'Rich Picture' of the situation. 3. Establishing a 'Root definition' to provide a precise text based description of a situation that embodies the elements of the problem described by the mnemonic CATWOE where;

- C describes the receivers of the results of the transformation.

- A describes the 'actors' who carry out the transformation.
- T the transformation process or activity that embodies the problem situation.
- W is the viewpoint or 'worldview' implied in description
- O describes the owner who controls the transformation.
- E describes the environment or natural constraints of the system.

4. From the root definition a conceptual model of a system can be produced in graphical and text form to provide an ideal 'TO BE' description of the situation. 5. A comparison of the idealised 'TO BE' model with the 'Rich Picture' of the existing situation. 6. Analysis and discussion of the issues raised by comparison, with a view to proposing changes. 7. Action to implement changes.

The relatively unstructured diagrams resulting from application of the methodology cannot easily be compared with the rigorous, formal presentation of other modelling methods such as GRAI, Petri nets or IDEF methods. At a high level of abstraction however an $IDEF_0$ model represents a system in a similar way using the 'Context' and 'Viewpoint' diagrams for AS IS and TO BE models and where the investigation to establish ICOMs can be loosely compared to a CATWOE root definition. *C*ustomers can be seen as the recipients of $IDEF_0$ outputs. *T*ransformations as IDEF0 functions. *A*ctors and *O*wners as $IDEF_0$ mechanisms and controls. Interestingly Wu (1994, p 210) proposes $IDEF_0$ as a modelling method that could be used at stage four in the Checkland Soft Systems methodology as a diagramming method for a conceptual model.

In reviewing development of the methodology since its inception (Checkland and Scholes, 1990) reflect that 'SSM not only develops and changes but also gets used in different ways by different users in different circumstances.' and the approach although not specifically developed for manufacturing enterprise applications has been used to solve manufacturing problems Checkland (1989).

A4.2 THE VIABLE SYSTEMS MODEL (VSM)

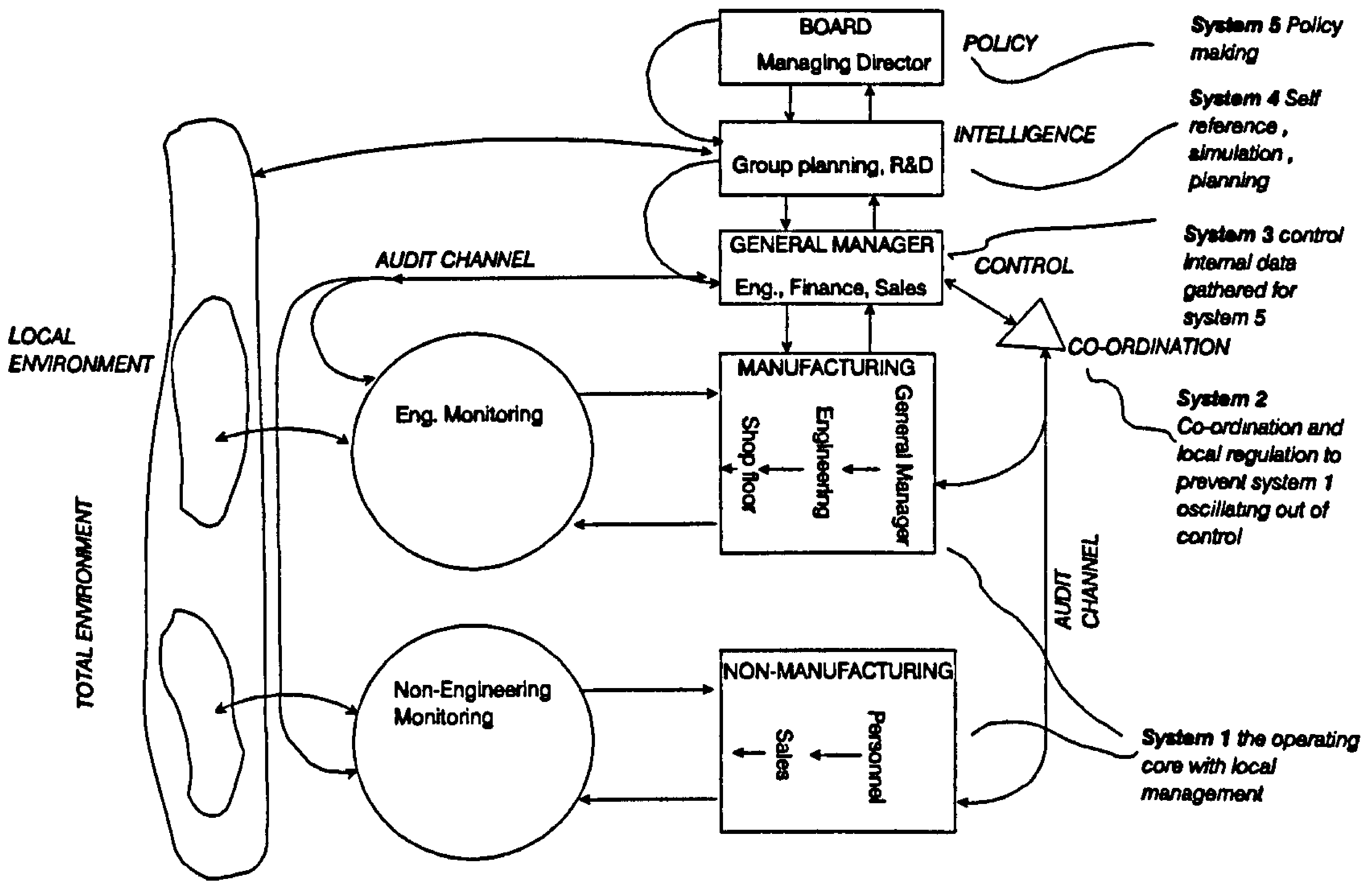


Figure A4.1 The Viable Systems Model (adapted from Espejo, 1989b)

The Viable Systems Model (VSM) approach developed by Beer (1979, 1981, 1984) has evolved from Operations Research (OR) and Cybernetics. Beer perceives the human nervous system as his exemplar, the nervous system follows a number of key principles to ensure its survival, the brain has to regulate a large number of variables (temperature, balance etc.). It has to learn to adapt to changing situations and develop over time. Analogies can be drawn with the control and management necessary for large organisations such as manufacturing enterprises. His approach is based on the precept that there are five generic sub-systems interactively involved in any viable organisation involving human beings; operating core, control and co-ordinating mechanism, internal information systems, external information systems and policy making they are shown in an example in figure A4.1. Figure A4.1 has been adapted to illustrate the VSM in a manufacturing domain. The VSM has been developed as a general systems approach to develop strategies or organisational policies and manufacturing applications have been cited by Espejo and Harnden (1989) and Kehoe et al., (1993).

A4.3 THE GRAI (Graphe à Résultats et Activités Interliés) METHODOLOGY

(Graphs with results and activities interrelated)

The GRAI methodology (Doumeingts, 1984, Doumeingts, 1985, and Pun et al, 1985) has been developed to 'analyse and design CIM systems with particular emphasis on Production Management and Flexible Manufacturing Systems' (GRAI Laboratory, 1987). The GRAI approach in common with $IDEF_0$ and unlike many modelling methods has been developed to deal specifically with manufacturing.

The GRAI conceptual view of manufacturing organisation proposes that there are three sub-systems, the *'Physical system'* consisting of the means of production, men, machines and material converting raw material into products. Above the physical system is a *'Decision system'* a hierarchy of decision centres, at the top of the hierarchy are long term strategic decisions and at the lower levels of the hierarchy are the real time decisions that directly control manufacturing. Finally, connecting the Physical system and the levels of the Decision system hierarchy, is the *'Information system'*.

Application of the method produces a graphical model that represents the operation of each decision centre in terms of its activities, the time frame of operation, the decisions made and the information used. Graphical representation is based on two types of diagram, GRAI grids and GRAI nets.

The GRAI grid is a top down description of the structure of decision centres showing a hierarchy of time horizons and periods as rows in the grid and functions as columns in the grid (see figure A4.2).

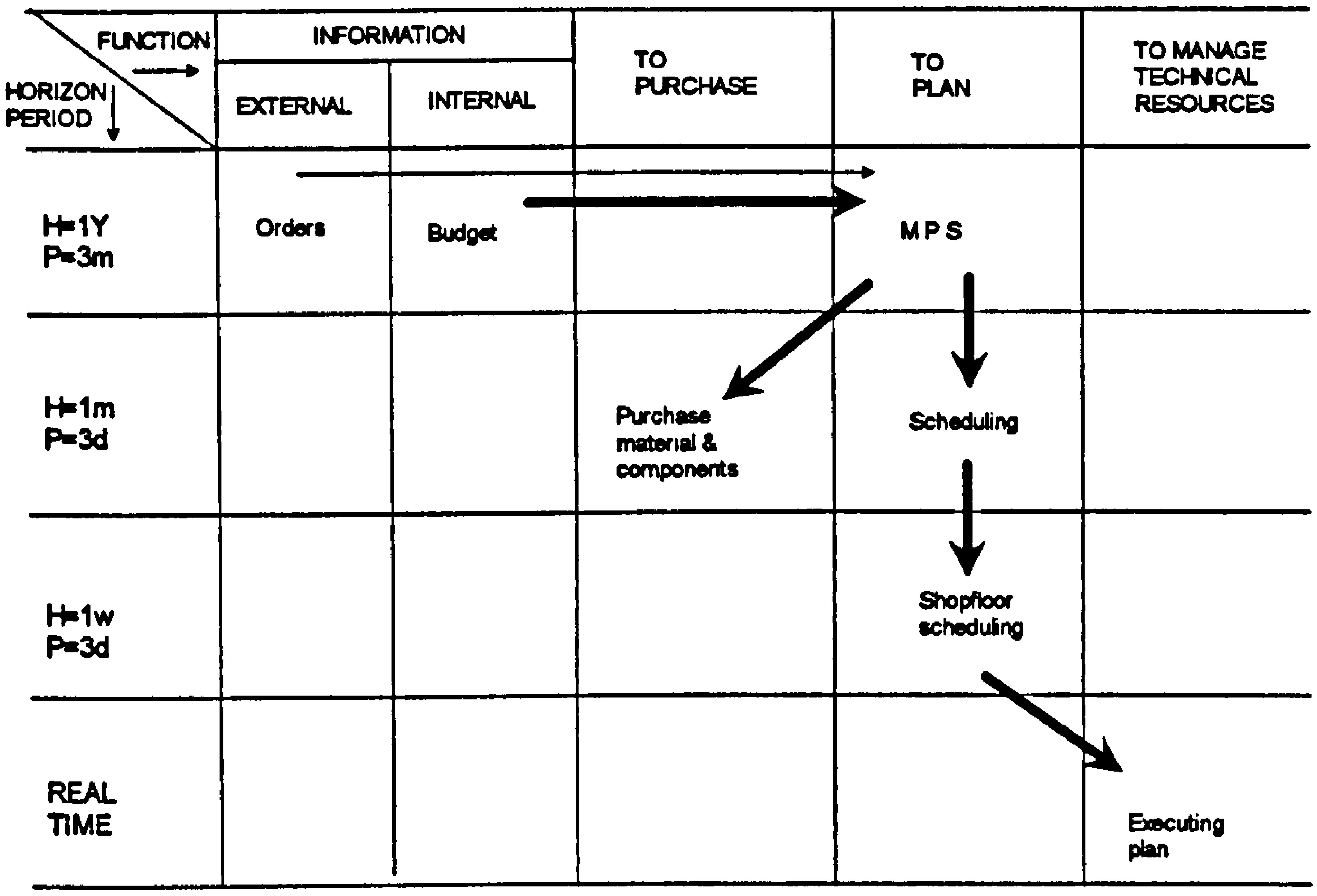


Figure A4.2 A GRAI grid for a 'make to order' company.

Each block of the grid represent a potential decision centre, flows of information are identified with single arrows and the transmission of decisions shown as thick arrows.

A GRAI net (an example is shown in figure A4.3) is a form of decomposition diagram that relates decisions identified in the GRAI grid to the information and resources required to execute the decision. For a detailed account of the application of Nets and Grids the reader is referred to 'The rules of the method and analysis of GRAI Grids' (GRAI Laboratory, 1991).

Decomposition to expose greater detail is accomplished by 'exploding' an overall (global) grid into detail grids.

In comparing GRAI and IDEF$_0$ some fundamental differences are evident. The GRAI method is focused on the identification and analysis of decision centres and in the GRAI grid only 'important' information is identified. In contrast to the central IDEF$_0$ focus on activities and the relationship of activities in terms of information or objects.

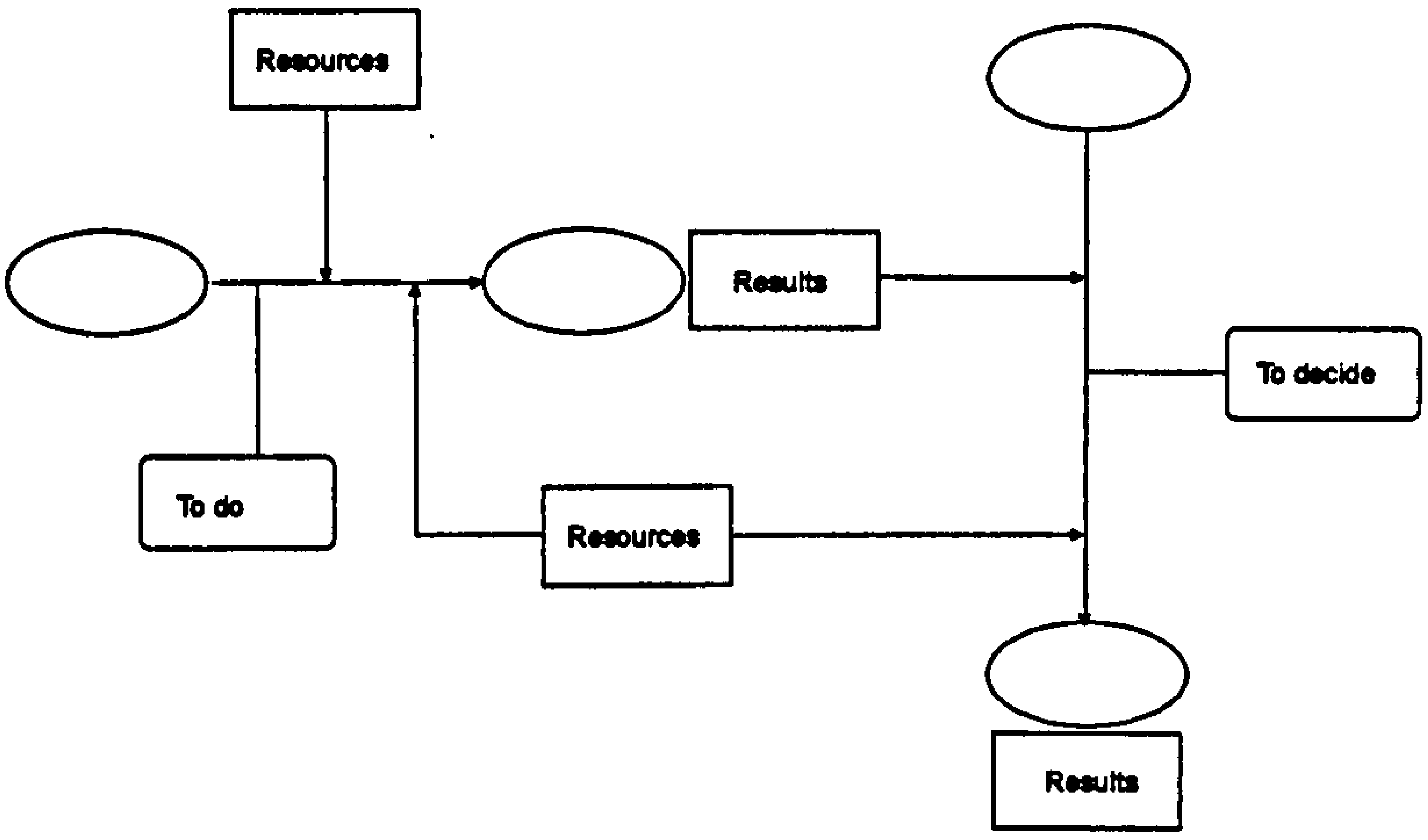


Figure A4.3 A GRAI Net (Source: Roboam and Pun, 1989)

A timescale in the form of planning horizons and planning periods (in effect the planning horizon for a decision and the length of time a decision is effective) is a dimension in the GRAI grid that cannot be explicitly represented graphically using IDEF$_0$.

A4.4 THE STRUCTURED SYSTEMS ANALYSIS AND DESIGN METHODOLOGY (SSADM)

In the UK, SSADM is a widely accepted, structured methodology (Cutts,1991, Longworth and Nicholls 1987) that utilises several graphical models for the analysis and design of software systems. The complete methodology is based on three phases; feasibility study, Systems analysis and Systems design and comprises eight stages; problem definition, project identification, analysis, specification of requirements, selection of system options, logical data design, logical process design, physical design.

The methodology uses graphical modelling in the form of data flow diagrams and entity-relationship and entity life history diagrams. The data flow diagram used in SSADM is based on the older DFD technique propounded by DeMarco (1979). In SSADM the data flow diagram represents activities or functions using rectangles, the sources or destinations of data using ellipses, data flows using arrows and data stores using open-ended rectangles (shown in figure 4.6). The detailed rules for model building advise that there should be no more than three levels of decomposition in contrast to $IDEF_0$'s unlimited approach.

$IDEF_0$ cannot be directly compared with the complete SSADM methodology however the SSADM data flow diagram has its roots in the DFD described by DeMarco and as such comparison of the basic principles of data flow diagrams and $IDEF_0$ is valid.

A4.5 THE NIJSSEN INFORMATION ANALYSIS METHOD (NIAM)

The NIAM information modelling method has been developed in Europe and Australia (Nijssen and Halpin, 1989) and is widely used in ESPRIT projects (Los et al, 1992). The method is oriented towards situations where an information processing system is used to communicate between users and an object system such as a manufacturing system. A complete review of the diagrams used in the method and the NIAM methodology is given by Nijssen and Halpin (1989) which includes all the steps necessary to get from a NIAM model to a relational database. There are some important differences between NIAM and the more established Entity/Relationship methods such as $IDEF_{1X}$. A fundamental concept is that an Information Structure Diagram (the NIAM equivalent of an E/R diagram) distinguishes between Non-Lexical Object Types (NOLOTs) which are real life objects and their descriptive data - Lexical Object Types (LOTs). NOLOTs and LOTs are equivalent to entities in conventional E/R modelling but NIAM does not attach attributes and consequently does not apply normalisation to database design.

A4.6 THE CONTROLLED REQUIREMENTS EXPRESSION (CORE) METHOD

The design of CORE (Curwen, 1990) was funded by British Aerospace as a method to develop system and software requirements specifically for Aerospace manufacturing. Some aspects of the method are based on SADT and Parnaby et al (1988) claim that CORE provides 'some useful additions to $IDEF_0$'. Application of the CORE method involves producing seven types of diagrams:

- Viewpoint structure diagrams
- Tabular entry diagrams
- Data composition diagrams
- Isolated thread diagrams
- Combined thread diagrams
- Isolated operational diagrams
- Combined operational diagrams

The diagrams together with structured text descriptions called 'Node Notes' supplementing each diagram form a complete CORE model. The diagrams of particular relevance to this research are the Viewpoint structure diagrams and the various thread diagrams.

Viewpoint structure diagrams are the result of a 'viewpoint analysis' to establish all the viewpoints to be considered in the problem. The viewpoints are represented in a hierarchical tree developed using a set of rules based on partitioning viewpoints into user views, functional views, non-functional views, data views etc..

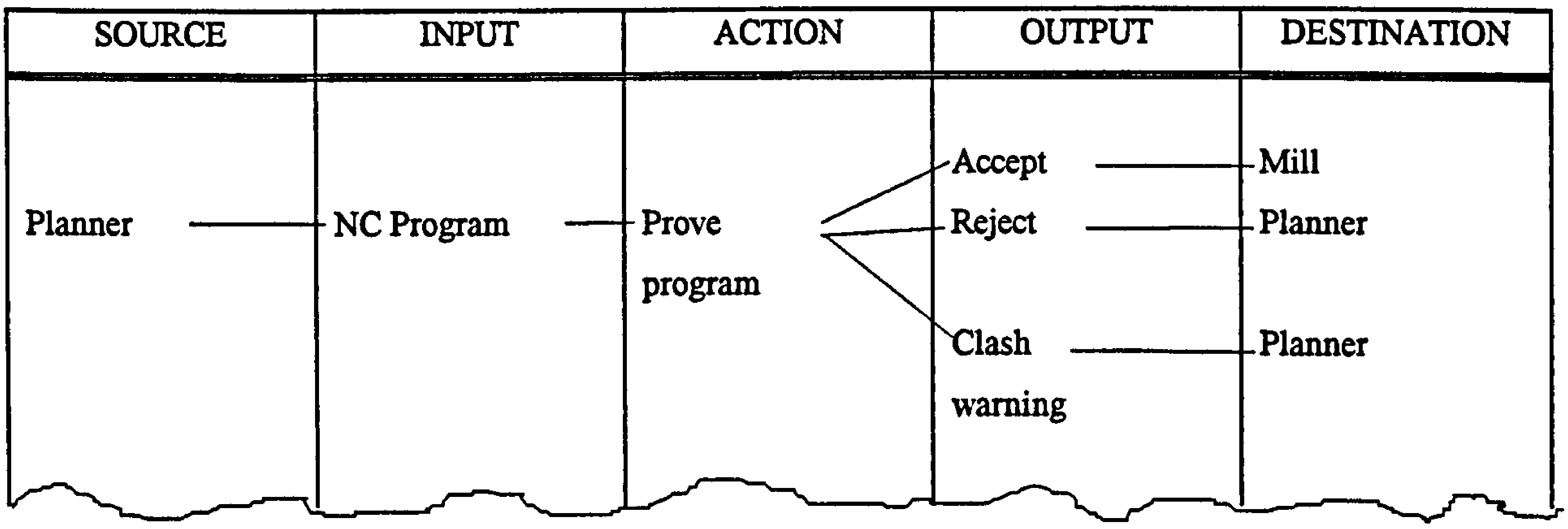
Tabular entry diagrams are used to collect information on the processes involved in each viewpoint. Figure 4.4 is an example of a Tabular entry diagram showing structure of the information collected for each process (a process is termed an 'action' in CORE).

Figure A4.4 shows one (prove program) of the many actions that could be involved in the Bridgeport milling machine viewpoint and the four categories of information necessary to complete the tabular entry for the action.

Tabular collection diagrams describe input and output specifications and identify the actions in a particular viewpoint (the viewpoint in figure A4.4 is that of the 'Bridgeport milling machine'). For every action in each viewpoint an Isolated thread diagram is then produced.

Figure A4.5 shows a thread diagram for the 'prove program' *action* in figure A4.4. Thread diagrams are similar to DFDs and $IDEF_0$ diagrams. Arrows entering the left side of boxes are inputs, outputs are on the left side, boxes describe a sequence of actions and the sources of diagram input arrows and destinations of diagram output arrows are labelled.

BRIDGEPORT MILLING MACHINE VIEWPOINT



SOURCE	INPUT	ACTION	OUTPUT	DESTINATION
			Accept	Mill
Planner	NC Program	Prove program	Reject	Planner
			Clash warning	Planner

Figure A4.4 A CORE tabular entry diagram

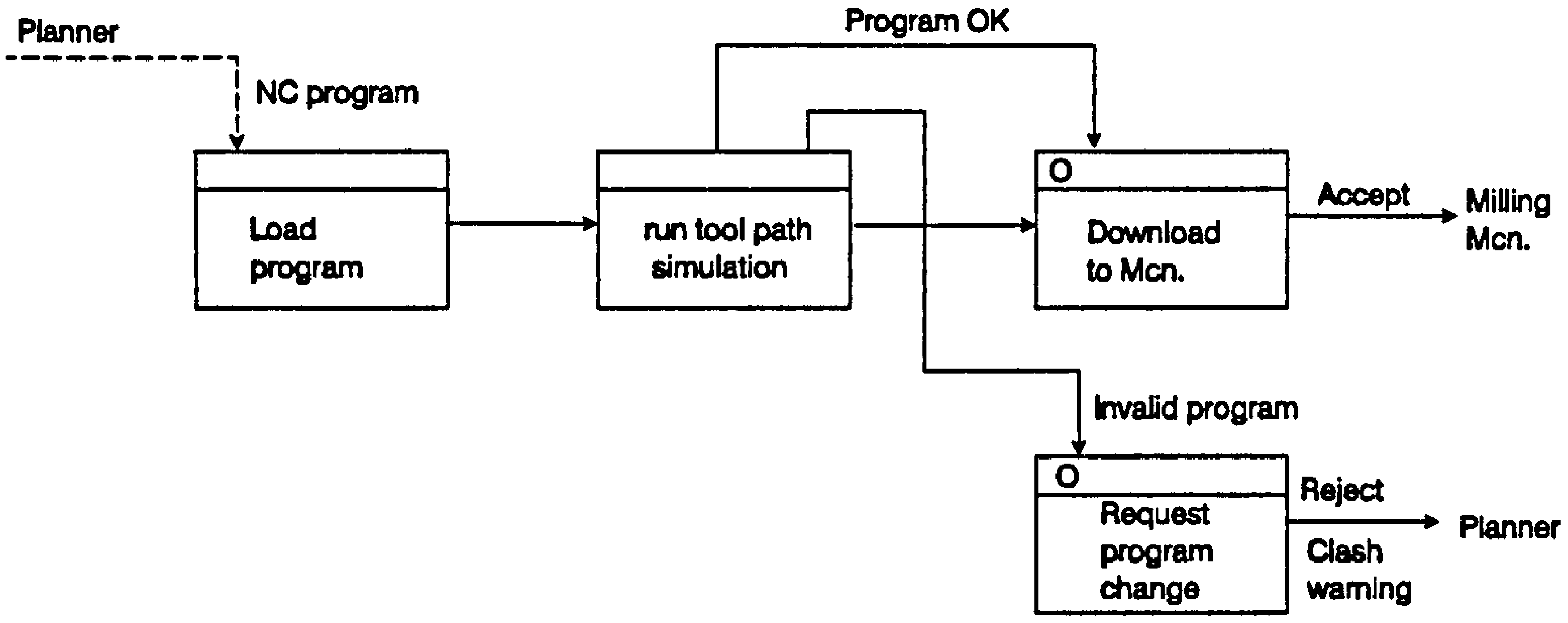


Figure A4.5 An individual thread diagram for the 'Prove program' *action*

Figure A4.5 illustrates some of the graphical conventions of CORE :

- The ordering of boxes from left to right is significant and indicates the sequence of actions.
- Control information is shown entering or leaving the top of boxes.
- If boxes are aligned vertically actions may be carried out concurrently (not in the case of figure A4.5). No partial alignment overlap of actions is allowed.
- A dotted line indicates a control that must be triggered by an event, in this case it could be demand for a machined component.
- '*Critical*' data is shown with a dotted line, where critical data is 'eventually used and used only once' and 'consumed when read and not overwritten'.
- '*Non-critical*' data is shown with a solid line, is data that 'overwrites previous data' and 'can be read many times before being refreshed'.

In figure A4.6 some important features of *action* box control syntax are illustrated.

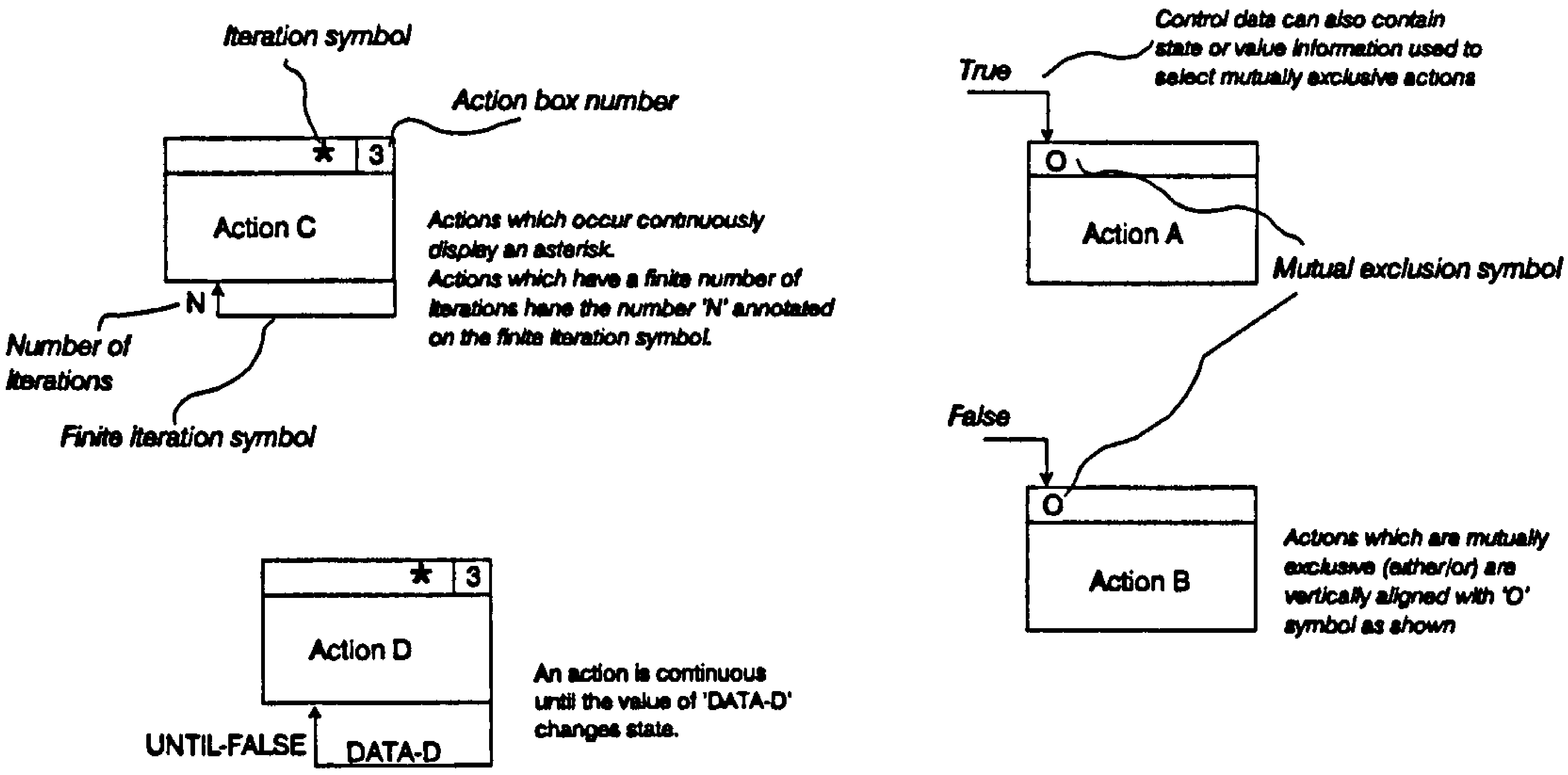


Figure A4.6 Examples of CORE *action* box syntax

(Adapted from Curwen, 1990)

The symbol 'D' used in the top centre of an action box indicates that an action box has been decomposed, decomposition involves the same parent/child syntax checking as IDEF$_0$. 'Mechanism' arrows are shown entering the lower edge of an action box. In CORE terminology a 'mechanism' can be the viewpoint name to which the action belongs or an implementation partition.

Combined thread diagrams are a composite of Individual thread diagrams used to describe the relationships between the different viewpoints being considered.

A4.7 DISCRETE EVENT SIMULATION

Computer based discrete event simulation uses mathematical models to predict the changes in a system as it evolves over time. 'Events' are points in time when an instantaneous occurrence may change the state of the system. The input to models is stochastic, based on statistical distributions and will produce an output that is in itself random and is therefore an estimate of the behaviour of a model. Simulation could be done using manual calculations without the use of formal graphical descriptions but the complexity of manufacturing systems and the amount of data to be stored and manipulated demands the use of a computer. The development of computer graphics, RAM and hard disk memory capacity over the last ten years has led to the routine use of animated displays for events and the states of models. The graphical system description aspects of discrete event simulation are, in many cases, incidental to the mathematical models underlying modelling, although they are now an essential user interface for system definition and the interpretation of modelling results. For this research discrete event simulation was considered outside the context of static graphical manufacturing enterprise systems modelling.

A4.8 PETRI NETS

Petri nets (Petri, 1980) have been developed to model systems such as communication networks and information systems and have the ability to represent serial and concurrent events (Peterson, 1981). The Petri net method has been applied in a wide range of fields and has been used extensively to model manufacturing systems (Eswara Reddy, et al., 1992, Zhang, 1989, DiCesare et al, 1993). A Petri net diagram is a directed multi-graph representing events, the conditions that control events and the relationship between events and conditions. The method is mathematical and is 'specially suited to model and analyse discrete event dynamic systems' (Silva, 1993) but unlike simulation the graphical representation is an integral aspect of the model. In the context of manufacturing systems a diagram consists of circles representing the conditions of a system (places), bars representing events (transitions), the state of a condition is represented by a dot (a token) in the specified 'place' circle and directed arcs (arrows) show the direction of material or information flow between 'places' and 'transitions'. Much work has taken place to develop a body of research high level predicate/transition nets (Genrich and Lautenbach, 1981) and subsequently Coloured Petri Nets (Jensen, 1990). The fundamental Petri net method characterised by Peterson (1981) does not attempt to model 'time' although research work has been carried out to extend the initial work using a time dimension for transitions or places (Son, et al. 1991). For the purposes of this analysis the basic graphical representation is considered.

A4.9 CRITICAL PATH ANALYSIS (CPA)

CPA (Moder and Phillips, 1970) is a modelling method to solve sequencing problems based on identifying a logical sequence of activities or tasks and identifying the events (beginning and ends) associated with those activities together with the time between events. It is essentially a mathematical approach but the graphics used to describe events and relationships are an integral part of the method. It is used in three basic forms, activity on arrow, activity on node and the Programme Evaluation and Review Technique (PERT), for the purposes of the review in chapter four the activity on arrow approach is considered. Although CPA is not normally considered in a discussion of manufacturing enterprise modelling methods CPA is a graphical structured analysis and design method capable of modelling the logic of events in such systems. In contrast to the more recently developed systems modelling methods CPA is universally accepted, established and routinely used in a wide range of applications including manufacturing systems. It is normally considered a Project Management tool for large, 'one of a kind' civil and mechanical engineering projects. However in an interesting application in the shipbuilding industry Wade and Karaszewski, (1992) have proposed an approach that uses CPA to analyse functions in an IDEF$_0$ model. Its strength in terms of a comparative analysis lies in its accepted success and routine use as a graphical modelling method, its usability, accessibility, descriptive capabilities and its potential as a benchmark for the acceptance of manufacturing enterprise modelling methods.

APPENDIX 5

EPSRC-CDP GRANT ANNOUNCEMENT

EPSRC

Engineering and Physical Sciences
Research Council

RESEARCH OFFICE
DERBY UNIVERSITY
KEDLESTON ROAD
DERBY

DE22 1GB

Polaris House
North Star Avenue
Swindon SN2 1ET
Telephone 0793 444000
Central Fax 0793 444010

Tel (Direct Line):
Grant Ref: GR/K39400
Date: 02 September 19

STANDARD RESEARCH GRANT ANNOUNCEMENT

In respect of Grant Condition 12: (b) Commercial Exploitation through the BTG, applies

Dear Sir/Madam

The Council is prepared to make a Standard Research Grant towards the cost of the research proposed by the Investigator(s) named below. Payment of the Research Grant will be made subject to the Council's Research Grant Conditions listed below and any additional conditions specified. The Council must be informed within one month if the research grant is not acceptable to your Institution on these terms. The Institution must confirm acceptance of this research grant and inform the Council of the actual start date by return of form SD1 within 28 days of the actual start date.

Signed Barbara Hilton

SECRETARIAT, ACME

IMPORTANT: Please pass the enclosed copies to the Investigator(s) named below.
(~~One copy is enclosed for each Investigator~~).

GRANT PERIOD: 36 Months STARTS: 01/10/94 ENDS: 30/09/97

INSTITUTION: 6070 DERBY UNIVERSITY

PRINCIPAL INVESTIGATOR: PROF RW BAINES
SCHOOL OF ENGINEERING

PROJECT TITLE: BEST PRACTICE MODELLING METHODS IN MANUFACTURING ENTERPRISES

	£	Months	Posts
STAFF			
RA Range 1B	50,754	36.00	1
RA Range 1A	0	0.00	0
Technician	0	0.00	0
Other	10,500	12.00	1
STAFF TOTAL	61,254	48.00	2
TRAVEL & SUBSISTENCE	19,814		
CONSUMABLES	2,150		
EXCEPTIONAL ITEMS	8,400		
EQUIPMENT	3,756		
SUB-TOTAL	95,374		
INDIRECT COSTS	24,502		
GRANT TOTAL	119,876		

Further details on staff posts awarded appear below

Rate of indirect costs = 40%

Payment limits	
FY	£
94/95	8,386
95/96	33,544

Page 1 of 4

CO-INVESTIGATORS

MR GJ COLQUHOUN LIVERPOOL JOHN MOORES UNIV
ENGINEERING & TECHNOLOGY MANAGEMENT

STAFF POSTS

Spine	Grade & Grade Pt		Date of Scale	Posts	Months	Start Date	Increment Date	Name / Comments
3	RA1B	2	01/04/93	1	36.00	01/10/94	01/10/95	
	OTHER			1	12.00	01/10/94		SECRETARIAL

APPENDIX 6

KBSI RESEARCH GRANT AGREEMENT

KNOWLEDGE BASED SYSTEMS, INC.

February 3, 1994

Mr. Gary Colquhoun
Liverpool John Moores University
Fax 44-51-298-2447

Dear Mr. Colquhoun:

Ms. Caley McBroom is out of town attending a conference, so I will be handling your ordering procedure.

I am pleased to inform you that conditions for the Academic Grant have been met and your Academic package will be sent today by International Federal Express. I only ask that you pick up the shipping and duties.

A bankers draft will be acceptable and may be made out to the amount listed below in U.S. dollars.

The total cost of the package is as follows:

PROSIM	$5995.00
Grant	- $5840.00
TOTAL	$ 155.00
Technical Reports	$ 99.95
Shipping/Handling of FedEx International 7 lb. Package	$ 92.00
GRAND TOTAL	**$ 346.95** (three hundred forty-six dollars and ninety-five cents)

An invoice will be attached for your convenience in mailing.

As always, customer satisfaction is our priority. Please let me know if you have any questions.

Sincerely,

Sally Penick

Sally Penick
Marketing Representative

One KBSI Place
1408 University Drive East
College Station, Texas 77840-2335
409.260.5274
Fax: 409.260.1965

APPENDIX 7

IDEF3 MODEL OF ‘RUN ZENO’

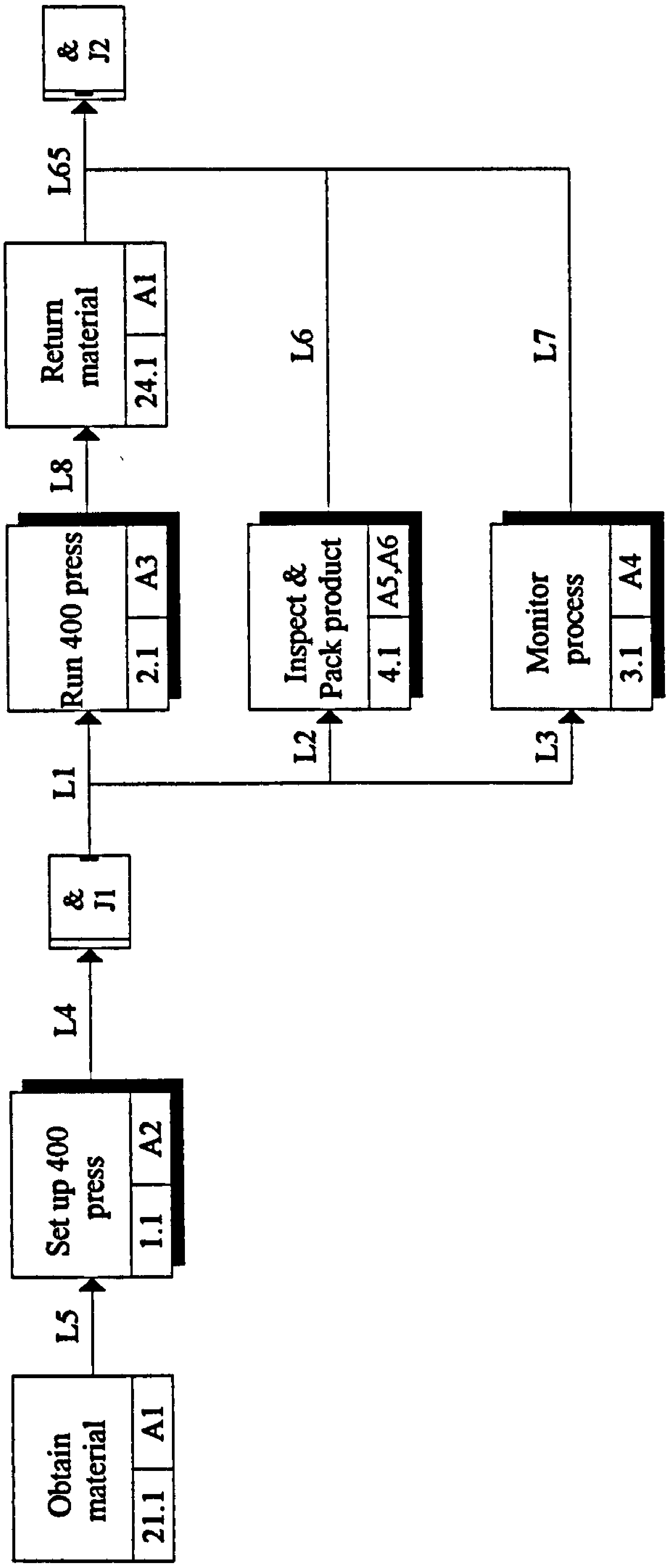


Figure A7.1 IDEF3 diagram 'Run ZENO'

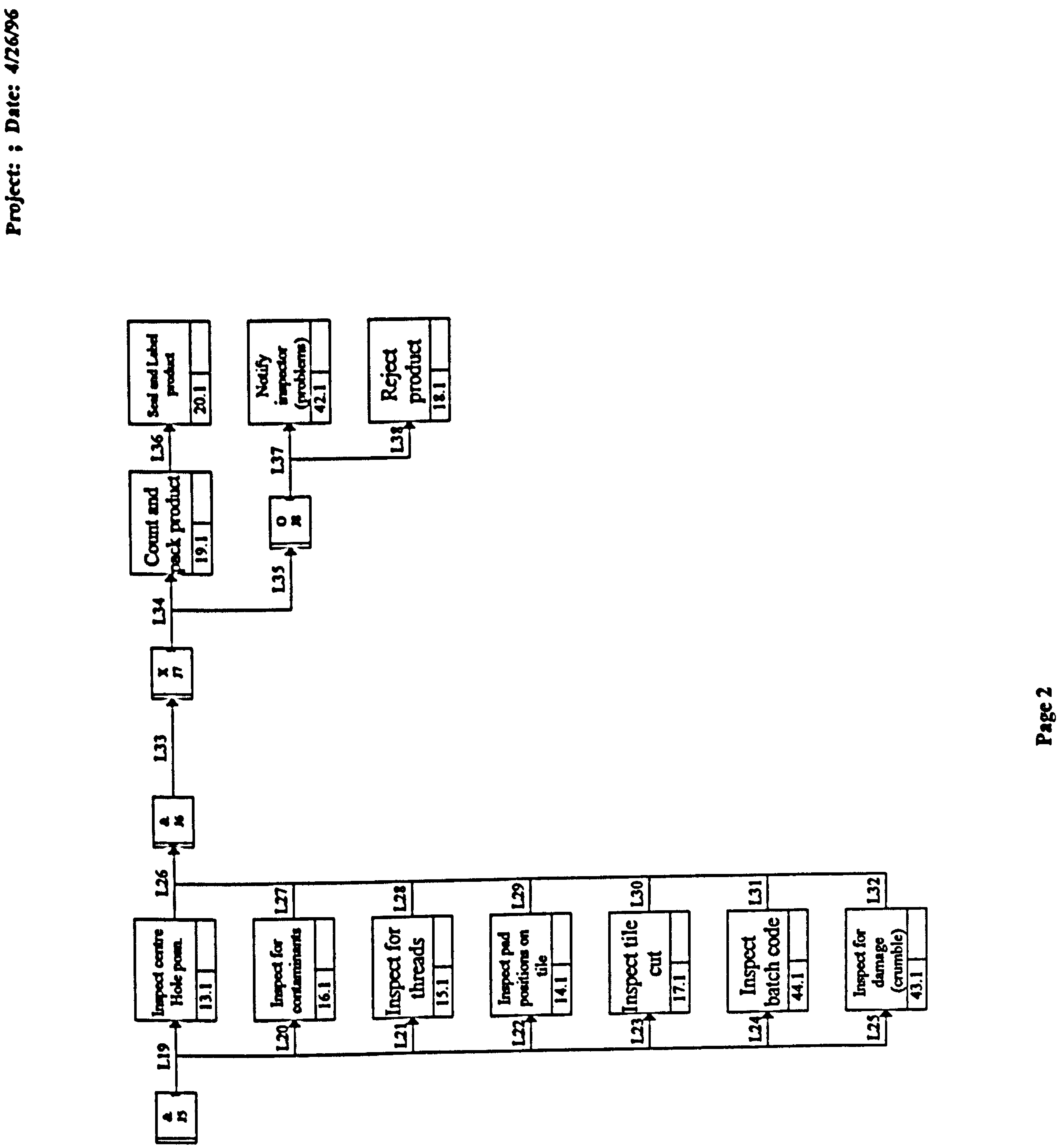


Figure A7.2 IDEF3 diagram 'Inspect and pack product'

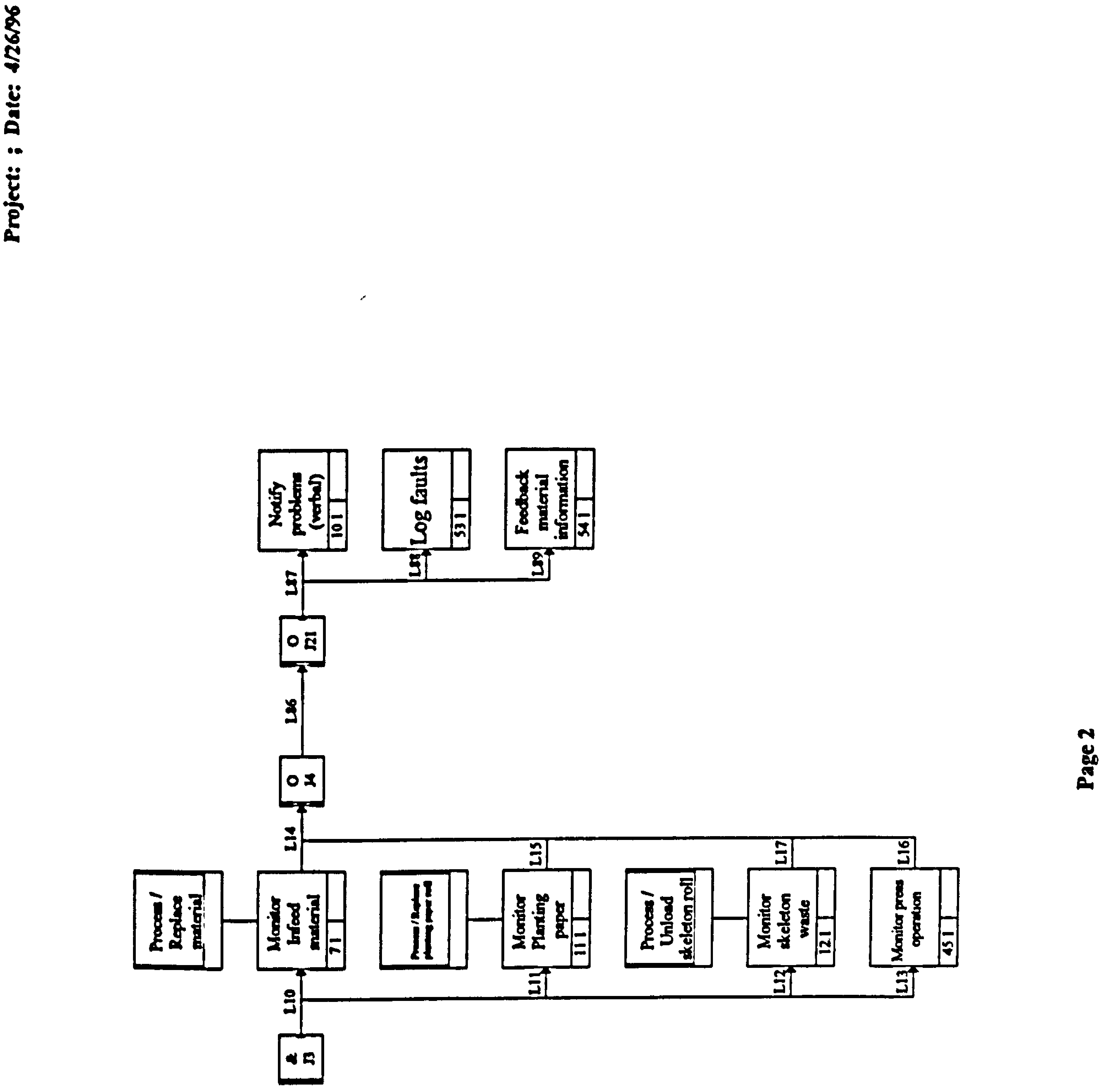


Figure A7.3 IDEF3 diagram 'Monitor process'

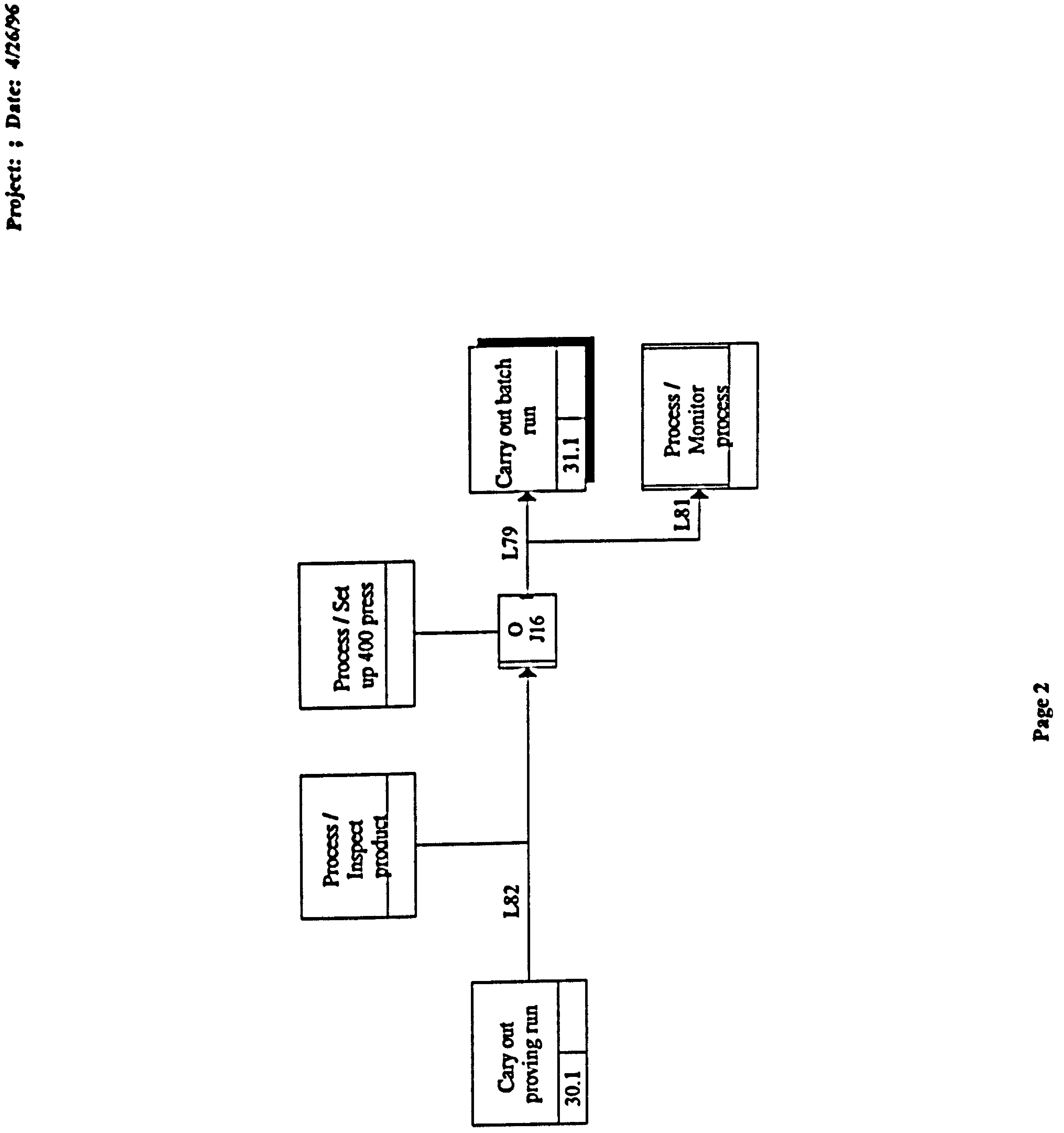


Figure A7.4 IDEF3 diagram 'Run 400 press'

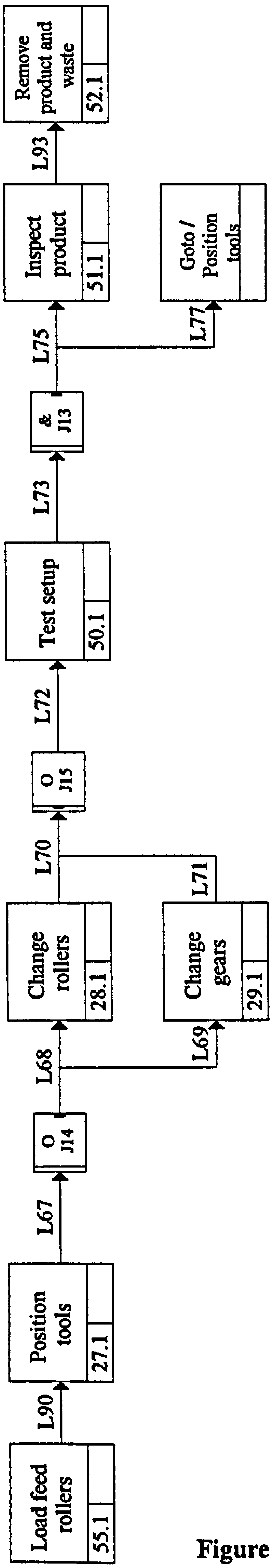


Figure A7.5 IDEF3 diagram 'Set up 400 press'

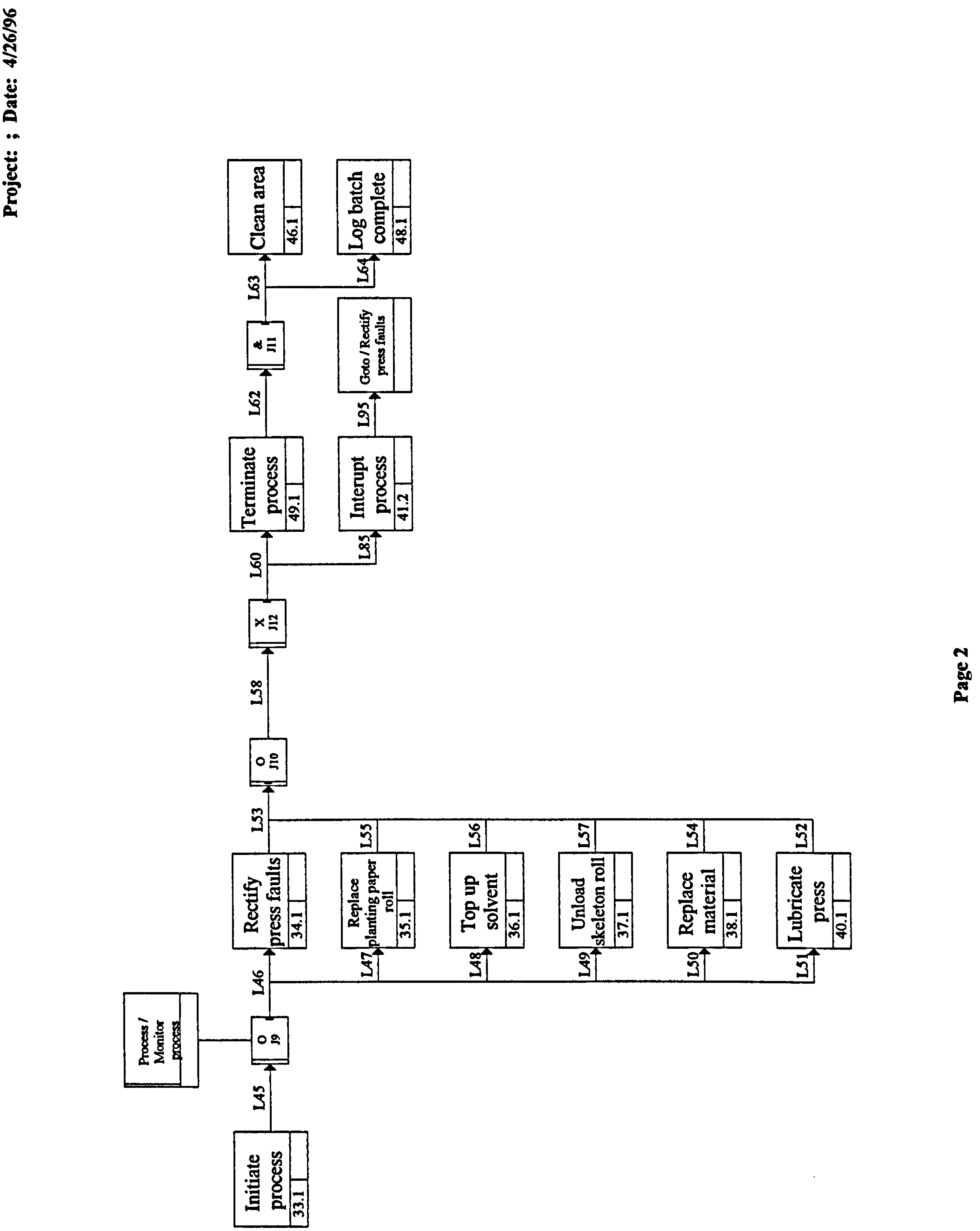
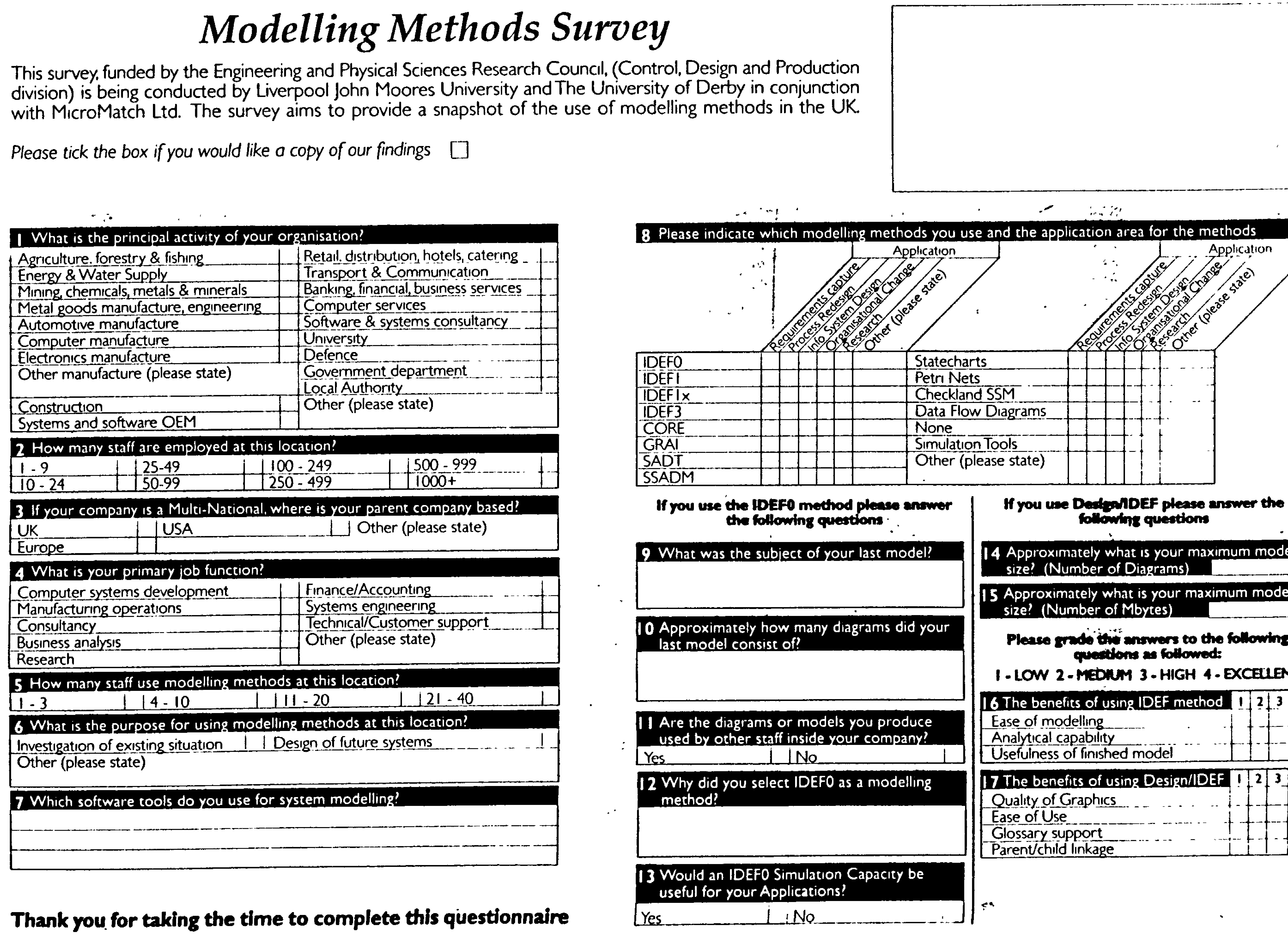


Figure A7.6 IDEF3 diagram 'Carry out batch run'

APPENDIX 8

THE MODELLING METHODS QUESTIONNAIRE



Modelling Methods Survey

This survey, funded by the Engineering and Physical Sciences Research Council, (Control, Design and Production division) is being conducted by Liverpool John Moores University and The University of Derby in conjunction with MicroMatch Ltd. The survey aims to provide a snapshot of the use of modelling methods in the UK.

Please tick the box if you would like a copy of our findings ☐

1 What is the principal activity of your organisation?

Agriculture, forestry & fishing		Retail, distribution, hotels, catering	
Energy & Water Supply		Transport & Communication	
Mining, chemicals, metals & minerals		Banking, financial, business services	
Metal goods manufacture, engineering		Computer services	
Automotive manufacture		Software & systems consultancy	
Computer manufacture		University	
Electronics manufacture		Defence	
Other manufacture (please state)		Government department	
		Local Authority	
Construction		Other (please state)	
Systems and software OEM			

2 How many staff are employed at this location?

1 - 9		25-49		100 - 249		500 - 999	
10 - 24		50-99		250 - 499		1000+	

3 If your company is a Multi-National, where is your parent company based?

UK		USA		Other (please state)
Europe				

4 What is your primary job function?

Computer systems development		Finance/Accounting	
Manufacturing operations		Systems engineering	
Consultancy		Technical/Customer support	
Business analysis		Other (please state)	
Research			

5 How many staff use modelling methods at this location?

1 - 3		4 - 10		11 - 20		21 - 40	

6 What is the purpose for using modelling methods at this location?

Investigation of existing situation		Design of future systems	
Other (please state)			

7 Which software tools do you use for system modelling?

Thank you for taking the time to complete this questionnaire

8 Please indicate which modelling methods you use and the application area for the methods

	Application: Requirements capture	Process Redesign	Info System Design	Organisational Change	Research	Other (please state)
IDEF0						
IDEF1						
IDEF1x						
IDEF3						
CORE						
GRAI						
SADT						
SSADM						

	Application: Requirements capture	Process Redesign	Info System Design	Organisational Change	Research	Other (please state)
Statecharts						
Petri Nets						
Checkland SSM						
Data Flow Diagrams						
None						
Simulation Tools						
Other (please state)						

If you use the IDEF0 method please answer the following questions

9 What was the subject of your last model?

10 Approximately how many diagrams did your last model consist of?

11 Are the diagrams or models you produce used by other staff inside your company?

Yes ☐ No ☐

12 Why did you select IDEF0 as a modelling method?

13 Would an IDEF0 Simulation Capacity be useful for your Applications?

Yes ☐ No ☐

If you use Design/IDEF please answer the following questions

14 Approximately what is your maximum mode size? (Number of Diagrams)

15 Approximately what is your maximum mode size? (Number of Mbytes)

Please grade the answers to the following questions as followed:

1 - LOW 2 - MEDIUM 3 - HIGH 4 - EXCELLEN

16 The benefits of using IDEF method	1	2	3
Ease of modelling			
Analytical capability			
Usefulness of finished model			

17 The benefits of using Design/IDEF	1	2	3
Quality of Graphics			
Ease of Use			
Glossary support			
Parent/child linkage			

Figure A8.1 The modelling methods questionnaire

APPENDIX 9

PROCESS PLANNING FOR BATCH MANUFACTURING

PROCESS PLANNING FOR BATCH MANUFACTURING

In a batch manufacturing piece part production environment the process planning activity plans the manufacture of components and products and involves the design or re-configuration of manufacturing methods, establishing the necessary resources and capacity (tooling, equipment, manufacturing times, staff, material, etc.). A process planner receives component design information detailing component geometry and attributes such as surface finish, tolerance hardness, etc., together with batch sizes. He applies his experience and uses available data to produce a process plan (the actual terms used are often company specific, i.e. operation layouts, route sheets, planning summary, etc.). The process plan provides a sequence of manufacturing processes, operation details for each process, set up and cycle times and tooling, fixture and gauge definition.

In the UK generally the decline of manufacturing has meant changes in organisation and staff reductions and a shrinking population of skilled staff. Traditionally process planning was seen as a separate, de-coupled function that took place after product design. The decision making processes involved in deriving a process plan are complex, the planner relies on his manufacturing experience and access to standards and previous process plans. To make manufacturing decisions, the shape, size, range and finish that a process is capable of producing must be known. To identify a specific machine, the power and capacity must be balanced with raw material (specification and size) and tool properties (wear rates, geometry, etc.). Reducing skills on the factory floor, has resulted in a need to provide more comprehensive manufacturing instructions by fewer planners for ever more technologically complex manufacturing. The result can be process plans that are inconsistent, inaccurate and out of date due to engineering changes, batch size variations and changes in available technology.

A recognised problem of process plan design is the difficulty in maintaining consistent plans for the same manufacturing features when created by different planners and, to a lesser extent, plans created by the same individual. Studies have been carried out that show the diversity of decision making encountered with the subsequent proliferation of tooling, fixtures machines and process routes. Process planning has a high clerical content both searching for data and document preparation with as little as 20% of the planners time being spent in technical decision making. It is in the clerical activity that computer assistance to the planner can provide the most immediate, improvement using word processing facilities, standard plan formats and a common engineering database.

The process planning activity itself has also changed as Computer Aided Process Planning (CAPP) systems have developed from simple databases through retrieval systems (Chang and Wysk, 1985) to the semi-generative systems (Zhang and Alting, 1994) commercially available today. In a computer based integrated manufacturing environment process planning is an essential element in the flow of information between Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM). There is recognition that CAPP has the potential to provide the essential link between CAD and CAM (Alting 1986, Chu and Wang 1988, Bok and Nee 1988, Sutton 1989, Wang and Wysk 1988). The aim of CAPP system developers is that systems will be able to take the geometric description of a component, apply planning logic and then produce the manufacturing instructions without human intervention. Much research and development work has been carried out in the area, in 1989 Alting and Zhang claimed that more than 200 papers have been published on the subject since 1970. Commercial development has led to CAPP systems becoming available and being used by major manufacturers in the UK.

APPENDIX 10

PART NUMBER/PROCESS MATRIX

Ceme Centre Floor to Floor Processing *Sets: 52*

Part No.	No. Off Per Assy	Class	Process Activity Cycle Times (sec)															
			Profile Gas	Profile Plasma	Dress [chamf]	Tum. Shot	Table Shot	Ext. Shot	Punch	Bend	Ext. Roll	Ext. Mill	Drill	Chamfer	Manual Weld	Robitic Weld	Re-Work	Total Ops
Boot [9R-8866]		A													420	496	480	1396
9R-8866/1	2	A	192		120		60											372
9R-8866/2	1	B								30				30				60
9R-8866/3	1	B								30				30				60
9R-8866/4	1	C																0
9R-8866/5	2	C	80		120	30												230
Top Hat		A													420	529	300	1249
9R-8514	2	A	88		120		60											268
9R-8515	2	B	94		120	90							600					904
9R-8516	1	C		26	60	30												116
9R-8517	1	B		16	60	30												106
Spacer	2	C		2														2
Carcass [Boom 9R-8508]																		0
9R-8509	1	A									75600							75600
9R-8510	1	A									75600							75600
9R-8511	1	A		92	60			14400										14552
9R-8512	1	A		92	60			14400										14552
9R-8518	1	B		23	60													83
9R-8519	1	B								38								38
9R-8520	1	B								38								38
9R-8522	2	C		27	1680													1707
Kit 100 [Plate Assembly 9R-7704, 9R-9472, 9R-8585 & 9R-8586]																		0
9R-7704/1	1	A	208		60		60											328
9R-8533	1	B		11	60	15												86
9R-8585/3	2	B		61	120		120			76								377
9R-8585/4	2	C		107	120	30												257
9R-8586/3	2	B		61	120		120			76								377
9R-8586/4	2	C		107	120	30												257
9R-9472/1	1	A		38	60		60						1					159
102-6741	1	C		30	60	15												105
Kit 200 [Support Assembly 9R-8279]																		0
9R-0290	1	A	125		60		30											215
9R-0291	1	A	54 5		60		30											144.5
9R-0292	2	C		50	120		60			68								298
9R-0546	2	B	300		120	180												600
9R-0741	1	A		71	60		30											161
Kit 300 [Tower Assembly 9R-9385]																		0
9R-0461	2	B		40	120	30												190
9R-1450	2	B		30	120	30				68								248
9R-2541	2	C		30	120	30				68								248
9R-9378	1	B		26	60		30											116
9R-9379	1	A		48.5	60		30		49	184								371.5
9R-9381	1	A		45	60		30		40	94								269
9R-9382	1	A		48.5	60		30			184								322.5
9R-9383	1	A		45	60		30		40	188								363
9R-9384	2	B				30				76								106
9R-9446	1	B		15	60		30			38								143

Table A10.1 Part number/Process matrix

APPENDIX 11

BSD SCHEDULING/MANAGEMENT SOFTWARE SPECIFICATION

SOFTWARE SPECIFICATION
SCHEDULING/MANAGEMENT

BSD STEEL SERVICE CENTRES

Toronto Industrial Fabrications
Dunlop & Ranken Estate
Whitehall Road
Leeds LS12 6JG

Tel: (0113) 2311911
Fax: (0113) 2311982

INTERNAL USE ONLY

Sheet 1 of 4

The above should be complete with the following as minimum for stages 1 & 2 of implementation-

☐ Control will comprise of three basic functions:
- Produce schedules, documents and data.
- Control work centre schedules.
- Track inventory.

☐ Operating platform, environment and users.
- PC based.
- Windows environment.
- 4 user system password protected.
    - 2 read only (a) - with 'What if' scheduling capabilities, i.e., to be able to examine and experiment with schedule, without the authority to issue or change the master schedule.
    - 1 read only (b) - with ability to produce picking document, no 'what ifs'.
    - 1 full user - with authority to examine, issue/produce schedules and documents.

SYSTEM REQUIREMENTS

1. Produce Schedule and documents (format to be designed by BSD with A4 size documents).
1.1 Work centre schedules - Daily for each work centre.
1.1.2 Work centre number.
1.1.3 List of part numbers in sequence of loading.
1.1.4 Batch/works number against each part.
1.1.5 Date of issue.
1.2 Route card - Per batch.
1.2.1 Part number and description.
1.2.2 Material specification and thickness.
1.2.3 Graphical outline of part via .DXF import.
1.2.4 List of work centres in order of processing and alternate route alongside.
1.2.4.1 Batch/works number.
1.2.4.2 Quantity in batch.
1.2.4.3 Date of issue.
1.2.4.4 Description and number of work centre.
1.2.4.5 Cycle times at work centre.

1.2.4.6 Sign off column at each process with scrap and rework noting.
1.2.4.7 Note column (e.g., tooling).
1.2.4.8 Accepted nest number.
1.3 Sub-contract schedules and purchase order.
1.3.1 Quantity in batch.
1.3.2 Date of issue.
1.3.3 Batch/works number.
1.3.4 Part number and description.
1.3.5 Due date, to be returned to BSD works.
1.3.6 Signatures for dispatch and return.
1.4 Dispatch/picking document (3 Ply).
1.4.1 Purchase order number.
1.4.2 Kit number.
1.4.3 List of components in Kit with quantities and batch/works number.
1.4.4 Signature acceptance for driver and customer.

2. Management information.
2.2 Resource utilisation (work centres and staff).
2.3 Routings, alternative routes and Bill of materials.
2.4 Work in Progress (*WIP)*, shop status.
2.5 Overdue's and delays.
2.6 Costs. (May be displayed via 3rd party database)
2.6.1 By resource.
2.6.2 By works order number.
2.6.3 *WIP* and Inventory on shop floor (and Projected).

3. Rough cut scheduling for profiling only - Over 12 week horizon.
3.1 Data file output to nesting software.
3.1.1 Part number.
3.1.2 Due date.
3.1.3 Quantity.
3.1.4 Material grade.
3.1.5 Thickness.
3.1.6 Plasma or gas operation.

4. Detail scheduling for profiling only - Daily with up to 2 week horizon.
4.1 Data file output to nesting software.
4.1.1 Part number.
4.1.2 Due date.
4.1.3 Quantity.
4.1.4 Material grade.
4.1.5 Thickness.
4.1.6 Plasma or gas operation.
4.1.7 Hi/Lo priority.

5. Control work centre schedules.
5.1 Demand/customer schedule for kits (level 1 items).
5.1.1 Quantity of kit.
5.1.2 Due dates.
5.2 Produce due dates and quantities (work to list) for individual part numbers within kit ordered (level 3 items).

5.2.1 Via BOM explosion and part routings.
5.3 Produce infinite capacity work centre utilisation using backward scheduling.
5.4 Allow use of alternate routes/resources via manual interaction.
5.5 To be capable of running in 2 modes.
5.5.1 Rough cut schedule to plan gross plate requirement for profiling only - 12 week horizon, not to include 'on-hand' inventory.
5.5.2 Detail scheduling to plan due date and quantities for all work centres, including profiling - 2 week horizon on a daily re-plan basis.
5.5.2.1 System must have ability for user to adjust capacity, resources (alternate routes), quantities and due dates in order to balance customer demand to available capacity. This should be on a 'what-if' interactive graphical display type application without compromising master schedules.

6. Track inventory.
6.1 Calculation of *WIP*.
6.2 Finished components.
6.3 Scrap & Rework.
6.3.1 Schedule and inventory level must be updated.
6.4 Over production quantities (with part numbers) from nesting with relevant schedule adjustment.
6.5 Historical production.
6.5.1 Quantities manufactured to date.
6.5.2 Capacities and utilisation's (resources) to date.
6.5.3 Late orders to date (inc. remaining outstanding jobs).
6.5.4 Dispatched orders.

7. Inputs to system.
7.1 Dynamic inputs.
7.1.1 Customer Kit schedules (kit required with due date on a roll out diary).
7.1.2 Exceptions on resources.
7.1.3 Alterations on inventory level.
7.1.4 Scrap and rework with reason codes and work centre.
7.1.5 Feedback from nesting system via data file, after detail schedule only.
7.1.5.1 Part identification against quantity nested.
7.1.6 Alterations to planned schedule.
7.1.6.1 Delays on batches, system to assume order completed when given time has elapsed unless otherwise stated (Stages 1 & 2 only).
7.1.6.2 Uncompleted orders.
7.2 Fundamental inputs.
7.2.1 Resource capacities (machines and personnel) with calendar hours.
7.2.2 Fixed costs.
7.2.3 BOM.
7.2.4 Process routes and alternate routes, inc. sub contract possibilities.
7.2.5 Part groupings (for like tooling).
7.2.6 Part Classifications.
7.2.7 Kanban re-order levels (inventory file links).

8. System configuration and backup.
8.1 System to be tailored to BSD requirements over 3 month implementation programme, with start to be negotiated after order placement.
8.2 Subsequent changes to be made possible with BSD to cover costs.

8.3 Operator training, for up to 4 persons if required.
8.3.1 To be split, with training for 1 initial user, and follow up for additional users.
8.3.2 Follow up internal training to be by BSD personnel.
8.4 Maintenance contract.
8.4.1 Modem link, with security access.
8.4.2 Help desk.
8.4.3 Any re-training due to changes in system not specified by BSD.
8.5 Manuals.
8.5.1 As system is to be configured, manuals to be written by BSD personnel in terms of useability (visual), procedures and interpretation of results.
8.6 Consultancy.
8.6.1 To be readily available during installation phase, with ongoing requirements at a cost to BSD.

STAGE 3 DEVELOPMENT

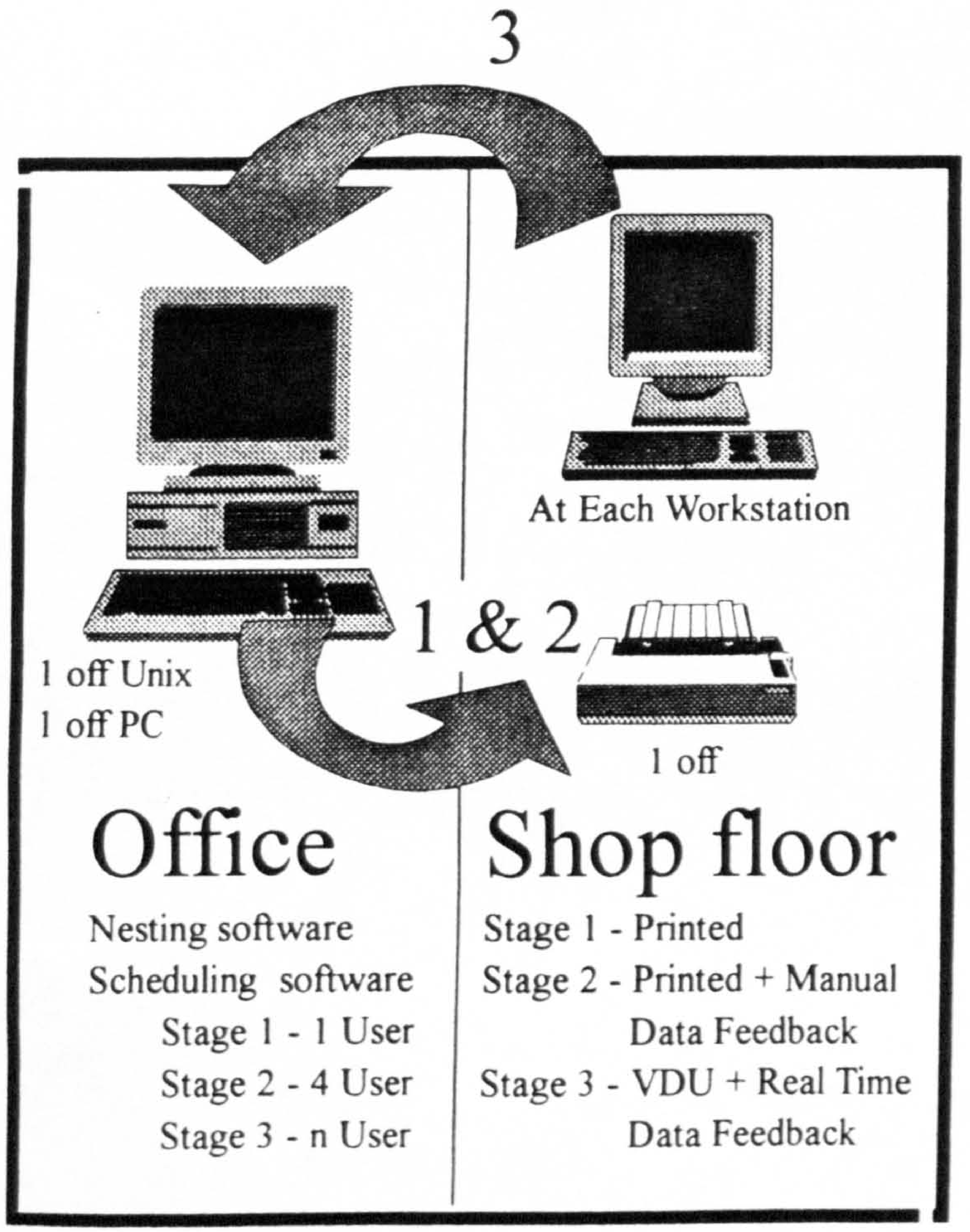
1. Data collection from shop floor (real time).
1.1 Shop floor terminals.
1.1.1 Bar-code labels.
1.1.2 Bar-code scanning equipment.
1.1.3 Hand held data collection.
1.1.4 Dumb terminals.
1.2 Shop floor document printing.
1.2.1 Reports.
1.2.2 Bar-code labels.
1.3 Control of scrap and rework in real time.
1.3.1 Bar code sheets with reason codes for error/problem.
1.4 Productive measurements of personnel.
1.4.1 Bar code sheets with reason codes for non-productive time.

DIAGRAMS ATTACHED

1. CEME scheduling (Requirement schematic).
2. Information Models.
2.1 A22 - Establish manufacturing schedules.
2.2 FEO - Establish manufacturing schedules.
2.3 A223 - Control work centre schedules.
2.4 A221 - Establish nesting data.

CEME SCHEDULING

For 'World Class Manufacturing'



3

At Each Workstation

1 & 2

1 off Unix
1 off PC

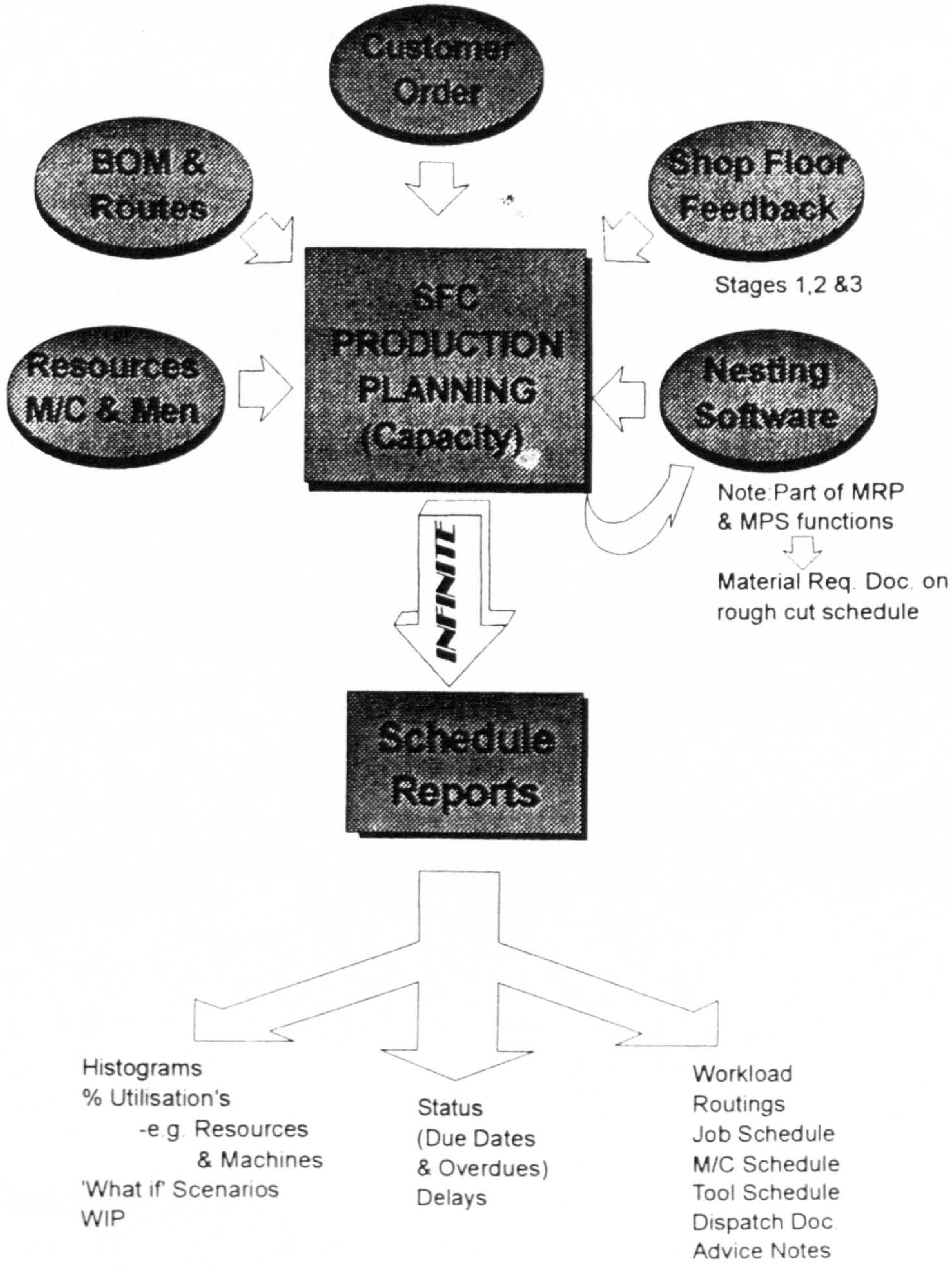
1 off

Office

Nesting software
Scheduling software
Stage 1 - 1 User
Stage 2 - 4 User
Stage 3 - n User

Shop floor

Stage 1 - Printed
Stage 2 - Printed + Manual Data Feedback
Stage 3 - VDU + Real Time Data Feedback



Customer Order

BOM & Routes

Shop Floor Feedback

Stages 1,2 &3

SFC PRODUCTION PLANNING (Capacity)

Resources M/C & Men

Nesting Software

Note:Part of MRP & MPS functions

Material Req. Doc. on rough cut schedule

INFINITE

Schedule Reports

Histograms
% Utilisation's
-e.g. Resources
& Machines
'What if' Scenarios
WIP

Status
(Due Dates
& Overdues)
Delays

Workload
Routings
Job Schedule
M/C Schedule
Tool Schedule
Dispatch Doc
Advice Notes