A Computer Integrated Manufacturing System for Small Scale Production of Electronic Units

A thesis presented in partial fulfilment of the requirements

for the degree of

Master of Technology

in

Production Technology

at Massey University

Author: Ronald John Biersteker

Year: 1995

Abstract

This research project concerns the design of a rapid response, computer integrated Printed Circuit Board (PCB) Component Assembly System (CAS). The CAS system forms an integral part of a commercially viable Manufacturing Pilot Plant (MPP) for the design, production, and assembly of high quality special purpose PCBs in low volumes.

The design of the CAS system begins with the identification of the characteristics and deficiencies of conventional low volume, high variety PCB manufacturing systems.

Next, a vision for the MPP as a whole is presented, with particular emphasis on the CAS system.

A Generic Manufacturing System Design Methodology (GDM) is then derived, and is applied to the design of the CAS system.

Through the GDM a working CAS system is constructed, based around a central CAS Master and 3 assembly workstations.

The working CAS system is then analysed through a comparison with a typical conventional low volume manual assembly system. The results support the expectation of superior performance from the envisioned system.

Finally, areas requiring further work are identified.

Acknowledgements

I wish to express my sincere thanks to my supervisor, Dr. Ross R. Nilson.

Dr. Nilson has provided much guidance and encouragement throughout my studies, including the writing of this thesis.

I am very grateful for his supervision and advice.

I also wish to thank Mr. Alan C. Wright.

Mr. Wright evaluated the final draft of my thesis and provided valuable feedback.

Finally, I wish to thank the staff, technicians and postgraduates of the Department of Production Technology, Massey University.

These people, especially the technicians, have willingly given valuable assistance and support.

I am very grateful for having had the opportunity to pursue and complete this course of study.

Contents

List of Figures

List of Tables

List of Exhibits

Chapter 1

Introduction

1.1 Research Project Overview

This research project relates to the design and development of computer integrated, rapid response manufacturing systems.

The primary objective is to design and develop a system for the assembly of Printed Circuit Boards (PCBs). This system, referred to as the Component Assembly System (CAS), is an integral part of the Manufacturing Pilot Plant (MPP), which offers three services:

- PCB design,
- bare board production, and
- PCB assembly.

By necessity, the CAS system must be designed in accordance with the overall objectives of the MPP.

The MPP is aimed at a market made up of customers who promptly require small quantities of special purpose PCBs.

Manufacturers in this market sector typically use conventional production systems characterised by:

- high manual labour content - low technology content operations, and
- the inability to produce a high quality, Plated Through Hole (PTH) bare board.

These conventional systems tend to exhibit problems such as: long response times to customer enquiries, stock ordering errors, poor product quality, and very long lead times, particularly when uncommon components are required, or when the bare board must be sourced externally. These problems all reduce customer satisfaction.

As the level of dissatisfaction experienced by customers increases, there comes a point where some customers will no longer view the delays and defects as minor or "allowable". If this situation arises, there will exist in the market a new challenge or opportunity for manufacturers and potential manufacturers. The challenge for these manufacturers is to develop manufacturing capabilities with the potential to achieve *major* gains in the quality of the product and the standard of service, thereby establishing a niche market, or becoming market leaders.
The MPP aims to capture a share of the market by overcoming the problems associated with conventional systems, and providing superior products and services to customers.

1.2 Thesis Overview

The design, development, and analysis of the CAS system is a logical progression. This progression is outlined below.

In Chapter 2, the vision for the MPP is described. The chapter begins with a more detailed discussion of the characteristics and problems associated with conventional manufacturing systems. A solution is then provided, in the form of the envisaged MPP. This vision represents the intuitive phase of the design process.

In Chapter 3, existing manufacturing system design methodologies and philosophies are examined. From these methodologies, a Generic Manufacturing System Design Methodology (GDM) is derived. The GDM consists of two parts. The first part is the structured design process, and consists of 6 distinct stages. The second part consists of general considerations, each providing a unique, but essential perspective on the design process.

The 6 design stages are summarised below.

- Stage 1: define the characteristics of the market in which the MPP operates.
- Stage 2: formulate a strategy for the MPP in the form of a set of objectives, based on the outcome of the market analysis performed in Stage 1.
- Stage 3: examine existing manufacturing systems, identifying areas of strength and applicability, and areas of weakness or incompatibility.
- Stage 4: define the system at a conceptual level, that is, define *what* the system must do

to fulfil the objectives. In addition, critical and non-critical elements of the system must be identified.

- Stage 5: define the system at a functional level, that is, define *how* the system must function to fulfil the objectives. This requires the specification of the physical properties of the system.
- Stage 6: implement the design.

This methodology represents the analytic phase of the design process.

In Chapter 4, the relationship between market demands and the selection and management of processes and resources is investigated.

This relationship is represented by the Product-Process matrix. This matrix identifies three generic types of manufacturing system, namely: jobbing, batch production and mass production. These systems are referred to as Traditional Manufacturing Systems.

The key areas of each system to be considered are: characteristics of the market requirements, selection and management of resources, and common problems and potential solutions.

The purpose of thoroughly examining these systems is to ensure that each element of the system may be seen in the correct context.

In Chapter 5, philosophy-driven manufacturing systems are investigated. These systems are distinct from the Traditional Manufacturing Systems as they are not defined by a specific location in the Product-Process matrix. This is because some systems may overlap with other systems, and collectively they do not cover the full spectrum of systems as the Traditional Manufacturing Systems do. Consequently, they must not be viewed as alternatives to each other.

The systems that are considered are: Integrated Manufacture and Computer Integrated Manufacturing (CIM), Just in Time (JIT), Group Technology (GT), and Material Requirements Planning (MRP) and Manufacturing Resource Planning (MRP II). These systems are referred to as Modern Manufacturing Systems.

The key areas to be considered are: characteristics, objectives and benefits, development motivation, a typical application, implementation, and common problems.

The purpose of thoroughly examining these systems is to ensure that each element of the system may be seen in the correct context.

In Chapter 6, the first 4 stages of the GDM are applied. These stages are: market analysis, formulation of a strategy and objectives, an assessment of how existing manufacturing systems relate to the MPP, and the development of models of the CAS system at a conceptual level. In addition, the key processes identified in the conceptual models are ranked according to importance. The purpose of ranking the processes is to identify which processes in the conceptual models will provide the foundation for the functional models.

In Chapter 7, the final stages of the GDM are applied. These stages are: the development of models of the CAS system at a functional level, and the implementation of the design.

In Chapter 8, an experiment is conducted. This experiment is aimed at testing the performance of the CAS system against a conventional assembly system. The objective of the experiment is to determine whether the CAS system outperforms the conventional system in key areas of production including: stock level checking, setup, assembly, soldering, and lead clipping. The results are presented and analysed.

In Chapter 9, a summary of the thesis is presented. This is followed by a series of conclusions. Finally, areas requiring further work are identified.

Chapter 2

A Vision for the MPP

2.1 Introduction

The objective of this chapter is to define the motivation behind the development of the Manufacturing Pilot Plant (MPP), and to present a vision for the MPP. This provides an appropriate perspective of the MPP as a whole and places subsequent discussion in the proper context.

2.2 Conventional Low Volume - High Variety PCB Production Systems

Typically, manufacturers operating in the target market of the MPP utilise conventional production systems. These systems involve high levels of manual labour, and low levels of technology. The three basic services (design, production and assembly), as carried out by a conventional small scale manufacturer, are considered below.

Design is by necessity labour intensive, but is assisted by the use of Computer Aided Design (CAD) packages.

High quality double-sided Plated Through Hole (PTH) boards are not usually produced in-house. Instead, the manufacturer must contract out this work. This can significantly lengthen the total production lead time.

Assembly is a manual operation, involving two steps. First, kits must be assembled, which contain all the required components. Kitting can be a very time consuming task with large, complex PCBs. This is because replenishment orders must be generated manually, and stock records must be updated manually. Second, assemblers must build the products either by copying a sample of the complete PCB, or by copying an image of the PCB such as a plot of the graphic overlay.

Consequently, customers of conventional manufacturers may be dissatisfied with the quality of the product and the standard of service: for example, products may be defective, the lead time may be very long, and the response of the manufacturer to enquiries may be slow or incomplete. These problems result from poor selection and management of resources and/or failure to identify and take advantage of new opportunities, such as new technology. The root causes, however, may be failure to identify the fundamental importance of customer satisfaction, which itself leads to a failure to understand customer requirements; or failure to aim for market leadership[1].

2.3 The Vision

The discrepancy between what customers demand and what manufacturers supply indicates that there exists in the market a new opportunity. To take advantage of this opportunity and operate profitably, a manufacturer must set up a production system with the capability to achieve *major* gains in the quality of the product and the standard of service. This is the motivation behind the development of the MPP.

It is envisioned that the MPP will be a computer integrated system in which design, production and assembly will be performed on, or supported by linked Personal Computers (PCs). This link will have two aspects: the physical link, in the form of a network; and the data link, in the form of software - both data and applications.

A key part of the system will be the CAS Database. This database will contain the information required to link design data to production system data.

Product designers will have on-line access to production and inventory data, including: stock currently on-hand, the identity of suppliers of stock not on-hand, and the current production schedules. Furthermore, designers will be able to order stock and modify the schedules with the

---

[1] Achieving market leadership may not be appropriate in all markets.

same systems.

The design data, remaining in computerised form, will be used to drive the production and assembly systems.

The Wet Line, for the production of the bare board, will consist of all the processes required to produce double-sided Plated Through Hole (PTH) boards, including: computer controlled drilling; computer controlled electroless and electroplate (panel plate); photoprocess; and computer controlled copper and solder electroplating, etching, photopolymer resist stripping, solder reflow, and panel separation. The raw material used to make the boards will be 250mm * 450mm double-sided copper clad epoxy laminate.

The CAS system is for the assembly of PCBs. The strength of this system will be derived from two linked systems:

- a system for the automatic presentation of components, and
- a graphics-based prompting system that identifies where the presented component is to be inserted on the PCB.

These systems, at a conceptual level, must form the foundation and dictate the basic framework of the CAS system. Other essential assembly systems must be compatible with this framework.

The CAS system will consist of two levels. The first level is the CAS Master. It will contain the CAS Database, and the software required to convert the design data into production instructions. The production instructions will be down-loaded to each member of the second level. The second level will consist of assembly workstations. Each workstation will consist of a PC and a computer controlled component storage and presentation system. The PC will activate the storage device to present the correct component to the assembler, and also indicate where the component is to be placed. This will be achieved by presenting a graphic image of the PCB on the PC screen and by highlighting the location of the component. Additional information will be displayed to assist the assembler, and will relate either to the product, or to an individual component. These systems have the potential to increase product quality in two key areas, namely, product consistency, both within and between batches; and the occurrence of insertion errors.

The use of stock will be recorded, and this information will be used to update the CAS Database.

The CAS system is a significant departure from conventional assembly methods, not only at the technical level, but also at a more fundamental level. The CAS system will not make use of component kits. Instead, the workstations will permanently store frequently used, or common components. Uncommon components will be dealt with on an order by order basis.

It is envisaged that the CAS system will incorporate computer based systems for: accounting, scheduling, stock control and ordering, internal and external communications, testing and test data analysis, and general administration. Furthermore, feedback systems may be devised, not only for maintaining accurate data records, but also for improving or enhancing production instructions and procedures.

Finally, if the MPP is able to achieve *major* gains in the quality of the product and the standard of service over conventional manufacturers, a market niche may be established. This may only occur, however, if *customers* do not view the MPP and conventional PCB manufacturers as alternative suppliers.

Chapter 3

Manufacturing System Design Methodologies

3.1 Introduction

The objective of this chapter is to derive a Generic Manufacturing System Design Methodology (GDM) suitable for the design of a modern, special purpose manufacturing system, namely the Component Assembly System (CAS).

This chapter is divided into three sections.

The first section investigates seven existing manufacturing system design methodologies. These methodologies vary considerably in scope and applicability. Although not all are directly applicable to the design of the CAS system, they all contribute to a broad understanding of the design process.

The second section evaluates the methodologies with the objective of blending them to form the basis of the GDM.

The final section presents the GDM. The GDM consists of two parts. The first part is the structured design method, consisting of 6 stages. The second part consists of a series of general considerations that are applicable throughout the design process.

3.2 Investigation of Existing Design Methodologies

Seven existing manufacturing system design methodologies are discussed below. They range in scope from those for general manufacturing system design, to those for the design of a specific type of manufacturing system.

3.2.1 The Focused Factory [1]

During the 1970s, manufacturers in the United States of America were suffering from major problems. Although the exact nature of the problems was not clear, the symptoms were. The primary symptom was the inability to compete successfully in world markets.

To address the problems, Skinner (1974) proposed the concept of the Focused Factory.

The Focused Factory is based on four key ideas:

- that low cost is not necessarily the only, or most important factor of competition,
- that it is not possible for an organisation to compare favourably against every performance measure,
- that each functional area of the organisation must share common objectives; objectives that are consistent with overall business objectives, and
- that simplicity, repetition and experience lead to competence.

It is necessary first to understand market needs and then to devise an appropriate business strategy. This strategy must focus the entire organisation on achieving outstanding performance in specifically targeted areas.

This is accomplished by establishing a set of compatible and consistent objectives. Skinner (1974 p.114) aptly states that a plant must be focused on a 'limited, concise, manageable set of products, technologies, volumes and markets'.

This does not exclude an organisation from operating in several fundamentally different markets, where production objectives would be in direct conflict. However, an organisation that does operate in more than one market must differentiate between the markets and set up a number of suitable semi-autonomous production units. Such a unit is referred to as a 'plant within a plant' [1 p.121].

On discussing organisation cultures, Peters and Waterman (1991 p.76) relate an observation that supports the Focused Factory concept. They report that in the excellent companies 'people way down the line know what they are supposed to do in most situations because the handful of guiding values is crystal clear'.

3.2.2 Reengineering [2,3]

Reengineering[2] entails a 'radical redesign of business processes to achieve major gains in cost, service, or time' [3 p.26]. The first stage of reengineering is to ask: 'If we were a new company, how would we run this place?' [3 p.25].

Traditionally, organisations were structured according to the principles of specialisation of labour. As a consequence, dissociated departments formed. Reengineering allows an organisation to break from tradition by 'looking at the fundamental process of the business from a cross-functional perspective' [2 p.108].

Information technologies are the principal enabling tools of the integration effort. The full benefits of this modern technology can not be realised, however, simply by automating or computerising existing systems or processes. Although such an approach may improve performance, it lacks the key element of reengineering which is to challenge the very existence of systems and processes.

The key principles of reengineering include:

- devising a strategy outlining what the organisation plans to do. This strategy is based on a clear understanding of customer requirements, and is implemented by 'designing from the outside in' [3 p.29],
- organising jobs on the basis of a particular outcome or objective,
- organising jobs and processes such that information which is generated and used locally is processed and stored locally,
- the use of communication facilities to integrate physically separated systems,
- coordinating concurrent and interdependent processes while they are in progress, and
- designing processes and organisational structures such that the person performing the process is able to monitor and make informed and timely decisions about the process.

3.2.3 World Class Manufacturing Action Agenda

Schonberger (1986 pp.217-218) has proposed an 'action agenda for manufacturing excellence'.

---

[2] Also known as Process Innovation or Core Process Redesign.

It is aimed at improving operations to build competitive strength.

The key principles of the action agenda include:

- developing a close relationship with each customer,
- reducing work in progress (WIP) inventory,
- reducing process, setup and changeover times,
- reducing the distance between processes,
- increasing the frequency of production or delivery of items,
- maintaining only a small number of good suppliers,
- reducing the range of parts,
- organising production such that defect-free products are easy to make,
- maintaining high standards of housekeeping to reduce problems due to disorganisation,
- multi-disciplinary training of personnel,
- allowing personnel to record and make use of production data,
- ensuring that personnel are given the opportunity to attempt to solve their own problems,
- extracting the full potential from existing equipment before purchasing new equipment, and when purchasing new equipment, focusing on simple, low cost, movable equipment,
- aiming for multiple, rather than single machines and product lines, and
- automating in small steps, and only when other avenues for improvement and variability reduction have been pursued.

Schonberger (1986) recommends that manufacturers develop a strategy aimed at implementing these principles.

3.2.4 Guidance for the Development of World Class Manufacturing Systems

Young (1991) gives guidance on the development of world class manufacturing systems in which the manufacturing strategy is used as a 'competitive weapon' [4 p.10].

The key principles, or characteristics of the strategy include:

- making customer satisfaction the highest priority,
- ensuring that the strategy is consistent with customer requirements and incorporates business goals,

- integrating and coordinating functions such that they share common goals,
- keeping things simple,
- recognising that technologies, both process and information technologies, do not necessarily improve competitiveness as they also lead to higher costs and other complications,
- encouraging all employees to make improvements as opportunities arise,
- initiating the change process with a 'trigger point' [4 p.15]. This is a situation where all personnel recognise the need for change and are motivated to bring it about,
- encouraging employees to take an active interest in the performance of the organisation, and
- leading the implementation of the strategy by setting an example.

3.2.5 Principles of Action Linking Strategy to Technology

Clark (1989) suggests that technology in itself is not the primary means to gain competitive advantage. This is because the technology may also be available to competitors.

Instead, competitive advantage is gained by:

- devising a strategy that extracts the full potential of the technology, or some other distinctive competence, and
- successfully implementing the strategy.

He goes on to suggest a number of 'principles of action' [5 p.96] regarding strategy and technology, including:

- recognising the capabilities of the core processes and making full use of them to meet customer requirements, thereby linking 'the world of technology with the world of business' [5 p.96],
- making use of the available sources of technical expertise, including successful manufacturers in other fields, and universities and technical institutes,
- recognising the increasing need for speed and rapid response, and designing systems accordingly,
- integrating functions to maximise the effectiveness of the key operations of the organisation, and
- using information technologies to integrate internal and external operations [5].

3.2.6 Manufacturing Systems Engineering

Hughes (1987) has proposed the methodology of Manufacturing Systems Engineering (MSE). MSE is a method of designing manufacturing systems in which technology is linked with business goals.

This methodology consists of 4 stages.

- Stage 1: formulate the manufacturing strategy. This involves establishing the purpose, objectives and basic structure of the manufacturing system, focusing especially on developing superior capabilities in target areas.
- Stage 2: formulate the concept of the system. This involves analyses of markets, financial resources, and existing manufacturing systems; defining the system at a conceptual level; and preparing a feasibility study.
- Stage 3: design the elements of the system in detail. This involves designing organisational structures, process capabilities, plant layout, and control systems; and investigating alternatives.
- Stage 4: implement the system. A fundamental part of implementation involves devising plans outlining the implementation process.

MSE is an iterative process. At any point during design it may be considered advantageous to revise one or more preceding stages.

3.2.7 Structured Techniques

Taylor (1990) has proposed the concept of Structured Techniques for the development of information systems.

The key principles of Structured Techniques include:

- providing structure to the design process so as to simplify management and progress monitoring,
- the use of diagrams for describing systems and communicating ideas,
- the use of standards and standard techniques for communicating information, not only during system design, but also in the implemented system,
- determining what data is needed and when it is needed, and
- differentiating between the logical aspects of a system (namely, what the system will do), and the physical aspects of the system (namely, how the system will do it). This ensures that the

design of the system is consistent with business goals and that technical details are not specified earlier than necessary.

Flatau (1988) has proposed an approach to designing Computer Integrated Manufacturing (CIM) systems that is similar to MSE and Structured Techniques. It consists of 4 stages.

- Stage 1: identify the business goals.
- Stage 2: define the logical data required.
- Stage 3: define the physical data required.
- Stage 4: define the physical functions of the system.

3.3 Evaluation of Existing Design Methodologies

The methodologies discussed in Section 3.2 (pp.10-15) provide a basis for the GDM which is to be applied in the development of the CAS system. The GDM is derived below.

The methodologies discussed in Section 3.2 (pp.10-15) place much emphasis on the need to develop a business/project strategy, which outlines the goals of the organisation/project. These goals concern satisfying the requirements of a specific group of people, typically the customer. This implies a precise understanding of the requirements of that group.
The first two principles have thus emerged:

- identifying the customers, and defining their requirements, and
- defining a strategy aimed at meeting those requirements.

The methodologies also consist of 2 groups of principles:

- those that emphasise a procedure, and
- those that emphasise a concept, or a specific goal or outcome without reference to a procedure.

Of the principles that emphasise a procedure, 4 are of special interest:

- examining existing manufacturing systems to identify applicable principles and philosophies that may be incorporated into the system; and incompatible principles and philosophies that should be avoided, or adapted and used with caution,
- defining the system at a conceptual level, that is, defining what the system must do without specifying how it must be done,

- defining the system at a functional level, that is, defining how the system concepts are to be implemented, and
- designing the system by beginning with the basic system as a whole, or the system framework, and progressively developing it to increasing levels of detail.

The first principle has the potential to ensure that the designer is able to take advantage of the successes, and avoid the mistakes, of other designers. Consequently, the resulting new system may be viewed as an extension to, or the progression of current best-practice.

The following two principles are the constructive stages of the design process. The method by which these stages are implemented is defined in the final principle.

The principles that emphasise a goal or outcome of a procedure focus on best-practice techniques. These may be generalised and defined as broad objectives, or general considerations to support the structured design process.

In summary, the methodologies provide a set of design procedures, or stages, and a set of general considerations. The resulting generic methodology is discussed fully in the next section.

3.4 A Generic Manufacturing System Design Methodology

The GDM has been derived from the methodologies discussed in Section 3.2 (pp.10-15), and is to be applied to the design of a modern, special purpose manufacturing system, namely, the CAS system.

The methodology consists of 6 stages, and is supported by a set of general considerations.

3.4.1 Stage 1: Define the Characteristics of the Target Market

The first stage involves identifying who the income-generating customer is, and defining what their requirements are. This fundamental requirement is based on the simple notion that the profitability of an organisation is dependent on the ability of that organisation to satisfy customer requirements, and to do so competitively. More simply, an organisation must be capable of capturing a share of the market.

In practical terms, this stage may be thought of as a series of intellectual exercises in which the designer takes the viewpoint of different types of customers, asking "If I was this customer, what would I consider to be important?". Although the Manufacturing Pilot Plant (MPP) can not realistically be expected to satisfy every need of every customer, the value of viewing the services of the MPP, in totality, from the perspective of the customer must not be underestimated.

Similarly, it is also necessary to be aware of the capabilities and limitations of other members of the chain of supply, such as suppliers and delivery services.

3.4.2 Stage 2: Define the Objectives

The second stage involves the development of a strategy or plan of how the organisation intends to serve customers. This involves defining a set of consistent objectives based on the outcome of the market analysis performed in Stage 1.

The objectives remain valid beyond the process of designing the system, acting as a guide for short term and long term decisions, as well as the foundation for performance measurement.

The strategy must not be rigid and unchangeable. Rather, it must be modified in response to changes in markets, resources and other constraints and opportunities.

The strategy and objectives apply not only to the organisation as a whole, but also to the individual elements of the organisation.

3.4.3 Stage 3: Examine and Analyse Existing Manufacturing Systems

The third stage involves undertaking a detailed examination of existing manufacturing systems to identify:

- the way in which processes and resources are selected and managed to meet market demands,
- the means by which problems are overcome, and
- the methods of taking advantage of new opportunities or technologies.

These systems must be examined thoroughly so that each element of a particular system may be observed in the correct context. This is vitally important when attempting to implant elements of one system into another.

3.4.4 Stage 4: Develop Conceptual Models

The fourth stage involves the development of models defining the manufacturing system at a conceptual, or logical level. These are models that detail *what* the system is required to do. They associate customer requirements with process outcomes, and outline aspects such as: core processes, material flow, and information flow.

3.4.5 Stage 5: Develop Functional Models

The fifth stage is a logical progression of the fourth stage. It involves the development of models defining the manufacturing system at a functional, or physical level. These are models that detail *how* the conceptual models are implemented. They define the internal mechanisms of processes, and the interactions between processes or system elements.

This is the beginning of the implementation phase as it involves defining the physical elements and interactions of the system.

3.4.6 Stage 6: Implement the Design

The sixth and final stage is the implementation of the system.

3.4.7 General Considerations

Other important issues to emerge from the methodologies are also considered. These issues do not represent distinct design stages, but are of value throughout the design process. For this reason they are referred to as general considerations.

The general considerations include:

- recognising that people are central to the system, and designing the system accordingly,
- designing the system from a cross-functional perspective, focusing on outcomes, rather than individual activities,
- standardising systems, information presentation and communication, and other features to provide consistency throughout the system as well as the design process,
- designing systems capable of extracting the full potential from technology,
- coordinating processes to maintain effective and efficient material and information flow,
- adopting an attitude of constantly seeking to eliminate or avoid waste such as: unnecessary

delays, costs and WIP inventory,

- designing systems in which orderliness, simplicity, and ease of use are apparent and encouraged,
- ensuring that resources are used solely for the purpose of achieving the overall objectives, and
- being aware of, and understanding the objectives by which other manufacturers operate, in particular, potential customers.

3.4.8 The GDM in Perspective

To view the GDM in the proper perspective, it is necessary to make several observations.

First, the design process must be guided by a vision or idea of the final system. This vision may, for example, be based on the knowledge of the potential capabilities of particular technologies, or the knowledge of new markets or new opportunities in existing markets. Consequently, the designer has partially implemented, although perhaps only intuitively, all the stages of the GDM. Furthermore, in this circumstance the GDM is not strictly followed. For example, the constitution of the conceptual models is influenced by the functional properties and capabilities of the envisioned system.

Neither a vision alone, nor a design process alone is sufficient for the development of a new system. It is necessary to have a vision *and* a suitable design process. The vision depicts the "destination", while the design process outlines the "journey". The GDM must be implemented with a constant focus on the envisioned, or final system as a whole.

Second, to assume that each stage of the GDM is applied only once, and in strict order, implies that *every* issue relating to the final system can be foreseen, understood, or specified as it emerges. This is unlikely to be the case in reality, and is precisely the reason why a structured, rigorous design process is required. Consequently, it may be considered advantageous to review or revise preceding stages at any time during the design process.

Third, Stage 6, the implementation of the design, is considered to be part of the design process because the design process is a series of linked and interdependent, and sometimes iterative steps. To separate implementation from design may convey the incorrect idea that the design, once completed, is unchangeable.

Fourth, the GDM is a design approach. It does not guarantee that the final system will be the optimum system. Furthermore, the GDM must not be viewed as the only method for designing manufacturing systems. Rather, the GDM is simply a structured method for addressing the fundamental issues that must be addressed in the design and development of business systems.

Finally, the GDM is aimed at the design, or re-design of manufacturing systems. The monitoring and evaluation of manufacturing systems is beyond the scope of the GDM.

Chapter 4

Traditional Manufacturing Systems

4.1 Introduction

The objective of this chapter is to investigate existing manufacturing systems to identify the way in which processes are selected and managed to meet market demands. For an organisation to be commercially viable, the internal mechanisms (processes) must be matched to market demands (products). This match is defined in the Product-Process matrix in Table 4-1 (p.21).

Table 4-1 The Product-Process matrix

Process	Product: Low volume, High variety	Product: Medium volume, Medium variety	Product: High volume, Low variety
Jumbled flow	***Jobbing***		Efficiency
Intermittent flow		***Batch Production***	
Continuous flow	Flexibility		***Mass Production***

The matrix reveals a principal diagonal region containing three types of production system, namely: jobbing, batch production, and mass production. These systems are referred to collectively as Traditional Manufacturing Systems.

Although these systems are shown as being distinct, the boundary between each is not distinct. Rather, the main diagonal region is a continuum of manufacturing systems.

To operate in a position other than in this diagonal region may result in an increase in costs or a reduction in flexibility, without an improvement in market share.

Each of the three systems will be discussed presenting *typical* characteristics in terms of market demands and process selection. In addition, common problems and potential solutions will be discussed.

The relationship between Traditional Manufacturing Systems and the Manufacturing Pilot Plant (MPP) will be discussed in a subsequent chapter. The purpose of providing such extensive descriptions of these systems, prior to discussing their relevance to the MPP, is to ensure that the fundamental principles and techniques of each system may be seen in the correct context.

4.2 The Traditional Job Shop

The traditional job shop is recognised by the production of a high variety of products in low volumes, using a jumbled-flow plant layout.

4.2.1 Market Demands

The market in which job shops operate is unique, and may be characterised by the requirements of a typical customer, the properties of the product, and the way in which the manufacturer responds to customer requirements.

4.2.1.1 A Typical Customer

Typically, customers request the manufacture of either one, or several units of a unique product to satisfy a particular need. Some customers provide a complete design specification, while others provide only a problem definition.

In the case of large projects, the customer may regularly monitor progress. With such a high degree of customer input it is not unusual for changes to be made to the product as production progresses.

From the point of view of the manufacturer, the combination of many typical customers results in the overall production of a diverse range of products in low volumes.

4.2.1.2 Product Related Attributes

The functional properties of the product depend on customer requirements and resources, and as a consequence, product quality varies.

Common to all products, however, are higher costs and longer lead times when compared with the higher volume production of a similar product [6].

4.2.1.3 Planning and Marketing

Manufacturers have very little influence over the timing and nature of customer demands. As a result, demand is irregular and unpredictable. This leads to a high degree of future uncertainty, and prevents the manufacturer from making long term plans [7,8].

Advertising is useful, however, in that it informs potential customers of the existence and specialist capabilities of the manufacturer. While advertising may increase the workload, it has little impact on future uncertainty unless orders are accepted with due dates well into the future.

4.2.2 Process Selection

The characteristics of the market influence the way in which resources are selected and managed.

4.2.2.1 Equipment and Layout

As the focus of job shops is on flexibility rather than efficiency, the size of the production system is usually small, unless the products in which the manufacturer specialises are very large.

Most equipment is of a general purpose nature and is relatively inexpensive [8]. General purpose equipment is necessary to cope with the high variety, while low cost equipment is necessary as the total production volume is low.

Equipment is grouped according to function, which has led to the description of jobs shops as being process-oriented, or having a functional layout [9]. In some cases, however, tools and equipment may be brought to the product or work site.

4.2.2.2 Labour

The workforce consists primarily of highly skilled people capable of undertaking a variety of tasks competently [7]. The reason for this is that most operations have a very high manual labour content [6]. Consequently, although flexibility of both labour and equipment is fundamentally important, the strength of the job shop lies in the capabilities of the workforce. For this reason, a narrow range of skills is considered a liability [8].

4.2.2.3 Stock

As all products are built to order, long term forecasting of material requirements is not possible. Consequently, high value materials are purchased only when required. Although there is potential for maintaining low stock levels, there is a tendency for off-cuts, scrap, low value items, and obsolete materials to accumulate. The manufacturer must find a balance between the level of investment in these materials, assuming they are of financial value, and the likelihood that they will be of future use.

With long lead times, and multiple orders in progress simultaneously, work in progress (WIP) inventory can become high.

Finished goods are held only in extraordinary circumstances.

4.2.2.4 Production

As each product is unique, there are no formal process routes [8]. Instead, a group of workers may work on a project from initiation to completion, determining the process route as production progresses.

4.2.3 Common Problems

Job shops are often plagued with problems. Key symptoms include: long lead times, high WIP inventory, and queues at work stations [6,7,10]. These problems, frequently found simultaneously, are avoidable, but have arisen as a result of the application of misleading techniques such as batching and queuing, or inappropriate objectives such as high utilisation of capacity [7,8].

The magnitude of these problems is illustrated by studies which have shown that it is not unusual for a part to spend 95% of the time on the shop floor waiting in queues [11]. In this situation, complexity is extreme, chaos abounds, and customer dissatisfaction is high.

The effects of variable and unpredictable demand are transmitted right along the supply chain. As a result, suppliers may be unreliable [12].

One of the key consequences of producing to order to meet unpredictable demand is that smooth production schedules can not be developed [12]. This can lead to permanent queues and transient bottlenecks [8].

One further problem is that as the facility expands, higher volume orders may be accepted to increase machine utilisation. This attempt to use the job shop as a batch production system leads only to the compounding of the problems described above.

It is important to note that not all problems are intrinsic to the job shop, but result from incorrect implementation, or poor management.

4.2.4 Potential Solutions

Improvement activities must be aimed at:

- reducing queues through significant under-utilisation of capacity,
- improving quality,
- improving changeover responsiveness,
- reducing WIP inventory, and
- training and cross-training personnel [7,8,10].

Job shops that have grown to become very large, complex and inefficient, are looking towards concepts used in flow-line processes, or are subdividing the plant into cells, to eliminate non value-adding activities, and to reduce complexity.

4.3 The Traditional Batch Production System

The traditional batch production system is recognised by the production of a medium variety of products in medium volumes, using an intermittent-flow plant layout.

4.3.1 Market Demands

The market in which batch manufacturers operate is unique, and may be characterised by the requirements of a typical customer, the properties of the product, and the way in which the manufacturer responds to customer requirements.

4.3.1.1 A Typical Customer

Batch manufacturers have two types of customers:

- those purchasing standard products manufactured on a regular basis, and
- those requesting the manufacture of non-standard, or special purpose products.

From the point of view of the manufacturer, the combination of many typical customers results in the overall production of a variety of products in medium, but varying volumes.

4.3.1.2 Product Related Attributes

As the range and diversity of products are relatively high, product quality tends to vary.

Product costs are normally lower than for similar products produced in a job shop, primarily because of the efficiencies gained when manufacturing a higher volume on temporarily dedicated equipment.
Although all products may be ordered in varying volumes, the cost of manufacturing a non-standard product in low volumes may be high.

Manufacturing lead times vary considerably, and are influenced by many factors. The primary factor is the complexity of the interactions of different orders following different routings within a single production system. This complexity can be extreme in plants that produce a large and diverse range of intricate products that require many different types of processes.

4.3.1.3 Planning and Marketing

Some planning, in particular the scheduling and purchase of raw materials, is possible for the production of standard products based on forecasts or historical data. Less planning is possible with non-standard products as there is greater uncertainty. Consequently, the acceptance of orders for non-standard products may lead to sudden and unforseen disruptions.

Batch manufacturers may produce a catalogue of the complete standard-product range, and may also advertise their job-oriented services. Furthermore, advertising may be used to raise awareness, or to provide incentives to stimulate demand. While advertising does not necessarily reduce uncertainty, it is a practical means of influencing demand.

4.3.1.4 Distribution

Products may be distributed either by the manufacturer, or an intermediate agent.

4.3.2 Process Selection

The characteristics of the market influence the way in which resources are selected and managed.

4.3.2.1 Equipment and Layout

Although much of the equipment may be general purpose in nature, there may be machines or processes dedicated to a specific product or product line.

The layout of equipment is one area that clearly reveals the intermediate nature of batch production. Towards the low volume, high variety region, manufacturers may favour a functional layout to maximise flexibility. As volume increases and variety decreases, however, manufacturers may choose to arrange part of the plant according to the processes required for a particular product or product line to gain efficiency and to reduce complexity.

4.3.2.2 Labour

Skilled people may be employed to set machines up, while less skilled people operate them. Operators may be tied to a particular machine or group of machines.

4.3.2.3 Stock

Uncertainty of future customer requirements, combined with a somewhat diverse product range, leads batch manufacturers to hold significant inventories of raw materials.

Batch manufacturers may build to order or build to stock. In the latter case significant quantities of finished or semi-finished goods may be held in stock.

4.3.2.4 Production

Each standard product will have an associated production routing that describes the ideal production method. Each non-standard product will have a unique routing, designed specifically for that product.

To simplify production and control, products are produced intermittently in batches. The required facilities are set up to produce a particular product in a predetermined quantity. On completion of a batch the facilities are set up for the next production run [12].

An area that has received considerable attention is that of determining batch sizes. While it is essential to remain responsive to customer requirements and to maximise the proportion of time the equipment spends actively in production, it is also important to avoid the generation of excessively large WIP inventories.

A precondition to manufacturing a non-standard product is that the volume be sufficiently high to justify setting up the equipment, unless the customer is not concerned with cost, but not too high that other production commitments can not be met.

4.3.3 Common Problems

Batch production plants share many of the same problems experienced in job shops: as queue lengths increase, WIP inventory increases, and control becomes more difficult. In addition, the detection of defective products is significantly impaired, and customer dissatisfaction increases. This is a significant problem if a variety of standard and non-standard products are manufactured simultaneously.

Further problems include:

- varying lead times,
- high levels of stored raw materials,
- poor response to customer requirements, and
- low flexibility [13,14].

Large batch production operations may produce a very large number of parts. If there is no adequate design retrieval system, new products may be designed, regardless of whether a similar product exists [15]. This leads to a proliferation of parts, designs and process routings, which further increases complexity and administration costs.

4.3.4 Potential Solutions

Support is declining for techniques that aim to maintain high WIP inventory, long queues, large batch sizes, high utilisation of capacity, and functional layout of equipment [7,16]. Instead, emphasis is being placed on reducing batch sizes, changeover times, WIP inventory, and lead times, improving quality, and simplifying shop floor control.

Group Technology (GT) and Cellular Manufacturing (CM) are effective means of addressing these problems, and are discussed in Chapter 5, Section 5.4 (pp.56-62).

In addition, Manufacturing Resource Planning (MRP II) systems are promoted as being able to solve many of the problems experienced by batch manufacturers. MRP II systems are discussed in Chapter 5, Section 5.5 (pp.63-70).

4.4 The Traditional Mass Production System

The traditional mass production system is recognised by the production of a small variety of products in high volumes, using a continuous-flow plant layout.

4.4.1 Market Demands

The market in which mass manufacturers operate is unique, and may be characterised by the requirements of a typical customer[3], the properties of the product, and the way in which the manufacturer responds to customer requirements.

4.4.1.1 A Typical Customer

Typically, customers purchase a small quantity of products periodically.

Although customers have no direct input into the design and manufacture of products, they may have considerable choice between manufacturers. This leads to aggressive competition between manufacturers.

From the point of view of the manufacturer, the combination of many typical customers results in the overall production of a narrow range of products for long periods. As a consequence, the total production volume is very high.

The product range is more correctly described as a family of products, since the production system is set up to produce a specific type of product, and will only tolerate minor changes to the product without a significant cost or time penalty.

4.4.1.2 Product Related Attributes

Mass manufacturers are expected to produce low cost products [17] of consistent quality. Manufacturing lead times must be short, and the product must be widely available [6].

In addition, many mass manufacturers must be innovative.

Although the product is standard, options may be offered regarding features such as: colour, styling, size or accessories.

4.4.1.3 Planning and Marketing

Planning is essential for mass manufacturers. Market research must be done very thoroughly

[3] The term "customer" refers to the ultimate customer.

as decisions regarding the products or processes are binding for a considerable time and may be very costly to alter if the payback period is not completed according to plan.

Marketing is very important and significantly effects sales. Advertising is a very powerful tool, and provides the means by which manufacturers directly influence demand.

4.4.1.4 Distribution

Customers purchase mass produced products through intermediate agents. As a result, a single product may be available from a number of outlets, each offering a different price and standard of service. Consequently, customers find it worthwhile to "shop around".

Clearly, the dynamics of the mass production market are totally different from the dynamics of the job shop market.

A detailed discussion of the wholesale and retail industries - for the distribution of batch and mass produced goods - is beyond the scope of this discussion.

4.4.2 Process Selection

The characteristics of the market influence the way in which resources are selected and managed.

4.4.2.1 Equipment and Layout

The type of equipment used and how it is organised depends entirely on the product and the way in which it is to be manufactured. Consequently, mass production organisations are described as being product-oriented [9].

Special purpose equipment is used and must be capable of performing operations repetitively, efficiently, and at high speed [18]. Automation and robotics are examples of the type of equipment mass manufacturers may favour.

The equipment is arranged such that the product flows directly through sequential operations [18,19]. Such a system is referred to as a flow-line.

The capabilities of the production system lie primarily in the technology rather than the skill of the workforce.

4.4.2.2 Labour

Low skilled workers are employed to operate the machinery, and normally perform simple repetitive tasks, such as loading and unloading machines, or assembling products.

Skilled workers may be employed to set up the plant initially and to maintain it.

4.4.2.3 Stock

Mass manufacturers must maintain tight control over stock if costs are to be kept to a minimum. Poor organisation can lead to large excesses or shortages, with serious consequences.

Ideally, mass manufacturers build to order. There are, however, two conditions that lead to the accumulation of finished products:

- where production rates do not fluctuate in harmony with demand rates, for example where demand is seasonal and the peak demand rate exceeds the peak production rate, and
- where the manufacturing lead time is longer than the time that customers are prepared to wait.

It is not uncommon, however, for distribution agencies to absorb some of the cost of maintaining high levels of finished goods in stock to meet the demands of customers.

4.4.2.4 Production

Traditionally, mass manufacturers have focused on achieving economies of scale, resulting in large plants, high production volumes, and low skilled workers performing repetitive tasks [20].

To maintain a steady flow through the plant, without accumulation at any point, each stage of production must have a process time similar to that of all other stages [8]. Coordination between processes may be achieved by ensuring that the production rate is dictated by the speed of the production line.

A combination of high capital costs and a focus on efficiency has resulted in policies of high utilisation of capacity [8].

A special example of mass production is the transfer line, where material handling between operations is also automated [21]. Transfer lines require not only a highly standardised product, but also a very high throughput, as the capital investment in equipment is very high [22].

4.4.3 Common Problems

As high production volumes are required for economic success, the market must be stable, with future demand expected to remain steady. There are two factors that may affect this:

- the risk of product obsolescence, and
- the risk of a major change in process technology.

A focus on efficiency without sufficient regard for other objectives has resulted in many plants being run at, or near, full capacity for long periods. This leads to a higher incidence of breakdowns, which leads to higher levels of WIP and finished goods inventory, and the inability to detect defective products quickly [21,23].

These problems are intensified by using buffer stores to keep machines running.

With regard to the production line itself, two problems exist:

- disruptions may bring the whole line to a halt, and
- changing the layout of the plant, or the product that is produced, is a costly and time consuming exercise.

Many factors influence the nature of demand for products, and this is especially true in mass production. As society becomes more affluent, there is an increase in the demand for unique, or customised goods.

4.4.4 Potential Solutions

One method of increasing the flexibility of the production system is to employ computer controlled equipment. These systems are more flexible than conventional non-programable machinery, however they can be very costly. While these more sophisticated systems extend the boundaries of flexibility, or the achievable variety envelope, they are of limited use outside the boundaries [24]. Computer Integrated Manufacturing (CIM) systems are discussed in Chapter 5, Section 5.2 (pp.35-44).

Market trends, such as the increasing demand for customised products, and reducing product life cycles, are placing much pressure on mass manufacturers. This pressure is forcing mass manufacturers to abandon the principles of economy of scale, which aim to maximise the volume of production of a single type of product, while minimising the cost and time required, and to focus instead on the principles of economies of scope, which aim to allow the production of a wider range of products without significant cost or time penalties.

The problems associated with high WIP inventory, and poor quality may be addressed by implementing the Just in Time (JIT) philosophy. This is discussed in Chapter 5, Section 5.3 (pp.45-55).

4.5 Selected Bibliography

Corke, D.K.

'Production Control in Engineering'. Third Edition. Edward Arnold Ltd, 1987.

Samson, D.

'Manufacturing & Operations Strategy'. Prentice Hall, 1991.

Schroeder, R.G.

'Operations Management: Decision Making in the Operations Function'. Third Edition. McGraw-Hill Book Company, 1989.

Chapter 5

Modern Manufacturing Systems

5.1 Introduction

In this chapter, a second group of manufacturing systems is examined. The systems in this group are:

- Integrated Manufacture and Computer Integrated Manufacturing (CIM),
- Just in Time (JIT),
- Group Technology (GT) and Cellular Manufacturing, and
- Material Requirements Planning (MRP) and Manufacturing Resource Planning (MRP II).

These systems, referred to as Modern Manufacturing Systems, are distinct from the Traditional Manufacturing Systems and can not be defined on the basis of the Product-Process matrix (Table 4-1 (p.21)). The following reasons account for this:

- to define these systems according to the matrix implies that:
    - they are based on the same fundamental principles and concepts, and
    - they are focused primarily on the selection of resources to meet the volume/variety demands of the market, and
- these systems are not confined to a specific area of the matrix but can cover a broad region, and may overlap other systems.

These systems are not defined by the nature of their internal mechanisms, or by the type of product produced. Instead, they are based on a philosophy: they are philosophy driven.

The existence of these Modern Manufacturing Systems does not mean that the Traditional Manufacturing Systems are obsolete. Rather, they may be carefully combined within a single system.

Each of the modern systems is discussed presenting typical features of the philosophy in terms of: characteristics, objectives, benefits, development motivation, application, implementation and common problems.

The relationship between Modern Manufacturing Systems and the Manufacturing Pilot Plant (MPP) will be discussed in a subsequent chapter. The purpose of providing such extensive descriptions of these systems, prior to discussing their relevance to the MPP, is to ensure that the fundamental principles and techniques of each system may be seen in the correct context.

5.2 Integrated Manufacture and Computer Integrated Manufacturing

5.2.1 Introduction

Integrated Manufacture is a philosophy aimed at transforming a manufacturing organisation from being a group of "individualistic" people, functions and elements into a cohesive group of "cooperative" and interdependent people, functions and elements. This enables the organisation *as a whole* to function effectively and competitively.

Computer Integrated Manufacturing (CIM) is an 'enabling technology' [22 p.13] of Integrated Manufacture. At the technological level, it is the primary means by which the philosophy is implemented.

CIM systems are characterised by two features:

- communication systems for linking various elements, and
- a data source shared by all elements [25].

To keep the concept of CIM in perspective it is advisable to regard it as a fundamental element of a broader philosophy, such as Integrated Manufacture. This ensures that the focus of attention is on the integration of all of the functions and elements of the organisation, by whatever means, rather than focusing only on the application of computer technology.

5.2.1.1 Differing Views of CIM

Two fundamentally different views of CIM systems have emerged. The key distinction between these views concerns the role of people in manufacturing processes.

One view represents a concept in CIM systems that has little application at present. It advocates the use of high levels of fully integrated, high technology automation and a workforce of minimal size [21 p.99,26]. The task of employees is not to produce goods, but to monitor the production systems.

The other view represents a concept in CIM systems that is of practical use to present day manufacturers. It advocates the use of computer technology to enable an organisation to meet the key business goals. This type of CIM system is not aimed primarily at minimising the size of the direct labour workforce, but is aimed at supporting and enhancing the activities of the workforce [27].

Ingersoll Engineers (1985 p.17) sound a warning against extremely expensive CIM systems, such as some Flexible Manufacturing Systems (FMSs), where 'technology leaps ahead of good business sense'. Such high-risk systems are unlikely to provide an acceptable economic return.

This discussion focuses on CIM systems used to support the activities of the workforce.

5.2.2 Objectives of Integrated Manufacture and CIM

Consider next, the objectives and potential benefits of Integrated Manufacture and CIM.

5.2.2.1 Objectives of Integrated Manufacture

The primary objective of Integrated Manufacture is to transform an organisation by integrating the elements of the organisation such that all work together towards a common goal. The underlying implications are that such a goal can be identified, and that all employees can understand and relate the goal to their own work. Most important is the need to change the attitudes of employees such that there is a willingness to cooperate and function as a team.

5.2.2.2 Objectives of CIM

The objective of CIM systems is to provide communication links between the various elements throughout the organisation. These elements may include: shop floor, administrative, and management systems, and where advantageous, systems in supply and distribution firms [25,28,29,30]. In this way, information from a common source is available to all who require it [23].

CIM systems are capable of linking functionally diverse systems, including: MRP and FMS systems; Computer Aided Design, Manufacturing and Engineering systems (CAD, CAM and CAE); and Automated Guided Vehicles (AGVs) and Automated Storage and Retrieval systems (AS/RS) [29,31].

5.2.2.3 Potential Benefits

It is claimed that Integrated Manufacture and CIM are able to provide the following benefits:

- higher quality,
- lower cost per unit,
- rapid response to market pressures, not only to changes in demand, but also to demand for innovation,
- smaller batch sizes (even as low as a single unit) with shorter lead times,
- rapid setup and changeover,
- increased productivity and flexibility, and
- the ability to increase product variety without incurring a substantial cost penalty [26,30,32,33].

Some of these benefits may be achieved partially through the CIM technology, and partially as a result of the necessary changes required before the technology can be installed [33]. These changes are referred to as 'pre-automation' [21 p.63] activities.

CIM systems allow low cost production of a high variety of products in low volumes. This is referred to as 'economies of scope' [34 p.6]. To offset the high capital investment in the technology, however, the total production volume may need to be very high [30].

5.2.3 The Origin of Integrated Manufacture and CIM

The philosophy of Integrated Manufacture is neither new nor unique.

It is not new since it is the formalisation of a philosophy that may be practised by default in many organisations, particularly small organisations. A plausible explanation for this is that Integrated Manufacture is 'plain common sense' [22 p.30].

It is not entirely unique since other philosophies exist which pursue similar objectives, particularly in relation to CIM, but are not identified as Integrated Manufacture. For example, in discussing CIM systems Kidd (1990 p.150) identifies the need for 'a broader approach which addresses *organisation, people* and *technology*'.

Manufacturers are under increasing pressure to revolutionise the way in which they operate. In particular, market pressure and global competition require manufacturers to restructure the organisation to meet customer demands, and to integrate stand-alone systems.

5.2.3.1 Market Pressure

To remain profitable, manufacturers must be capable of adapting to meet changing market demands. Competition was based predominantly on cost efficiency in the 1960s, productivity in the 1970s, and quality in the 1980s [24,35]. In the 1990s, *time* is emerging as the critical factor of competition, in particular, time to market [35,36,37]. In addition, quality and flexibility remain important [24,35]. While some factors may be more important than others, manufacturers must compete simultaneously on a range of factors, as dictated by the market.

Several trends in customer demands are also apparent in some sectors of the market. They include:

- a shift away from mass produced goods towards customised goods, and
- reducing product life cycles [38,39].

5.2.3.2 Growth of Organisations

Small organisations are typically very efficient. The primary reasons for this include:

- the lack of complexity,
- the ability of one person, or a small number of people, to maintain total oversight,
- the stability of management,
- the requirement that employees perform a range of tasks as needs arise, and
- the physical compactness of the facility and the proximity of workers to each other.

The manner in which organisations grow has a significant bearing on their performance. The primary cause cited for growth failure, where failure is identified by a reduction in competitiveness, is the absence of an overall plan or strategy to govern growth.

Consider the expansion of a small organisation with no strategy for growth. Unrestricted expansion leads to the need to divide the organisation into divisions or departments to maintain manageability. Although this seems a sensible approach, it can lead to problems. As each department grows, it becomes more independent, and physically isolated. Consequently, the need for complex systems, such as for transporting material or communicating information, increases. This growth leads inevitably to increasing complexity and chaos, waste and delays, and in all these, rising costs. The magnitude of the problem may be gauged by determining the proportion of resources expended on processes that do not *directly* provide value for the customer[4].

An additional problem is that departments purchase technologies in the pursuit of their own objectives, which may not be derived directly from the overall business objectives. This leads to incompatible stand-alone systems, referred to as islands of automation [23]. Islands of automation are discussed further in Section 5.2.3.3 (p.39).

There is a second type of growth that leads to complexity and inefficiency: Schonberger (1986 p.5) describes this as the 'more-of-the-same' type of growth, where new technologies are added to the existing system. This results in a system that is simply a larger version of the old one. A more appropriate approach is to determine whether the new technology allows a change in procedures, or the elimination of procedures, from a broader perspective [23]. This is of particular significance when manual systems are replaced by computerised systems [23]. It is in this type of situation that the principles of Reengineering, discussed in Chapter 3, Section 3.2.2 (p.11), can be used to advantage.

5.2.3.3 Islands of Automation

The behaviour of independent departments is not the only reason that islands of automation have emerged. The rapid progress and resulting flexibility of computer technology has allowed a variety of systems to be developed. Applications include: design systems, machining systems, expert systems, material control systems, and administration systems. Although many of the early systems were incompatible, the benefits of integration have since been identified. Further development in computer technology has led to the means by which these systems may be integrated [40].

Technology is not the only solution to the problem of system integration. Progress has been made in the development of standards, such as the International Standards Organisation Open Systems Intercommunication Standard, and protocols, such as the Manufacturing Automation Protocol (MAP), for the development of automated systems in manufacturing [23,41].

---

[4] Much care is required when gauging such information.

5.2.4 A Typical Application

The philosophy of Integrated Manufacture may be of use to any manufacturing organisation suffering from poor performance and showing symptoms such as: excessive delays, high production and overhead costs, complexity, and poor communication.

From the point of view that CIM systems allow efficient communication of information between various elements of an organisation, and the elimination of data duplication, CIM may benefit a variety of organisations. The benefits of CIM systems, however, are most evident in small organisations producing a variety of products, many of which are tailored to the requirements of each customer; in low volumes; at short notice; and at low cost [28]. This is because the data processing required to transform the output of one function, such as design, to the input of another function, such as production, is performed automatically. In addition, programable equipment may be set up automatically.

Because of this flexibility and speed, CIM systems allow manufacturers to offer a range of products in a number of different market sectors and to compete against manufacturers who use Traditional Manufacturing Systems designed to produce a narrower range of products in a narrower range of volumes for a particular market [34].

Clearly, the level of investment in computer technology and automation is dependent on the expected short and long term financial returns, as the organisation must remain a commercially viable enterprise.

5.2.5 Implementation

5.2.5.1 The Implementation Strategy

The strategy for the implementation of Integrated Manufacture and CIM must outline planned changes to the manufacturing system, taking into account present business goals, and anticipated future needs [30,33,42]. The strategy should be flexible.

5.2.5.2 The Need for Balance

Before implementing the Integrated Manufacture philosophy, manufacturers must understand what the philosophy is, what the goals of the organisation are, the nature of the market, and the strengths and weaknesses of the organisation and key competitors. This allows the manufacturer to implement a balanced system. Examples include balance between independence and interdependence, and between manual operations and automation.

Consider the balance between interdependence and independence.

- The development of a new product requires a cooperative effort between many functions of the organisation, and representatives of parties outside the organisation, to determine the fundamental properties of the new product. This requires interdependence, and leads to rapid development, with major obstacles overcome in the early stages.

  Working out the precise details of the product requires teams of competent specialists, which are necessarily somewhat independent, but who work within the established system framework.

- Maintaining a source of up-to-date data requires interdependence between information generators and users.

  Ensuring that workstations can operate despite a breakdown in the communications system requires a degree of independence [43]. This may be achieved by a combination of Local Area Networks (LANs) and semi-autonomous or modular workstations [23].

  In addition, distributed databases combined with a central database management system may be favoured over a single centralised database.

5.2.5.3 Human Considerations

People are the most valuable resource to manufacturers. This requires that organisational issues be addressed when implementing new technology, especially CIM technology [25,29]. This is because technology in itself will not cause people to cooperate [44]. Although technology improves the efficiency of data transfer, it does not necessarily improve the clarity of the information, therefore the ideas of one system user must still be interpreted by other system users. For this reason human integration must have priority over computer integration, and must not be replaced or displaced by computer integration.

Cooperation is enhanced by the formation of teams between management and shop floor workers, and between different skill levels [25,44].

Before implementing a CIM system, three important questions must be answered.

- Will the system bring an acceptable financial return?
- Will the system work as intended? and
- Will the people who are expected to use the system want to use it and use it properly?

The third question is most important, and can only be answered with proper communication before and during implementation. Early commitment from employees can greatly improve the implementation process and the likelihood of success.

5.2.5.4 Quality

Integrated Manufacture embraces the principles of Total Quality Control (TQC) which emphasises:

- preventive maintenance,
- defect prevention,
- employees measuring the quality of their own work and being responsible for it, and
- the need for continual improvement.

Furthermore, reduction of waste and complexity allows employees, particularly managers, to focus on key issues such as satisfying customer requirements, rather than continually battling with the day to day problems.

Undertaking product design and development as a cooperative effort ensures that products are not only designed and built to meet customer requirements, but are also designed for ease of manufacture.

CIM also plays a key role in quality.

A single data source ensures that all system users work with, and base decisions on the same data. This may require that certain procedures be established for updating the data source, and that the person who generates the data enters it into the system and is responsible for the accuracy of the data.

In addition, the automation of data processing and transfer, together with the interconnection of systems contribute to greater precision in operations, such as ensuring the availability of the correct materials, machine tools, machining programs, and billing procedures.

5.2.5.5 Simplification and Simplicity

In the context of Integrated Manufacture, simplification signifies the elimination of unnecessary complexity. The benefits of simplification include reductions in overhead costs, waste, work in progress (WIP) inventory, delays, and confusion. In addition, systems become more responsive.

In the context of CIM, simplicity signifies that the structure of the CIM system is based on the logic of the data flow and material flow. The computer system is designed to fit the manufacturing system which is itself designed to accomplish a set of goals. The CIM system must not be allowed to become like a 'supermachine' [21 p.78] which dictates company policy.

5.2.6 Common Problems with CIM

5.2.6.1 Data Accuracy

If data is frequently inaccurate, the level of confidence in the system will drop [26]. This may result in failure to use the system properly leading to a further reduction in data integrity. This vicious cycle ends with the abandonment of the system.

The level of care taken when data is entered manually into the system depends on:

- whether the person entering the data understands the significance of the data and the possible consequences of inaccurate data [26], and
- whether the person entering the data recognises any personal and organisation-wide benefits to be gained as a direct result of the data being available and correct.

Because of the high speed at which computerised systems are capable of operating, inaccurate data may propagate further through the system before detection than with manual systems. As a result, the consequences may be more severe [26]. Consequently, backup systems and procedures are necessary. In addition, security measures may be required.

5.2.6.2 Implementation Failure

CIM implementations are not always successful. Several manufacturers have found that in the early stages of implementation the performance of the system is below expectation [26]. This is not entirely unexpected, as CIM is a long term strategy [30].

Other manufacturers have experienced low payback rates [25].

One pitfall to be avoided in the implementation of technological systems of any sort is to overlook the need to accompany, or precede the technological change with an organisational or social change [26,45].

CIM implementations may fail if there is no overall plan or strategy for implementation. CIM may erroneously be viewed as the solution to all problems. Before an existing system is automated, it is necessary that the strengths and weaknesses of the system, and the functional properties of the system be fully understood [30,46]. Failure to do so, will almost certainly result in the development of an inadequate or inappropriate system.

5.2.6.3 Operational Difficulties

The supplier of computer technology may be a restraining factor in the development of a CIM system. Suppliers may develop systems that are incompatible with the systems of other suppliers. As a result, the manufacturer is restricted to purchasing systems from only one supplier, and therefore the sophistication of the systems is limited to the rate of innovation of the supplier.

Although CIM reduces internal uncertainty, measures for dealing with uncertainty, such as buffers, should not be eliminated entirely [26]. Instead, careful use of such measures ensures that the manufacturing system remains robust but efficient.

Although CIM systems are promoted as being flexible, this flexibility must be viewed objectively. While they may be more flexible than the traditional technologies, there is always a limit to the scope of the flexibility. As with traditional technologies, beyond the limits of flexibility, the usefulness of the system declines rapidly [24].

5.2.6.4 Resistance to CIM

Resistance to the implementation of CIM can be strong. Many reasons for resistance are based on the perception of a threat. Examples include the threat of losing a job, and the threat of an unfavourably job change.

5.2.6.5 The Futuristic CIM System

Apart from the high cost of fully automated, small workforce plants, there is a danger that such plants will exhibit the same problem that Integrated Manufacture, through CIM, is designed to overcome. This problem is that such plants can become very complex and dissociated. Many teams of specialists, from outside the organisation, are required to design, build and maintain the various elements of the system. Increasing independence of the teams leads to increasing independence of the systems, and the resulting complexity leads to increasing costs. Clearly, top management must have an overall strategy for the organisation, and must understand and maintain control over the work of external experts to ensure that *overall business goals are met.*

5.3 Just In Time

5.3.1 Introduction

Just in Time (JIT) is a manufacturing philosophy advocating the elimination of waste, and constant improvement. This applies to the production system, as well as to the manufactured product.

5.3.2 Objectives of JIT

Several of the numerous, but complementary descriptions of the objectives of JIT are listed below.

- 'To improve productivity and reduce cost continuously' [47 p.4].
- 'The various facets of JIT - waste reduction, continuous improvement, poka-yoke (mistake-proofing), etc. - all stem primarily from one central concept - the management of interdependence' [48 p.56].
- The definition given by Taiichi Ohno, a leader in the implementation of JIT at Toyota, is: 'In a nutshell, it is a system of production, based on the philosophy of total elimination of waste, that seeks the utmost in rationality in the way we make things' [49 p.61]. Waste is defined as anything that adds time, cost, or complexity but not value [36,50,51].
- 'A relentless, never-ending crusade for the total elimination of waste and respect for people' [42 p.8].
- JIT recognises that the correct ranking of performance measures (in descending order) should be:
  - Throughput: the rate at which money is generated through *sales*,
  - Inventory: the money invested in items that are to be sold, and
  - Operating Expense: the money spent on converting Inventory into Throughput [52].
- The key elements of JIT are workplace organisation, total employee involvement, and waste elimination [53].
- 'Waste-free production to meet known orders' [54 p.10].
- 'Continuously improve the manufacturing process by searching for ways to reduce process variation' [50 p.36].
- 'The central themes of just-in-time manufacturing are simplicity, quality and the elimination of waste' [55 p.35].

Although the definitions are consistent, each offers a unique perspective on JIT.

5.3.2.1 Potential Benefits

It is claimed that JIT is able to provide the following benefits:

- shorter production lead times,
- the ability to operate economically with smaller batch sizes,
- reduced variability,
- reduced uncertainty,
- reduced stock levels, and higher stock turnover rates,
- simple production and control systems,
- levelled production schedules,
- the ability to match the production rate to demand,
- greater customer satisfaction on the basis of quality, cost, and delivery reliability,
- closer relationships with suppliers and customers,
- increased competitiveness,
- reduced space requirements,
- improved plant layout,
- continuous incremental improvements, and
- increased skill level of workers [21,42,50,53,56].

Although these are considered as 'bonuses' [21 p.137] or 'by-products' [42 p.8], they may be redefined as secondary objectives.

5.3.3 The Origin of JIT

It is believed that JIT was first used in the ship building industry in Japan as a means to increase control over the delivery of key components.

Toyota adopted the philosophy to reduce costs and increase product quality, thereby increasing competitiveness.

At Toyota, JIT is simply a 'strategy to achieve non-stock or stockless production' [57 p.97]. It is an integral part of a wider system known as the Toyota Production System.

In the West, however, the meaning of JIT is less well defined. It is significantly broader and encompasses most aspects of the Toyota Production System.

5.3.3.1 The Toyota Production System

The development of the Toyota Production System was initiated by Taiichi Ohno, his associates, and an Industrial Engineering consultant, Shigeo Shingo [49].

The aim at Toyota is to reduce costs by eliminating waste (this corresponds to the broader definition of JIT in the West).

This concept has a sound basis. Toyota believe that the selling price of their products is determined by the market. Consequently, profit maximisation must begin with cost reduction.

$$\text{Profit} = \text{Selling Price} - \text{Cost}$$

This is contrary to many western manufacturers who hold the view that the selling price of a product is the sum of the production costs and the desired profit.

$$\text{Selling Price} = \text{Cost} + \text{Profit}$$

This subtle difference in emphasis has far reaching consequences as the discussion below will attempt to reveal.

Shingo (1989 pp.68-75) lists the following basic principles of the Toyota Production System:

- the elimination of waste, particularly the waste associated with producing too much or too soon,
- the supply of processes with the required items in the correct quantities and at the correct time (the narrower definition of JIT),
- the separation of workers from machines,
- low machine utilisation rates ensuring that resources are available during periods of high demand, and
- problem solving aimed at preventing the recurrence of problems.

In this document, the broad definition of JIT has been adopted.

5.3.4 A Typical Application

In Japan, JIT is considered appropriate only in repetitive manufacturing industries where product volumes and mixes are known well in advance of production. This is because the successful implementation of JIT techniques, such as kanban, requires extensive long range planning [58].

Maskell (1989 p.35) describes the ideal JIT application as one where demand is smooth and predictable, process technology changes infrequently, and a large percentage of standard or common parts are produced.

Many of the principles of JIT are applicable to a range of different types of manufacturing systems, including repetitive and discrete systems, job shops, and build to stock or build to order systems [7,55].

5.3.5 Implementation

A wide range of techniques and concepts are normally associated with the implementation of JIT. The most common are now considered.

5.3.5.1 Product Manufacture

Maintaining an uninterrupted flow of information, materials, and products is a key aspect in the successful implementation of JIT. The flow path extends beyond the boundaries of the manufacturing organisation to include suppliers and customers. The concept of the production chain - the dependent steps required to transform raw materials into a finished product - is very important.

With regard to flow, Arogyaswamy and Simmons (1991 p.56) state that 'The value added to a product ... [is] the result of separately performed but interdependent activities appropriately coordinated'.

Traditionally, manufacturers attempt to reduce interdependence between stages in production by uncoupling them and placing inventory buffers between them. Although greater independence is achieved, operating costs increase because the increase in WIP inventory leads to a reduction in the ability to detect defects quickly.

JIT promotes an increase in interdependence, as it leads to improved communication and coordination, and the potential for simplification [48,59].

By recognising that the elements of a production system are interdependent parts of the flow path, it becomes possible to focus attention on improving those elements such that the efficiency of the production system as a whole increases. This approach has the potential to lead to an increase in throughput. Striving for high efficiency of individual elements with no regard for overall system performance is unlikely to improve the overall performance of the system [48].

5.3.5.2 Supply

The primary means by which supply variability and uncertainty is reduced, and improved material flow is achieved is through the development of long term partnership-type relationships with suppliers [53,60].

This relationship involves responsibilities and benefits for both parties [61]:

- the manufacturer must provide the supplier with schedules outlining anticipated future material requirements, allowing the supplier to plan accordingly, and
- suppliers must produce quality products on time, and in the correct quantity, and deliver them to the point of use to eliminate unnecessary storage and handling [56].

The products of dependable suppliers may not be subject to inspection upon receipt [53,56]. In this way, suppliers are regarded as 'an extension to the manufacturing facility' [50 p.35].

Suppliers may be involved in the early stages of product development, to ensure that new products reach the market with a minimum of unnecessary delays and costs [53]. Clearly, such effort from the supplier is also in the best interests of the supplier.

5.3.5.3 Planning

Planning, including extensive market research, is fundamental to JIT manufacturing [58,62].

Excellent planning and management are essential to maintain "just in time" production, thereby preventing degeneration to the more complacent, less profitable state of "just in case" production.

With regard to planning the aim is to generate a number of rolling schedules, each outlining a target production level over a specific time horizon. They range from long term flexible schedules covering many months, to short term fixed schedules covering several days. While production may proceed only on the basis of actual customer orders, from which the short term schedules are derived, the advance arrangements made with suppliers is based to some degree on forecasts, from which the long term schedules are derived. The degree of uncertainty, and therefore, flexibility of the schedule, depends on the distance into the future to which the schedule relates.

The schedules have four key functions:

- to assist suppliers in long range planning,
- to assist in resource planning on the shop floor,
- to act as the production schedule used by the final stage of production, and
- to coordinate supply, manufacture, and distribution activities.

5.3.5.4 Technical Systems

To ensure a good match between demand and production rates, multiple small machines are favoured over few large, or high capacity machines. An added advantage of such equipment is the ability to reorganise the shop floor quickly to accommodate changes in demand.

It is fundamentally important to remember that this, like many other aspects of JIT, is a means to an end, namely, satisfying customers. Clearly, the nature of market demands, both present and future, and the stability thereof, determines the most suitable equipment and layout.

To facilitate smooth flow, JIT manufacturers favour flow-line, or cellular manufacturing techniques, seeking to minimise wastes such as transportation and handling. This product-oriented layout allows the use of simpler control systems, and reduces the number of potential sites for inventory to accumulate without becoming conspicuous or bothersome [7].

Support services are also organised according to production system requirements [59]. Of particular significance is the role of maintenance. Preventive maintenance is aimed at minimising the potential for disruptions, thereby ensuring resources are available when required [50].

Housekeeping is rigorously pursued as a means to minimise or eliminate that which may hinder production.

Reducing setup times is fundamental to JIT manufacturing as it provides the basis for the realisation of many of the potential benefits described in Section 5.3.2.1 (p.46). Several benefits warrant special mention. Reduced setup times allow shorter production lead times, and smaller batch sizes. This in turn leads to a reduction in WIP inventory, an increase in throughput, and greater responsiveness to the market.

In all these things, simplicity is essential. The advice of Young (1991 p.12) is '"keep it simple". Simple is cheap, simple is reliable, simple is flexible, simple is visible'.

5.3.5.5 Inventory

Limiting the accumulation of inventory, particularly WIP inventory, is a crucial aspect of JIT in that:

- waste associated with storage is reduced,
- defects are detected rapidly, thereby increasing the likelihood of discovering and rectifying the source of the problem without substantial waste from rework or disposal, and
- problems, such as disruptions due to defective products, that are normally hidden by higher

levels of inventory are exposed, and require rapid rectification if production is to continue smoothly [63].

This contrasts sharply with Traditional Manufacturing Systems where higher inventory levels are maintained to *accommodate* disruptions to production.

5.3.5.6 Quality

The role of quality in JIT is twofold:

- with a focus on the customer: quality products attract new customers and generate customer loyalty, and
- with a focus on production: quality at all stages of production minimises waste associated with defects, disruptions, and variation. Defective products must not be allowed to progress through production [53].

Several elements contribute to the standard of quality:

- simplification and standardisation of products, tools, and material handling equipment [53],
- inspection at every stage [64], or the use of mechanisms for detecting abnormalities, referred to by Shingo as 'autonomation' [57 p.58]. These are aimed at early defect detection and/or defect prevention, and
- customer relations. By being 'closer to customers' [60 p.37] manufacturers gain insight regarding market needs and demands.

The concept of internal customers plays a key part in the drive for quality. In addition, systems such as TQC and Statistical Process Control (SPC) are frequently used [53,65].

5.3.5.7 Human Considerations

In JIT manufacturing, people are treated with respect, as they are the most vital resource [42,63].

From a management point of view, two concepts that contrast sharply with traditional Western manufacturing principles are promoted:

- managers involved with the production system are required to know and understand the processes, and
- barriers between management and workers, both physical and psychological, are strongly discouraged. Instead, a cooperative team effort is promoted to achieve common objectives.

Workers are trained to be multi-skilled so that they are able to move to where the work is [60].

This ensures that production output matches demand.

As the contribution of workers to production is so critical, many techniques are used to enhance production such as: employee involvement, skill development, participative decision making, problem solving, quality circles, pride in workmanship, and recognition for good work [49,50,53,55,63].

5.3.5.8 Production Dynamics

The kanban[5] system is the classic shop floor control system, developed at Toyota.

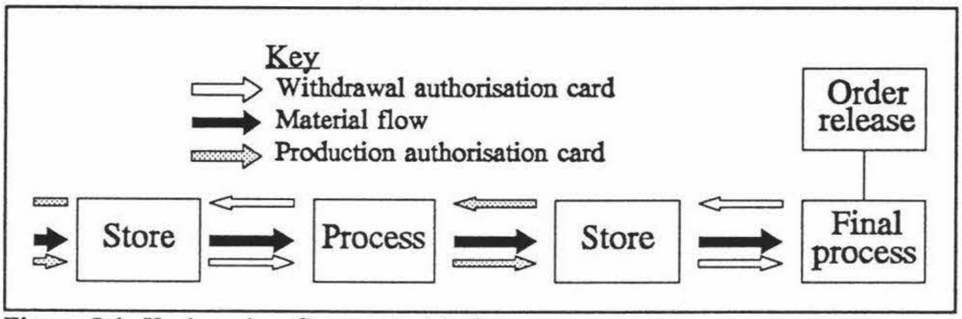

Figure 5-1 Kanban shop floor control logic

Figure 5-1 (p.52) represents the kanban control system at a conceptual level.

Kanban is essentially a triggered, or "pull", control system, where each workstation authorises the *preceding* workstation(s) to continue production.

Ultimately, overall control rests with the final stage of production, typically final assembly. Orders are released to the final stage, and, as production progresses, the release of replenishment orders propagates upstream.

The benefits of such a system are significant:

- control is simple,
- changes in production are easy to accommodate,
- over-production is avoided, and
- the status of production, such as order progress or areas of high workload, can easily be determined [66].

In addition, several other concepts are used which are a significant deviation from traditional

[5] The term kanban translates to 'coded card' [54 p.20].

methods of manufacturing:

- matching production to demand through the use of mixed modelling, hence the need for short setup times,
- stopping production when the daily quota - based on *actual* customer orders - is met. Overtime and undertime are of little importance in comparison with satisfying customer orders, and
- if possible, a maximum of 2 shifts are scheduled per working day, with a time span between each shift allowing for maintenance and other activities. The aim is to ensure that when resources are required, the are ready for use.

5.3.5.9 Improvement

JIT allows no room for complacency. On-going incremental improvement in all areas is regarded as the norm. Unfortunately, improvement means change, and change may provoke feelings of insecurity which may lead to resistance to improvement [67].

Improvement is not limited to the use of the resources of the organisation. Instead, to remain competitive in the long term, the product range must also be subject to improvement, to eliminate unnecessary costs, or improve performance [53].

5.3.6 Common Problems with JIT

5.3.6.1 Definitions

There are many differing views of what JIT is, not only at the operational level, but also at a more fundamental level. There is also confusion over how JIT relates to other systems such as: MRP, MRP II, and CIM [59].

5.3.6.2 Implementation

JIT is a philosophy. It must not be equated with kanban, or frequent deliveries in small quantities, or zero stock. These are simply several of the many techniques used to implement the philosophy. This has in some cases been the cause of JIT implementation failures. The implementation of JIT techniques without a sound understanding of the philosophy has led some companies, who were forced to take some action to remedy their lack of competitiveness, to implement techniques inappropriately, or the wrong techniques altogether [42].

Safayeni and his colleagues (1991 p.29) suggest that because of the 'success oriented' nature of many literature articles, many people do not realise just how great the task of implementation is. While significant improvements can be made with small investments and effort, one must keep in mind that Toyota has spent over 20 years implementing the Toyota Production System [65,67].

Maskell (1989 p.35) believes that one reason that the implementation of JIT is not as widespread in the West as it might be is because many aspects of it are very different from typical Western manufacturing practices.

5.3.6.3 Supply

Suppliers who do not produce "just in time" may purposely overproduce and store goods for subsequent delivery in multiple small lots. While this makes operations simpler for the supplier, it defeats the purpose of frequent deliveries since the cost associated with the waste of overproduction and storage is shifted to the supplier, and are ultimately passed on to the manufacturer [68].

A problem encountered by organisations that are small in comparison to their suppliers is that they can not bring much pressure to bear on suppliers to implement special delivery schedules, or to provide defect-free products.

5.3.6.4 Technical Systems

Ensuring that excess machine capacity is available during normal operation will undoubtedly result in lower machine utilisation rates when compared with Traditional Manufacturing Systems. This is seen as a weakness of the philosophy when using traditional performance measures and reasoning. This point helps to illustrate that the implementation of the JIT philosophy is not simple. Instead, it is likely to require many *fundamental changes* in the management of the organisation, and the way in which performance is measured.

5.3.6.5 Human Considerations

Giunipero and Law (1990) have identified several groups within organisations most likely to resist JIT implementation through lack of commitment. They are: marketing, design, engineering, and accounts payable.

5.3.6.6 Production Dynamics

Goldratt and Fox (1986 p.90) point out that low inventory kanban systems have a significant weakness. A major problem at one machine may bring the whole production system to a halt, causing a loss in production. This apparent weakness of the philosophy may be turned into a strength, since such a problem receives the immediate and undivided attention of management until it is resolved.

5.3.6.7 An Unbalanced Focus

Although the focus on cost reduction is important, it must not overshadow other activities and prevent the organisation from making progress, or from meeting other key business objectives such as producing defect free products, and adhering to the schedules. Furthermore, new product development and other forms of income enhancement are vital to the long term success of the organisation [69 p.44].

5.4 Group Technology

5.4.1 Introduction

The Group Technology (GT) philosophy is 'a way of organising and using information about part similarities to enhance the effectiveness and efficiency of part manufacturing' [28 p.237].

5.4.2 Objectives of GT

The primary goal of GT is to 'maximise production efficiencies by grouping similar and recurring problems or tasks' [70 p.3].

Additional objectives include focusing on flexibility and simplicity, and eliminating unnecessary costs and delays.

5.4.2.1 Potential Benefits

It is claimed that GT is able to provide the following benefits:

- reductions in setup and throughput times,
- reductions in WIP inventory,
- a reduction in part numbers,
- improved delivery reliability,
- reduced floor space requirements,
- greater worker satisfaction,
- rapid detection of quality problems, and
- simplification of production control [19,71].

5.4.3 The Origin of Group Technology

The concept of GT was first put forward by Mitrofanov in the Soviet Union in the 1940s. Since introduction, it has gained widespread attention, resulting in further development [72].

5.4.4 A Typical Application

Group Technology is most effective when implemented in higher volume job shops or batch production systems with a large number of in-house designed and manufactured parts and a functional layout of equipment. Such organisations can become complex. Job shops are discussed in detail in Chapter 4, Section 4.2 (pp.22-25), while batch production systems are discussed in detail in Chapter 4, Section 4.3 (pp.25-28).

5.4.5 Implementation

The concept of GT has two fundamental elements:

- the grouping of similar products into families, where similarities are based on design and production attributes, and
- the production of these families in manufacturing cells, or machine groups.

Each of these will be discussed below.

5.4.5.1 Product Families

(i) Classification and Coding Systems

Classification systems are used to divide the product range into groups of products with similar design attributes and process requirements [72].

Coding systems are used to identify individual products. In sophisticated systems, the elements of the code may represent the categories of the classification system. With the development of powerful computer databases and other software, the importance of coding systems has declined [73].

Given that the families are produced in dedicated cells, the process of dividing the product range into families must take account of limitations of resources, and predicted future changes in demand for the products [72].

(ii) Standardisation

Standardisation is a process that affects both product design and process requirements.

From a design point of view, standardisation gives designers a set of guidelines by which to work, and encourages a systematic approach to design. As a result, designers are able to focus on critical design features, and to standardise on non-critical features.

From a manufacturing point of view, standardisation leads to fewer tools and fewer setups, which leads to lower costs.

Standardisation also simplifies the process of cost estimation [12].

In addition, a thorough analysis of the product range may reveal a number of similar products that can be rationalised down to a single multi-purpose product. Some GT implementations have resulted in reductions in part numbers by over 75%.

This reasoning also applies to process planning, and may lead to a significant reduction in the number of process plans. In addition, standardisation of process routings allows designers to specify best-practice production methods [74,75].

The systematic approach to analysing and classifying products, and the motivation to standardise according to production capabilities encourages designers to focus on design consistency and excellence, but also subtly introduces the concept of design for manufacture. In this way, a closer relationship between the two functions is established.

(iii) Information Resource

To be effective, GT requires a centrally coordinated, computerised information resource with accurate, readily available information [15,73]. Rapid information retrieval allows designers to use or modify existing designs, and process planners to use or modify existing process plans [12,74]. Furthermore, a single data source ensures that inconsistencies and unnecessary duplication are avoided [15].

GT is seen as being able to provide a link between CAD and CAM systems. Consequently, it forms the basis of CIM [28]. In this way, GT is capable of putting the production function in an excellent position to pursue automation [76].

5.4.5.2 Cellular Manufacturing

Cellular manufacturing may be regarded as a technique in itself, or as a technique used in the implementation of GT [77]. Cellular manufacturing involves setting up sub-factories dedicated to the production of one or more product families [71].

Creating a number of cells from one single plant represents a considerable simplification in the basic operation of the plant, as each cell may be semi-autonomous.

(i) Physical Elements of a Cell

Ideally, a cell contains all the processes required to produce the products to which it is dedicated. Unfortunately, this is not always possible. For example, some processes may require a specific environment, such as painting processes. Other processes may be in the form of a single system and may be required by a number of product families, such as a foundry [72].

(ii) Layout

A cell is a compact, mini flow-line with a single dominant flow path. Burbidge (1971 p.33) describes the introduction of cells as a shift from 'process specialisation' - the traditional functional layout - to 'product specialisation', in which the layout of equipment in the cell reflects the process requirements of the product families it produces.

The compact nature of cells minimises transportation and the associated risk of damage, and reduces the number of potential sites for inventory to accumulate [76]. Any excess accumulated inventory can not remain inconspicuous, and quickly hinders normal operations, forcing remedial action.

Because of the reduced travel distances, and the lower WIP inventory, throughput times decrease [78]. This is an effective method of increasing system responsiveness to market demands. If lower throughput times are achieved without a decrease in available capacity, total throughput may be increased [76]. Unfortunately, this is not always achievable. Reorganising the plant into cells may result in an increase in the level of unusable capacity.

Cell flexibility, that is, the ease with which the cell may be rearranged to produce different products, is a function of the type of machines that make it up. Flexibility is increased through the use of multiple, small machines.

The structured layout of the production facility, based on material flow, encourages plant managers, schedulers, and other decision makers to focus on concepts such as cells, product flow, and other product-oriented methods designed to increase the overall effectiveness and efficiency of the system.

Cells may be set up to complete a product, and are therefore referred to as 'parallel cells' [18 p.26], or to perform a particular stage in the manufacture of a product, and are referred to as 'sequence cells' [18 p.26].

(iii) Quality

As products are produced in only one cell, there is greater accountability of product quality. Furthermore, due to the reduced delay time between operations, resulting from lower WIP inventory, defects are discovered sooner. The two key benefits of this are: the source of the problem may be easier to detect, and the consequences of the problem may be less widespread [71].

(iv) Scheduling and Control

Cells are typically semi-autonomous, and require a centralised coordination system. Orders are released to the cell to initiate production, but there is no dispatching within the cell [79].

As there is only one flow path, scheduling, control, and the tracking of tasks are greatly simplified [12,76]. Furthermore, interference and competition between products for resources is significantly reduced.

(v) Cells and Batch Production

Cells emulate mass production systems in that the number of fundamentally different products produced in it is minimal. Therefore, the batch size, defined as the number of products produced between major setups, may be very large.

Cells emulate job shops in that a variety of products, that is, those with minor differences, are produced sequentially within a single production unit. Therefore, the batch size, defined as the number of identical products produced, may be very small, allowing a closer match between production and demand [78].

In this way, manufacturers simultaneously gain the benefits of efficient, high volume production, and the benefits of flexible, rapid response, high variety production.

In addition, the transfer batch size may be reduced to one or a few units since the sequence of products through each workstation within the cell is identical. The exception to this is where products skip certain processes [72].

(vi) Inventory

Inventory levels, of both raw materials and WIP inventory may be significantly reduced [76]. This is due to simpler planning and control systems, shorter throughput times, the compact layout of the cell, and the flow-line characteristics of cell production [71,76].

In addition, a smaller product range, and improved control over inventory and product designs not only reduce administration time and costs, but also reduce the risk of inventory obsolescence [76].

5.4.5.3 Non Group-Able Products

Although most of the product range may be divided into families, there will normally be some products that do not belong to any particular group. These products may be produced in a separate "cell" which is simply a small job shop, with equipment organised according to function [80].

Manufacturers who have implemented GT may choose to maintain a portion of the plant as a job shop to maintain a degree of production flexibility, and to act as the plant workshop.

5.4.5.4 Human Considerations

For the cell manufacturing approach to be effective, it is essential that control be decentralised such that each cell is responsible and accountable for the products it produces. Schonberger (1986 p.10) describes cells as 'responsibility centres'.

Workers are required to be multi-skilled, and capable of operating a number of machines, so as to be able to move to where the work is. Increased teamwork may be required to maintain an acceptable level of output performance [72].

Greater responsibility and independence, and the ability to contribute to the manufacture of an entire product, increase worker satisfaction, which in turn improves morale [71,72,78].

GT is a means to break down barriers that often exist between design and production functions. This is because the process of classifying products according to design and production attributes requires cooperation between these two functions. Furthermore, defining a basis for standardisation also requires a cooperative effort. Once established, this association must remain a permanent and normal part of everyday operations. One of the benefits of such cooperation is that the development and introduction of new products become more effective and rapid processes [81].

5.4.6 Common Problems with GT

5.4.6.1 Product Families

The process of dividing the product range into families and assigning equipment to cells may be a very complex and time consuming task [21,72].

5.4.6.2 Data

Common problems associated with data include:

- maintaining data integrity,
- avoiding the duplication of data, and
- the inability of codes to accurately and fully describe the characteristics of a part [28].

In addition, with very large computer-based information sources, data processing speed may be slow [28].

5.4.6.3 Cell Manufacturing

Management may resist the reorganisation of the plant into cells either because it may be necessary to purchase more equipment, or because the short term costs and disruptions associated with the reorganisation may be perceived as being too high, despite the anticipated long term benefits.

As the capacity of each machine in a cell will not be identical, there will always be some unusable capacity. This is only perceived as a problem, however, if machine utilisation rates are considered more important than efficient production with the additional benefits listed in Section 5.4.2.1 (p.56).

5.5 Material Requirements Planning and Manufacturing Resource Planning

5.5.1 Introduction

Material Requirements Planning (MRP) and Manufacturing Resource Planning (MRP II) are computer-based systems that simulate manufacturing operations and employ mathematical procedures for planning purposes [55].

5.5.2 Objectives of MRP and MRP II

MRP is aimed primarily at planning purchase and production operations such that the right components are available in the right quantities, and at the right time to realise a predetermined production schedule [55].

MRP II is an extension of MRP and aims to plan for, and control the usage of all resources required in production [6,42].

5.5.2.1 Potential Benefits

It is claimed that MRP and MRP II are able to provide the following benefits:

- the elimination of unnecessary inventory,
- improved customer service,
- more effective use of resources,
- improved coordination of scheduling and ordering,
- the ability to simulate the effects of certain decisions, and
- improved long-term planning capability [56,82].

5.5.3 The Origin of MRP and MRP II

MRP was developed in the United States of America in the 1960s and superseded existing material planning systems because it incorporated the ability to automatically calculate the correct *timing* of the release of purchase and production orders, based on a production schedule. Although it was a significant advance, it lacked the ability to determine whether the production schedule could realistically be achieved with the available capacity. In essence, it was 'capacity insensitive' [42 p.7]. Schroeder (1989 p.455) describes this as a Type I MRP system.

A major advance in MRP systems was to incorporate a feedback loop in the planning logic, linking a more sophisticated capacity planning module back to the master production schedule. Consequently, the system was able to determine whether the production schedule was feasible, given the restrictions of available capacity. If the schedule was not feasible, it was necessary either to adjust the schedule, or increase capacity by, for example, scheduling overtime. Schroeder (1989 p.456) describes this as a Type II MRP system.

MRP systems were then taken a step further. During the 1970s MRP II systems were developed which included functions for the planning and control of all resources required in manufacturing, including equipment, material, finance and personnel. As a result, all planning and control functions were integrated into a single centralised system [55]. Schroeder (1989 p.456) describes this as a Type III MRP system.

Discussion will focus on Type II MRP systems to which the acronym MRP will apply. Where appropriate, special mention will be made of Type III (MRP II) system features.

5.5.4 A Typical Application

Although the recommendations in the literature regarding the most appropriate use of MRP are not unanimous, support for the application of MRP to discrete batch production, and opposition to the application of MRP to job shops or repetitive or continuous systems is dominant [9,10,51,83 p.42,84].

Exceptions to this view include support for the use of MRP in mass production assembly, and the suggestion that MRP can be of benefit to any type of production system [82,85].

Orlicky (1975 pp.38-39) has provided additional guidance by prescribing the following prerequisites to MRP implementation:

- a Master Production Schedule (MPS) outlining planned production of end items must exist,
- all inventory items must have a unique identification, and
- all information relevant to production planning must be available at the time of planning.

5.5.5 Implementation

5.5.5.1 The Master Production Schedule

The MPS is central to the functioning of MRP systems. It is a rolling schedule divided into planning periods of equal length, outlining planned production quantities for end items in each period. The horizon of the MPS must be longer than the total lead time for all end items for which production or purchasing of components is planned.

In determining the length of the planning period a compromise must be reached between a long period length, to reduce the data processing requirement and to achieve stability, and a short period length, to improve system responsiveness. Where end items are complex and part numbers are high, the minimum period length may be governed by the time required for the computer to execute the planning process.

5.5.5.2 Independent and Dependent Demand Items

End items are referred to as independent demand items, while the components that make them up are referred to as dependent demand items. The distinction between these items is fundamental to MRP.

Independent demand items are those for which demand is independent of demand for other inventory items. Instead, demand must be based on actual orders and forecasts. Examples include finished products, spare parts, and standard components used in a range of uniquely configured finished products. Standard components are treated as independent demand items when the production lead time of the finished product is longer than the normal delivery lead time. In such situations final assembly operations are driven by actual orders, and may be independent of the MRP system.

Conversely, dependent demand items are those for which demand depends on the demand for other inventory items. Examples include subassemblies, individual components and raw materials.

The significance of this distinction is that MRP plans the production and purchase of dependent demand items to satisfy the requirements for independent demand items as set out in the MPS.

5.5.5.3 Data Requirements

MRP systems require comprehensive information for individual inventory items, as well as information linking them to end items.

Typically, data on individual inventory items includes:

- purchase or production lead times and batch quantities,
- process routings,
- safety stock levels,
- scrap levels,
- quantities on-hand, and
- quantities on-order together with the anticipated delivery date [6].

Lead times are expressed as multiples of the planning period, however, where the lead time is significantly less than one period, it may be set to zero for planning purposes [6].

Product structure data provides the relationship between an end item and the components of the product. The highest level in the structure represents the end item, while the lowest level represents basic components such as raw materials. Each element in the product structure represents an inventory item, and each level represents a single stage in production.

5.5.5.4 The Explosion Process

The explosion process is the means by which MRP converts end item requirements into correctly timed requirements for individual components and raw materials. These requirements are referred to as gross requirements, and are also expressed as quantities required per planning period. In this process, MRP takes into account safety stock, scrap levels, and purchase and production lead times and batch sizes.

Net requirements are determined by allocating inventory on-hand and on-order to gross requirements.

MRP processes the MPS in chronological order so that inventory that accumulates as a result of discrepancies between what is ordered and what is required, due to preset batch sizes, may be allocated to future gross requirements in the netting process.

The product structure is analysed from top to bottom for a similar reason. The batch size at one level influences the requirements for all lower level items.

In addition, MRP checks open orders and reschedules them if necessary to keep them in line with the associated due date.

5.5.5.5 Coverage of Net Requirements

Net requirements are covered through the generation and release of appropriately timed purchase orders and production orders.

Capacity planning consists of a comparison between the process time required, based on production orders and nominal processing times, and the process time available. This procedure is carried out for each work centre, and reveals areas of overloading.

5.5.5.6 Production Control

The shop floor control system, found in MRP II systems, releases production orders to the plant and monitors progress of the orders. Where necessary, MRP II will reschedule orders that are late, assigning them a higher priority [86].

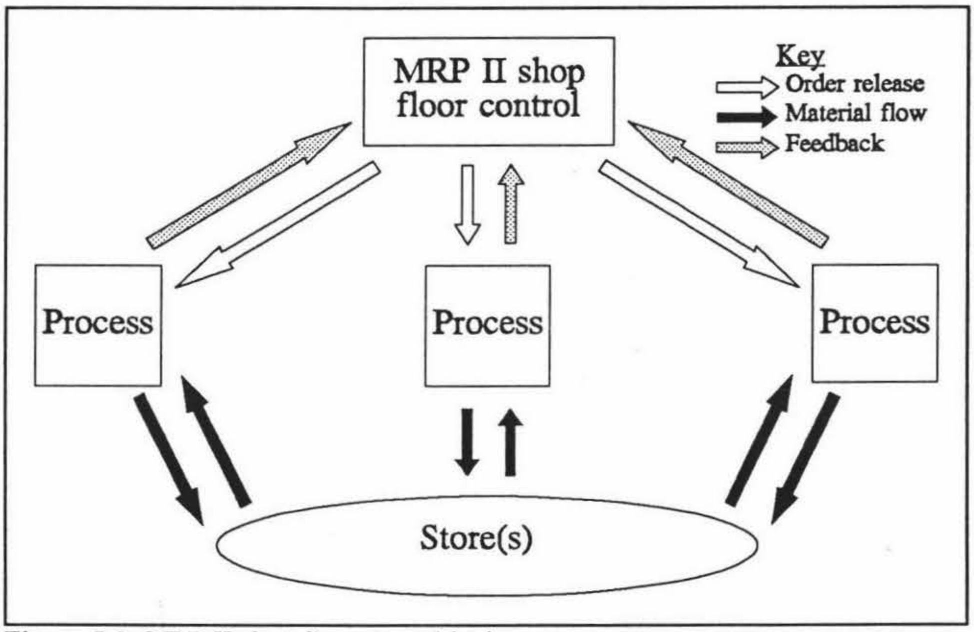

Figure 5-2 MRP II shop floor control logic

Figure 5-2 (p.67) represents the logic of the shop floor control system at a conceptual level, illustrating both information and material flow.

The key point to note is that MRP II controls each workstation independently. This is because the logic behind the shop floor control system is designed such that the system is able to cope with the complexities of traditional batch production. Therefore, MRP II systems are not able to take advantage of the efficiencies of production based on flow-line principles.

5.5.5.7 Modes of Operation

There are two basic modes, or types of MRP system: the regenerative system, and the net change system.

(i) The Regenerative System

The primary characteristic of regenerative systems is that the explosion process is performed infrequently but periodically for every item in the MPS. The information generated by the system covers every inventory item.

The main advantage of regenerative systems is that the total data processing requirement is low, since it is executed infrequently. The main disadvantages are that the explosion process is time consuming, and that the system is not responsive to changes in demand or supply. These changes only take effect at the next regeneration of requirements. As a result, the output of the system becomes increasingly out-dated as time passes.

(ii) The Net Change System

The primary characteristic of net change systems is that the explosion process is executed frequently but not for all items in the MPS. MRP searches for changes in the system inputs, such as the MPS or product structure, since the previous explosion process, and performs an explosion only for those items affected by the changes. The information generated by the system covers only those items.

The main advantages of net change systems are that the planning process is very rapid, the output of the system remains up-to-date, and the system is responsive to change. The main disadvantages are that feedback to the system must be immediate, and that the overall data processing efficiency is lower than for regenerative systems.

A key point of net change systems is that the user of the system should not act upon every output of the system. To provide stability to production, and for suppliers, the user should only act upon critical outputs such as those that require an increase in the order quantity, or an advance in the order release.

5.5.6 Common Problems with MRP and MRP II Systems

5.5.6.1 System Performance

There is considerable disagreement over the ability of MRP systems to function successfully. Although some authors describe MRP systems as being highly successful, many are critical of MRP [55,66,87,88]. Particular examples include Burbidge (1990 p.127) who describes MRP as 'obsolete' and Kanet (1988 p.59) who expresses concern over the 'fundamental problems in the basic approach of MRP'.

5.5.6.2 The Model of the Production System

One of the fundamental problems of MRP systems is that a static model with fully predictable behaviour is used to represent a dynamic, unpredictable manufacturing system. Calculations are based on nominal values for system characteristics such as production and delivery lead times, and safety stock levels. In reality actual lead times do not match nominal lead times and are influenced by factors such as:

- the length of the planning period of the schedule,
- the effect of growth and decay of queues, which is influenced by the overall loading of the plant, including the level of high priority orders, the size of batches, and the level of product variety [6],
- the effect of normal disruptions caused by breakdowns, absenteeism, and inconsistent quality, and
- day-to-day problems and disruptions within the plants of suppliers over which the manufacturer has no control whatsoever.

As a result, when actual lead times are shorter than nominal lead times inventory will accumulate, and workstations may stand idle. When actual lead times are longer than nominal lead times, inventory will accumulate at the problem area, if one exists, with shortages of inventory at subsequent processes [6,66].

The mismatch between actual and nominal lead times is made worse by the need to express the nominal lead time as a multiple of the planning period [6]. Actual lead times must be rounded *up* otherwise the item will never be available on time. If the length of the planning period is too coarse, the level of WIP inventory will become very high, and the total lead time will become very long due to the cumulative discrepancies.

The process of determining nominal lead times and other system parameters is not simple. Recognising that actual lead times will fluctuate about an average, the production planner may set the nominal lead time artificially high, for *all* items, to ensure that a high percentage of items will be available on time. The planner will, however, be under pressure to aim at short lead times to ensure that WIP inventory does not reach excessively high levels, and that the total lead times of end items may be kept relatively short so that production is based to a lesser extent on forecasts, and to a greater extent on actual orders.

5.5.6.3 The Scope of MRP and MRP II

MRP and MRP II are tools of production. Although there is a strategy embedded in the systems, namely to produce goods in the appropriate quantity and at the appropriate time, it is not sufficient as a manufacturing strategy.

To remain competitive, a manufacturer must implement a philosophy aimed at improving the production *system* by reducing batch sizes, lead times, WIP inventory, setup times, and eliminating sources of unwanted variation.

Several authors have suggested that MRP or MRP II can be used successfully in combination with JIT [55,89,90].

5.5.6.4 General Problems

- If the inputs to the system are inaccurate, such as the levels of on-hand inventory, the outputs will be incorrect. This may lead to two serious consequences: some end items may not be completed on time, or workers may disregard the output of the system, opting instead to follow informal procedures [86].
- MRP and MRP II systems are very complex, and require a high level of data input [85,86].
- MRP systems deal with uncertainties such as disruptions and poor quality through the provision of safety stock, and other safety factors. In this way MRP systems formalise bad habits rather than endeavouring to eliminate them [13,55].
- MRP systems have a 'wide selection of handles to pull' [6 p.43]. Adjustments may be made to batch sizes, safety stock levels, lead times, and scrap rates. Each time a change is made, the consequences of the change propagate through the supply chain causing shortages or surpluses and disruptions to production [6].
- Typically, orders are released at a particular point in each planning period, such as at the beginning. Order completion times are also calculated as being a particular point, such as at the end of the planning period. The resulting wave of order releases may lead to the overloading of resources used in the early stages of production. Also, a rush to complete orders may lead to overloading of resources used in the latter stages of production [6,91].

The problems described above are not always avoidable in reality. Some manufacturers, who may have thousands of individual parts to organise, many different finished goods to sell, and variable demand, may have no option but to use an MRP system. The benefits of having controlled material planning may outweigh the problems listed above.

5.6 Selected Bibliography

Corke, D.K.

'Production Control in Engineering'. Edward Arnold Ltd. Third Edition, 1987.

Gunn, T.

'The Mechanisation of Design and Manufacture'. An article in 'Capabilities of Group Technology'. Published by The Computer and Automated Systems Association of SME, 1987. Dearborn, Michigan. pp.31-46.

Hyer, N.L. and Wemmerlöv, U.

'Group Technology and Productivity'. An article in 'Capabilities of Group Technology'. Published by The Computer and Automated Systems Association of SME, 1987. Dearborn, Michigan. pp.3-12.

Ingersoll Engineers

'Integrated Manufacture'. IFS Publications Ltd, 1985.

Orlicky, J.

'Material Requirements Planning'. McGraw-Hill Inc, 1975.

Samson, D.

'Manufacturing and Operations Strategy'. Prentice Hall, 1991.

Schonberger, R.J.

'World Class Manufacturing: The Lessons of Simplicity Applied'. The Free Press, 1986.

Schroeder, R.G.

'Operations Management: Decision Making in the Operations Function'. Third Edition. McGraw-Hill Book Company, 1989.

Shingo, S.

'A Study of the Toyota Production System: From an Industrial Engineering Viewpoint'. Productivity Press, Connecticut, 1989.

Voss, C. and Clutterbuck, D.

'Just-in-Time: A Global Status Report'. IFS publications / Springer-Verlag, 1989.

Chapter 6

Design of the CAS System

6.1 Introduction

The objective of this chapter is to apply the first 4 stages of the Generic Manufacturing System Design Methodology (GDM) to the design of a system for the assembly of Printed Circuit Boards (PCBs). This system, referred to as the Component Assembly System (CAS), is an integral part of the Manufacturing Pilot Plant (MPP), which offers three services:

- PCB design,
- bare board production, and
- PCB assembly.

The MPP is aimed at a market characterised by the demand for the prompt delivery of high quality, special purpose PCBs in low volumes.

The 4 stages of the GDM to be applied are listed below.

- Stage 1: define the characteristics of the market in which the MPP operates.
- Stage 2: formulate a strategy for the MPP in the form of a set of objectives, based on the outcome of the market analysis performed in Stage 1.
- Stage 3: examine existing manufacturing systems, identifying areas of strength and applicability, and areas of weakness or incompatibility.
- Stage 4: define the system at a conceptual level, that is, define *what* the system must do to fulfil the objectives. In addition, critical and non-critical elements of the system must be identified.

6.2 Stage 1: Define the Characteristics of the Target Market

The first step in designing the MPP is to define the characteristics of the market at which the MPP is aimed. This involves identifying the requirements of customers in that market.

The MPP is aimed at serving customers involved in the development of prototype PCBs; the production of one-off, special purpose PCBs; or simply the infrequent production of a small number of PCBs. Typically, an individual customer will require high quality PCBs and will require them promptly.

Although the MPP offers three primary services, namely, design, production and assembly of PCBs, not all customers will require all three services.

Many of the customers of the MPP are expected to be small-scale operators. This expectation is based on the following generalisations:

- small-scale operators may not have personnel with a sufficiently high level of PCB design skills,
- few small-scale operators have the capability to produce Plated Through Hole (PTH) boards of a standard of quality comparable to higher volume producers,
- small-scale operators may wish to avoid the costs associated with maintaining a relatively large inventory of a wide range of components, together with the delays and costs of obtaining components not held in stock. From a broader perspective, some operators may wish to avoid setting up a production system altogether, and
- small-scale operators have greater restrictions on resources, in particular time.

The above generalisations have particular significance to the nature of the service provided to customers. The combination of customers periodically requiring the services of the MPP with the recognition that the core processes of many customers will not include PCB design and/or production suggests that the opportunity exists to establish and nurture a group of loyal customers. Excellent service, where "service" is used in the broadest sense, will allow the MPP to develop a long term relationship with each customer in the group. This situation is very different from the situation where there is no such loyalty. For example, cost can become a lower priority issue.

The target market of the MPP does not consist only of customers and the MPP. The third key group in the market consists of manufacturers competing with the MPP for business. The capabilities and other characteristics of competitors must be understood if the MPP is to be designed such that it offers superior service and products to customers. In short, the MPP must become, and remain, attractive to customers relative to competitors.

Many competitors utilise conventional production systems, which have been discussed at length in Chapter 2, Section 2.2 (pp.5-6).

Finally, the target market must not be viewed as a static system. Rather, it must be understood that, over time, changes in the market will become apparent. Some changes will occur subtly, while others will occur abruptly. Examples of changes include: the perception customers have of the MPP, customer requirements, the performance of competitors, and product and process technology.

By recognising or anticipating these changes, and acting on them, the likelihood that the MPP will remain a competitive member of the market will increase.

6.3 Stage 2: Define the Objectives of the MPP

The second stage of the GDM is to formulate a strategy for the MPP, in the form of a set of objectives, based on the analysis of the target market performed in Stage 1.

The objectives of the CAS system are derived directly from the objectives of the MPP.

6.3.1 Broad Objectives

The MPP has two broad, but distinct objectives:

- to operate as a commercially viable manufacturing system, and
- to operate as a teaching facility: exposing students to the problems encountered in real manufacturing systems; and as a demonstration facility: displaying the application of modern technology to small-scale manufacturing systems to interested industrial parties.

To be an effective and realistic teaching facility, the MPP must operate as a commercially viable system. Therefore, the second objective can only be addressed if the first objective is satisfied.

6.3.2 Operational Objectives

The basic objective of the MPP is to be a rapid response system producing a wide range of high quality PTH PCBs in low volumes. In the extreme, the production and assembly of a single PCB must be both feasible and economic.

To achieve this, attention must be focused on rapid information processing, short changeover times, short throughput times, flexibility, and minimising the occurrence of component insertion errors.

Flexibility, in the context of the MPP, allows for the production of a variety of products sequentially, and allows customers to choose which service(s) they require. Variety, in the context of the MPP, is defined by differences in the product, such as board size, and the number and type of components populating the board; and differences in production volumes.

With regard to product design, the following objectives apply:

- the product must be designed such that it meets or exceeds the requirements of the customer, and
- the product must be easily manufactured within the MPP.

With regard to the production of the bare board, the quality of the bare board must be comparable to the quality of boards produced by higher volume producers who use sophisticated, automated processes.

With regard to assembly, the following objectives apply:

- PCBs must be assembled such that the correct components are used, and that they are located and oriented correctly, and
- the standard of soldering and finishing must be high.

With regard to customer service, the following objectives apply:

- high quality raw materials must be sourced from reliable suppliers,
- there must be consistency in the quality of the finished product, not only between products within one batch, but also between batches, and
- the pricing of the product must be competitive, but not necessarily the lowest of all producers. If the MPP has something to offer which other producers do not, and customers regard it as being "worth it", they will be prepared to pay a premium for it.

These objectives are consistent with each other and with the broad objectives of the MPP.

6.3.3 Technology-Based Objectives

As PCBs are designed using Computer Aided Design (CAD) packages, it is advantageous to make full use of the design data to directly drive activities such as: stock ordering and control, production and assembly operations, and administration. The use of computers in the MPP is therefore essential.

The human - computer interaction, however, must be one in which the human remains in control.

While technology is able to offer significant benefits to production, investment in technology must be kept in perspective since the overall production volume is low, and the pricing of the finished product must remain competitive.

If the production and assembly processes are computer-based, and are driven by the design data, there will be a need to develop standards for the format of data files, both for the output of CAD packages, and for the MPP sub-systems. Close interaction with regular customers will allow systems to be developed, and located with the customer, for generating standard format design files. The objective of such systems is to increase the level of commitment of both parties.

Finally, the software must combine to form a simple, complete, integrated, and robust system. This is to ensure that:

- all elements function effectively within the whole system,
- the systems are outwardly simple, despite the internal sophistication and complexity,
- the systems function logically from the viewpoint of the user,
- the total process of satisfying customer requirements is comprised of a small number of sequential, logical steps, and
- the system is able to function effectively with variation, and is able to identify causes of problems and system failures. The level of robustness, and the sophistication of error detection facilities depends on the role of the individual process. Core processes, and critical links, for which failure would result in the inability to satisfy customer requirements, require special attention.

6.3.4 Objectives Common to Many Manufacturers

Finally, consider the customer-perceived factors of competition.

The most common of these factors includes: service, quality, cost, delivery performance and flexibility [69,92,93,94]. Additional factors have been identified, including: responsiveness, timeliness, dependability, reliability, innovation and time-to-market [22,35,37,69,95,96].

It may be argued that several of the factors listed above are synonyms, or are closely associated with others, and therefore need not be mentioned. The goal, however, is not to rationalise the list down to a few sweeping, and therefore vague factors. Instead, the goal is to understand the *exact* requirements of the customer as they are perceived by the customer. Even the factors listed above are open to interpretation and debate as to their precise meaning.

Although the factors listed above may not all apply directly to the MPP, they may define the characteristics of the market in which the *customer* operates as a supplier or producer. Awareness of these characteristics may allow the MPP to develop a special relationship with each customer. Consequently, design and production decisions may be made in the MPP that will be consistent with the un-communicated requirements of the customer.

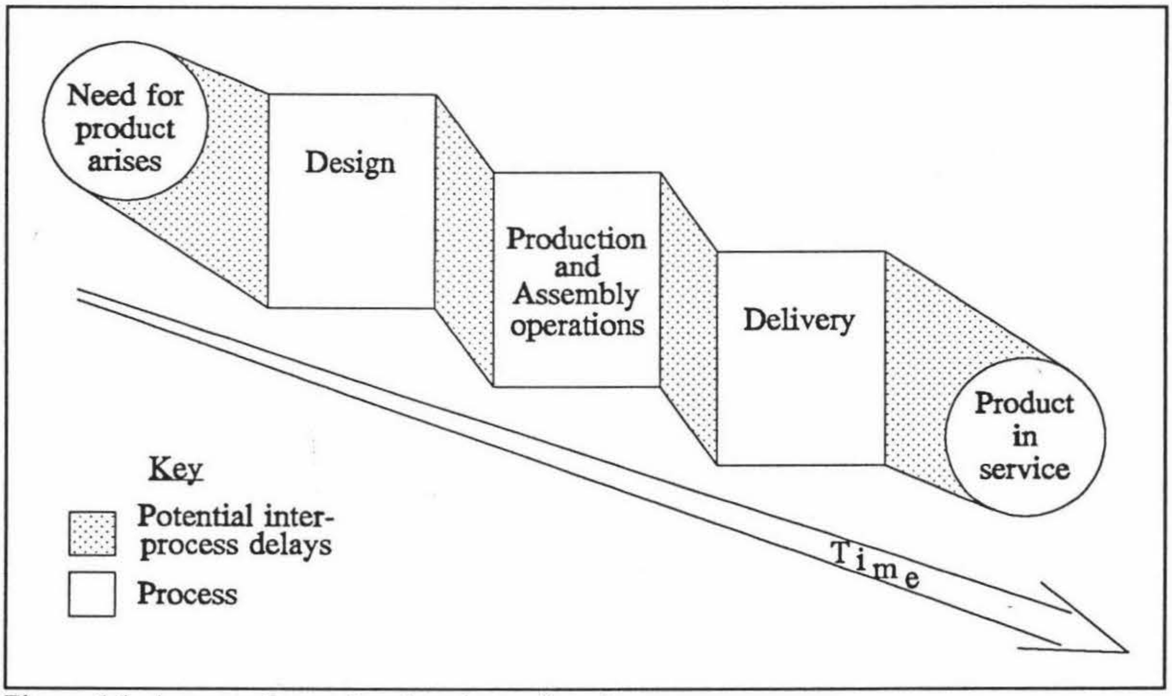

Figure 6-1 A perspective on time-based manufacturing

Figure 6-1 (p.77) illustrates how a manufacturer must take a broad view of production when considering how to satisfy the requirements of customers. This broad view involves approaching the process of producing products from the perspective of the customer.

Consider a customer whose primary objectives are time-based.

In Figure 6-1 (p.77), the time between recognising the need for a particular product and the point it goes into service is the "customer inconvenience time". The concern of the customer is that this time span be as short as possible, but not at the expense of other key requirements, such as quality. This time span should, therefore, also be of concern to the manufacturer. It would be unwise for a manufacturer to narrow the scope of focus and concentrate only on in-house activities such as design or production, without regard for other processes and potential sources of delay.

Therefore, by recognising this broader approach to satisfying customers a progressive manufacturer will strive to:

- become familiar with the requirements of the customer from the perspective of the customer,
- make it easy for customers to specify exactly what they require, in the form of a product specification or problem definition, and to communicate those requirements,
- design products to meet the requirements,
- reduce or eliminate the delays or difficulties between processes,
- minimise the total customer inconvenience time,
- produce high quality products with minimal installation delays and difficulties, and
- identify and make use of reliable, rapid, door-to-door delivery services.

Although this list is not exhaustive, it is clearly apparent that the ambition of the MPP to satisfy customers goes far beyond simply the design of PCBs, the production of bare boards, and the insertion and soldering of components into those boards. Rather, satisfying customers requires a series of linked, interdependent activities.

6.4 Stage 3: Examine and Analyse Existing Manufacturing Systems

The third stage of the GDM is to examine existing manufacturing systems.

This stage is divided into two sections.

The first section reviews the Traditional and Modern Manufacturing Systems discussed in Chapters 4 and 5 respectively, outlining how they apply to the MPP. Only *key* areas of similarity and contrast are discussed.

The second section contains two case studies. In the first, a highly automated PCB assembly facility is discussed. In the second, a typical conventional, low volume, manual assembly facility is discussed.

6.4.1 A Review of Traditional and Modern Manufacturing Systems

The purpose of examining existing manufacturing systems goes beyond simply identifying systems that have a history of success. Rather, the objective is to understand what the system is, what it is designed to achieve, and how the internal mechanisms of the system function to achieve those goals. From this understanding, it is possible to identify elements that are applicable to the MPP, and to adapt them into the MPP with a high degree of confidence that they will be successful.

6.4.1.1 Job Shop Principles and the MPP

Consider first the similarities between a typical job shop and the MPP. A high variety of products, where variety is defined in terms of the differences between individual products, are built to order in low volumes. In addition, customers deal directly with the MPP.

Building products to order requires that attention be focused on developing a production capability, as no product range is offered. Competition is based primarily on the performance of that capability.

A second consequence of building to order is that demand is unpredictable. Therefore, to provide rapid response service, frequently used stock must be kept on-hand and stock ordering systems must be directed at stock replenishment after use, rather than delivery before use, except for uncommon components.

While demand may be influenced by advertising, it does not affect the predictability of material requirements.

The production volume has a direct bearing on the type of equipment or methods used in production. Since the *total* production volume is low, investment in automated assembly systems is not justified. Consequently, assembly operations must be performed manually.

Supporting equipment and procedures must be general purpose in nature, or sufficiently flexible to cope with the individual product variety.

Consider also the fundamental difference between a typical job shop and the MPP. Overall, the variety of products produced in the MPP is very low. All products are variations of a single type of product - the PCB. Consequently, all products follow the same path through production. For simplicity, therefore, layout of the equipment should not be based on the function of the equipment - the process-oriented layout - as in a typical job shop.

6.4.1.2 Batch Production Principles and the MPP

Consider first the key similarity between a typical batch production system and the MPP. Each customer will require the production of a specific volume of PCBs. At the extremes, the MPP must allow the production of a batch of products, *and* the production of a single unit. At both extremes, production must be efficient and economic.

The production of a variety of products in varying volumes may mean that production lead times will be somewhat unpredictable, and that the total customer inconvenience time will vary depending on plant loading.

Consider also the fundamental differences between a typical batch production system and the MPP. As stated above in Section 6.4.1.1 (p.79), the MPP does not offer a standard product range. As a result, the planning, production and sales activities associated with standard products are not applicable.

Another significant difference is that it is not necessary to set up machines for production runs of a specific product. This is because the MPP is dedicated to the production of only one type of product.

6.4.1.3 Mass Production Principles and the MPP

Consider first the similarities between a typical mass production system and the MPP. Producing a single type of product on one production system allows the system to be tailored to that product, thereby ensuring consistency. In addition, layout of the equipment reflects flow-line principles, leading to a small, compact plant with minimal transportation distances, and simple control systems.

The plant can be designed for efficiency at the level where the variations between products are unimportant. One requirement for this is that the process times of each stage of production be similar, to ensure that inventory does not accumulate at one stage, with subsequent stages significantly under-utilised.

Another similarity is that staff are not required to be highly skilled at assembly operations. The response capabilities of the MPP lie with the technical systems, rather than the personnel. Consequently, the training time is very short.

Consider also the fundamental differences between a mass production system and the MPP. As there is no standard product range, the planning, production, marketing and sales activities associated with this are not applicable. In addition, as competition is not based on such products there is no need for extensive market research, research and development, and product innovation.

The customers of the MPP deal directly with the MPP, and not through intermediary agencies as with mass production.

Mass manufacturers have a very high investment in the production system, typically in the form of automation. As a result, emphasis has been directed towards achieving economies of scale. As the total production volume in the MPP is low, the focus of attention should not be on achieving economies of scale.

Another significant difference is the role of personnel. Although the manual labour content is high in the MPP, and assemblers need not be highly skilled, workers do not perform menial tasks with the technical systems performing the key value adding tasks, nor is their work controlled by the speed of the production system.

6.4.1.4 Clarification Regarding Flexibility and Efficiency

In the discussion above, it has been stated that the CAS system must be designed for flexibility because the product variety is high, but must also be designed for efficiency because the product variety is low.

This apparent contradiction requires clarification.

It must be noted first, however, that sweeping terms such as "flexibility" and "efficiency" are the subject of much debate regarding their exact meaning. In this context, however, these terms are given very broad and basic definitions:

- flexibility refers to an ability to cope effectively when encountering "uniqueness" frequently.
- efficiency refers to an ability to cope effectively when encountering "sameness" frequently.

Consider first, product variety at the highest level. The MPP is aimed at the production and assembly of PCBs only. The variety at this level, termed the *overall product variety*, is very low: only one type of product is produced. Consequently, in situations where differences between individual products are *not* significant, the focus of attention should be primarily on efficiency rather than flexibility.

Consider also, product variety at a lower level. The MPP is aimed at the production and assembly of special purpose, or custom designed PCBs in low volumes. The variety at this level, termed the *individual product variety*, is very high: the theoretical range of PCBs is almost limitless. Consequently, in situations where differences between individual products *are* significant, the focus of attention should be primarily on flexibility rather than efficiency.

6.4.1.5 Integrated Manufacture and Computer Integrated Manufacturing Principles and the MPP

These philosophies of integration provide substantial guidance in the design of the CAS system. This can be seen by comparing the objectives and potential benefits of Integrated Manufacture and Computer Integrated Manufacturing (CIM) with the objectives of the MPP.

The primary objective of Integrated Manufacture and CIM is to integrate the elements of the organisation together to pursue a common goal to achieve lower costs, higher quality, rapid response, shorter lead times, and rapid changeover relative to "non-integrated" manufacturers.

The main points of Integrated Manufacture and CIM, and how they apply to the design of the CAS system, are summarised below.

One of the fundamental objectives of integrating activities is to ensure that the activities are coordinated and compatible with each other and with the overall objectives of the organisation.

The application of modern technology makes it possible to break away from the traditional methods of PCB production and to develop completely new systems, taking advantage of the strengths of available technologies. In particular, information about the product generated by CAD packages may be used by other computer-based elements of the manufacturing system. As a result, computer applications may be developed and linked through a network. In addition, a single database may be developed and shared by the applications.

Care is required when designing these applications, and the means by which they interact, such that there is a balance between the degree of interdependence and the degree of independence. This balance must take into account possible future expansion or modification, as well as unpredictable events such as hardware failure and data corruption.

Technology allows repetitive data processing activities to be automated, and allows efficient data communication, both between systems within the MPP, and between systems in the MPP and systems located at the premises of customers or suppliers.

The design of CIM systems requires that the structure of the CIM system be simple, and that it be based on the logic of data and material flow.

6.4.1.6 Just in Time Principles and the MPP

The Just in Time (JIT) philosophy provides substantial guidance in the design and operation of the CAS system. This can be seen by comparing the objectives and potential benefits of JIT with the objectives of the MPP.

The primary objectives of JIT are to manufacture products efficiently with minimal waste; to focus on quality, timeliness, and simplicity; and to recognise, understand and manage interdependence. This can lead to increased customer satisfaction, reduced lead times, simpler systems, and a plant layout designed for unhindered material flow.

The main points of JIT, and how they apply to the design of the CAS system, are summarised below.

The principle of most importance is that of the flow of materials and information. It is essential that, in a market where rapid response is a key factor, the flow of materials and information between suppliers and the MPP, within the MPP, and between the MPP and customers be efficient, with minimal negative impact on the customer inconvenience time. This principle requires the optimisation of the total system, rather than the independent optimisation of sub systems.

When focusing on the concept of minimising waste, where waste is 'anything unused or not used to full advantage' [97 p.1636], the first step is to define "anything" in terms of the overall system objectives. In rapid response systems, the primary waste to be eliminated is the waste of time.

Another key principle is that of on-going improvement. This applies to design as well as to every-day operations. The system must be designed to allow modification. Once the system is in operation, opportunities for improvement should not only be found, but also acted upon.

The JIT philosophy supports the need for multi-skilled workers, capable of undertaking a variety of tasks as needs arise, or change.

High quality is stressed, not only to ensure that customers are satisfied with the product, but also to minimise the costs and waste associated with poor quality in production.

With a focus on the production system, the principle of interest is that the layout of the plant be based on the flow of material through the production processes. In practical terms, this requires that a flow-line be established. This concept may be extended to include the use of multiple cells, or mini flow-lines. Short setups are essential to minimise the length of non-productive delays between the production of different orders.

The techniques used in implementing the JIT philosophy are not all appropriate to the MPP. The fundamental difference between a typical JIT manufacturer and the MPP concerns the nature of the market. A typical JIT manufacturer operates in a market with stable and predictable demand, offering a standard product range. This allows the manufacturer to arrange for the supply of the required quantity of components at the right time. In short, comprehensive fore-knowledge allows extensive planning, not only of material delivery, but also the management and scheduling of operations, with the potential to lead to a production system that "runs like clock-work". The market in which the MPP operates is vastly different. As a result, techniques and procedures such as extensive market research, long range material planning systems, the kanban shop floor control system, and market persuasion programs are not appropriate for the MPP.

Furthermore, as the MPP is a very small organisation, it is not able to make large demands of suppliers.

6.4.1.7 Group Technology Principles and the MPP

The Group Technology (GT) philosophy provides substantial guidance in the design of the CAS system. This can be seen by comparing the objectives and potential benefits of GT with the objectives of the MPP.

The primary objectives of GT are to maximise production efficiencies by the grouping of similar parts, products, data, and problems; and to operate on them as a group. The potential benefits of this are to reduce part numbers, to be able to use flow-line techniques in production, and to reduce the problems and delays associated with situations that appear to be new.

The main points of GT, and how they apply to the design of the CAS system, are summarised below.

Grouping things by similarity has a number of applications. An important application applies to components. At the information level, all components belong to a single group. This allows similar computations to be performed on the information of any component. At the physical level, components are subdivided into smaller groups, such as those belonging to the family of surface mount components. Each group requires different assembly processes.

The principle of standardisation allows the design of procedures for generating, processing, and communicating data. Such procedures lead to consistency and the efficiency associated with repetition.

One of the requirements of GT is that the data has a single source and storage location to avoid duplication and the problems associated with it. This requires carefully designed information and communication systems.

In addition, by encouraging in-house designers to use standard components, that is, those which are held in stock, or are known to be readily available, production lead times can be kept short.

Cellular manufacturing complements GT as it allows a group, or groups, of products to be produced in a single cell. Such a cell is essentially a dedicated mini flow-line. As there is only one flow path, the control of material flow is very simple. The MPP is such a cell.

Cellular manufacturing simultaneously combines efficient, high volume repetitive production with responsive, high variety production into a single system. This supports the flexibility/efficiency requirement of the CAS system.

Workers are expected to be able to undertake a variety of tasks depending on needs. This is particularly important where products are produced in cells.

Manufacturing entire products within a single cell leads to greater accountability of product quality. In addition, greater satisfaction is gained by personnel who work on a product from beginning to end.

Not all aspects of GT are appropriate to the MPP. The fundamental difference between a typical implementation of GT and the MPP involves the products produced. GT is best suited to applications where there is a very high number of products designed and manufactured in-house. The GT philosophy has a significant impact on the method, and the management of the method, of the design and production of such products. In contrast, the MPP purchases all components, and assembles them to produce a single product. The only "products" produced in-house are the design and the bare board.

In addition, the real advantages of cellular manufacturing over the traditional process-oriented approach are not realised in the MPP as the plant is very small - a single cell - and there is only one type of product produced. Consequently, while the flow-line layout is the most suitable layout purely from a logical point of view, a non flow-line layout would not lead to significant problems, or complexity of control.

6.4.1.8 Material Requirements Planning and Manufacturing Resource Planning Principles and the MPP

The computerised resource planning systems, Material Requirements Planning (MRP) and Manufacturing Resource Planning (MRP II), provide substantial guidance in the design of the CAS system. This can be seen by comparing the objectives and potential benefits of MRP and MRP II with the objectives of the MPP.

The primary objective of MRP is to ensure that the right quantities of the right components are available at the right time to satisfy a specific production schedule. MRP II also plans and controls the use of all resources to satisfy the production schedule.

Potential benefits include the elimination of unnecessary inventory, and the assurance that sufficient resources are available to fulfil the production schedule.

The main points of MRP and MRP II, and how they apply to the design of the CAS system, are summarised below.

Although MRP and MRP II are not directly applicable to the MPP, as will be discussed below, the concept of using product-specific data in the manufacturing processes, coupled with the use of computers for time consuming data processing operations are relevant.

Consequently, opportunities exist for the computerisation of processes such as: stock level checking, stock allocation, update of stock records, billing, estimates of cost and production time, and administration. These processes may be driven by the design data if it is converted to a standard format.

Not all aspects of MRP and MRP II are appropriate to the MPP. The fundamental difference between MRP systems and the MPP concerns the nature of the market. A manufacturer using an MRP system offers customers a standard product range, for which demand is to some extent predictable and relatively stable. This comprehensive knowledge allows extensive planning of material requirements based on known and estimated order quantities and fixed product structures.

The MPP requires that components be replenished after use. This is contrary to MRP systems which attempt to drive on-hand stock levels to zero, and to ensure that materials for a specific order are ordered in time such that they are available when production of the order begins.

The shop floor scheduling system provided in MRP II systems is likely to complicate matters unnecessarily in the MPP, since flow-line principles are more appropriate than independent workstation control.

6.4.2 PCB Assembly System Case Studies

Two case studies are presented in this section. The first focuses on a higher volume, highly automated PCB assembly system, while the second focuses on a conventional low volume manual assembly system.

6.4.2.1 Case Study 1: The Unisys PCB Assembly Facility [98]

The Unisys PCB assembly plant at Roseville, Minnesota, was awarded the 1990 Factory Automation Award by the *Electronic Business* publication.

The Unisys plant is a highly automated, computer integrated plant focused on achieving low inventory, high quality, and flexibility.

The plant produces the 2200-series mainframe computers as well as distributed communications processors. Each week 2,500 PCBs are produced in 64 different configurations. The plant produces these PCBs in single unit batch sizes, and in any sequence with the setup time per configuration averaging less than 1 minute. Total production time per PCB is approximately 2 hours.

A key feature of the Unisys plant is that prototypes are built on the production line.

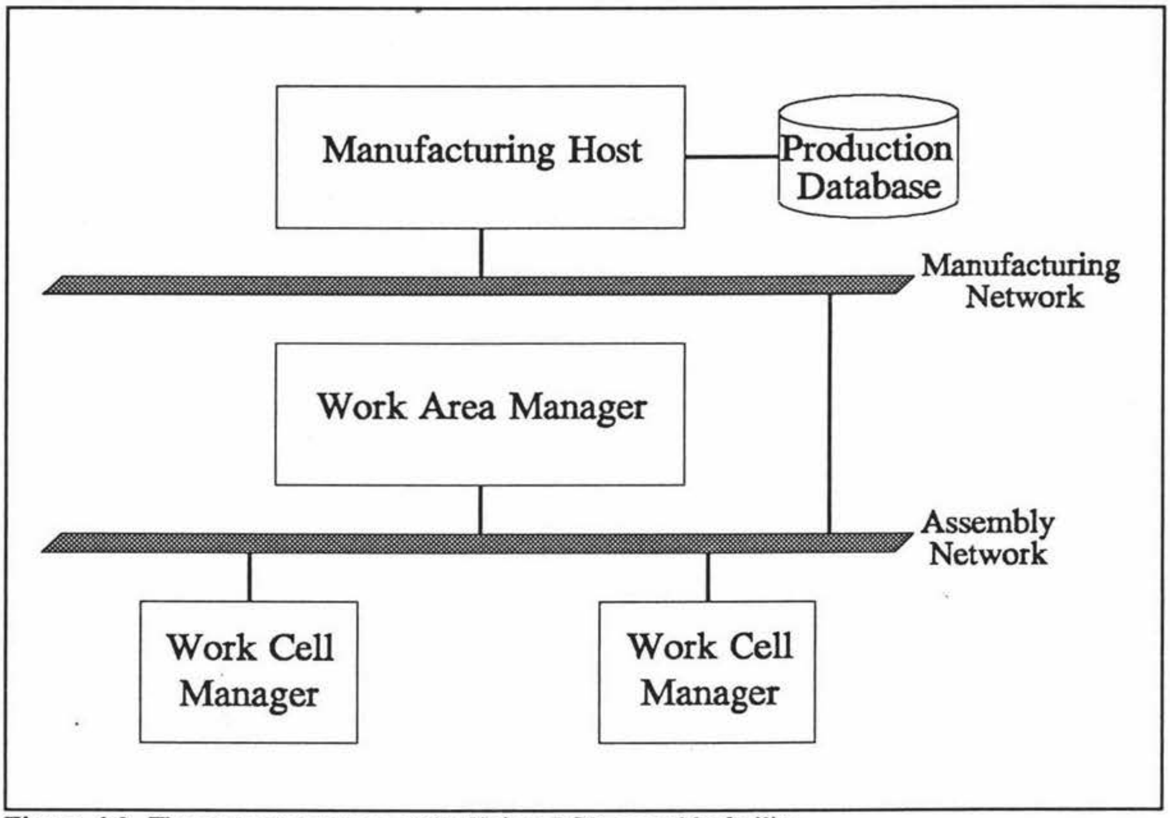

Figure 6-2 The computer system at the Unisys PCB assembly facility

(i) The Computer System

Figure 6-2 (p.87) is a representation of the computer system. It consists of three levels. Level One is the Manufacturing Host, a mainframe, which incorporates the Production Database. The Manufacturing Host provides overall plant control, executed through three, Level Two, Work Area Managers. These direct the Level Three, Work Cell Managers which control machines on the shop floor.

Bar code scanners and data feedback systems ensure that the Production Database remains up-to-date.

(ii) The Assembly Process

The assembly process consists of the following stages.

- Automated Pick and Place machines for surface mount components, followed by infra-red soldering.
- A series of auto-insertion machines for through-hole components, incorporating mis-insertion detection and correction capabilities. If a defective product can not be corrected automatically, it is removed from production. This process is followed by wave soldering.
- The final assembly stage involves the manual assembly of components that cannot be automatically inserted.
- Comprehensive tests are carried out to test circuitry performance, functionality, and resistance to environmental stress.

Although the assembly time of 2 hours is impressive, this figure must be taken in context, namely, that the time to produce a complete system is approximately 6 weeks, of which about half is testing time.

The average defect rate is 6%, of which approximately 50% is attributed to vendor limitations, and 50% to manual assembly errors.

(iii) Application to the CAS System

In terms of production volumes, and therefore the level of investment in technology, the CAS system has little in common with the Unisys plant. Further investigation, however, reveals that the CAS system can be modelled on the Unisys plant.

The design methodology derived in Chapter 3 requires that systems be designed to satisfy a set of objectives. Key objectives of the Unisys plant include low inventory, high quality, and flexibility. In addition, other objectives may be identified: the plant is a rapid response system designed to produce a variety of boards in single unit batch sizes, in any sequence. Emphasis on time-based performance leads to short throughput times and very short changeover times. At this level, the objectives of the Unisys plant are similar to those of the CAS system.

The key differences between the systems lie in how systems are implemented to achieve the objectives, but even in this area, there are significant similarities.

For the Unisys plant to function, it is necessary that CAD packages produce sufficient data to drive the production systems, such as the automated component insertion machines.

This data includes component identification, location and orientation information. This is the product-specific data. In addition, data is required detailing the location of each component in the plant, together with stock levels and other necessary information. This is production system-specific data, or simply, production data. These two sources of data form the basis of the information system capable of driving systems such as material planning systems, and the shop floor systems.

Consider also the product-oriented assembly system. Despite the variety of products produced, it is essentially a flow-line, with a degree of flexibility.

The above observations are very significant for the CAS system. Modern CAD packages are capable of producing all the data required for auto-insertion machines. Unfortunately, auto-insertion machines are not applicable in the CAS system due to the mismatch between the production volume and the required capital expenditure. Consequently, assembly operations are restricted to manual assembly.

Schonberger (1986), however, provides useful advice regarding automation and low volume operations. He suggests that it is possible to reduce costs and achieve other gains not by making use of automated systems, but simply by making the type of changes to the production system that would ordinarily be required before the automated systems could be installed; a process he terms 'pre-automation' [21 p.63]. This concept has particular relevance to the CAS system.

A computer driven assembly *assistance* system may be developed that is capable of recognising individual components. This system would:

- present the correct component to the assembler, and
- inform the assembler of the location of the component.

This computer-based link between design and production would form the foundation of the MPP computer system, however it must allow the integration of other production systems and support systems.

The concept behind the organisation of the assembly system is also applicable to the CAS system, despite the obvious differences in the way that concept is implemented. The CAS system may be organised as a mini flow-line, with elements of that flow-line dedicated to specific tasks; or specific components, such as surface mount, through-hole, and unusual components; and soldering.

Clearly, the Unisys PCB assembly plant and the CAS system have much in common. This commonality is found primarily in the underlying concepts and principles of the systems, and to a lesser extent in the specific ways in which the concepts and principles are implemented.

6.4.2.2 Case Study 2: A Typical Conventional Low Volume Manual Assembly Facility

Consider the case of a typical conventional manual assembly facility in which a variety of PCBs are assembled in low volumes. This type of system is also discussed in Chapter 2, Section 2.2 (pp.5-6), however, the focus in this section is only on assembly.

The use of technology ends with the completion of the design process, after which the design data must be converted from computerised data to a form more useful for manual operations, such as a printout of the parts list and a plot of the PCB overlay.

This information is sufficient for checking stock levels, kitting, assembly and billing.

The processes of checking stock levels, kitting and billing all require a detailed parts list, and are performed manually. Clearly, for complex PCBs such operations are time consuming and error-prone.

The assembler must be provided with: a parts list, a plot of the PCB overlay or a sample of the completed PCB, and a kit containing all the components required for the order. Assemblers must develop their own systematic method for assembly.

(i) Application to the CAS System

For very low volumes the only cost effective assembly method is the manual method. This does not mean that modern technology has no place in such a facility. Rather, because the total production volume is low, the investment in technology must be kept low unless the profit margin on the products is very high.

Not all aspects of conventional low volume assembly systems are appropriate to the CAS system. Making up kits for each order is not the most practical way of organising components when utilising computer controlled component storage and presentation systems. It is more practical to distinguish between frequently used components (standard components) and rarely used components (non-standard components). Standard components should be located permanently in the storage/presentation system in predefined quantities, while non-standard components should be dealt with on an order-by-order basis.

6.5 Stage 4: Develop Conceptual Models

The fourth stage of the GDM is to define the processes and functions of the production system at a conceptual level, and to develop clear but simple models that represent these processes and functions. These models detail *what* the system must do.

In addition, the processes are examined and ranked according to importance.

The models presented and discussed below will focus on the CAS system, but will include design and production to develop a complete and clear picture of the MPP.

The conceptual models are divided into two categories: on-line processes, and off-line processes. On-line processes are those that are performed as part of the process of completing an order, while off-line processes are those that occur when necessary, or when time is available.

6.5.1 A Conceptual Model of On-Line Processes

Figure 6-3 (p.92) is a model of the *minimum* processes required to satisfy the requirements of an individual customer: referred to as on-line processes. The processes represented in the figure are discussed below.

6.5.1.1 Initial Contact with Customer

The initial contact with the customer is of vital importance as the requirements of the customer are determined, and a contract between the customer and the MPP may be established.

The requirements of the customer may include design, production, and/or assembly. The information passed from the customer to the MPP will depend on the service(s) required.

6.5.1.2 Product Design

To design a product that meets or exceeds the requirements of the customer, the designers must be highly skilled, and motivated to satisfy customers.

To make full use of the capabilities of the production system, the designers must have some knowledge and understanding of the production system.

Designing a product that can be manufactured with minimal delays requires that components be used which are known to be on-hand or are available at short notice. This requires that:

- the designers have easy access to such information, and
- the MPP is able to make use of procedures to by-pass normal supply channels, which may

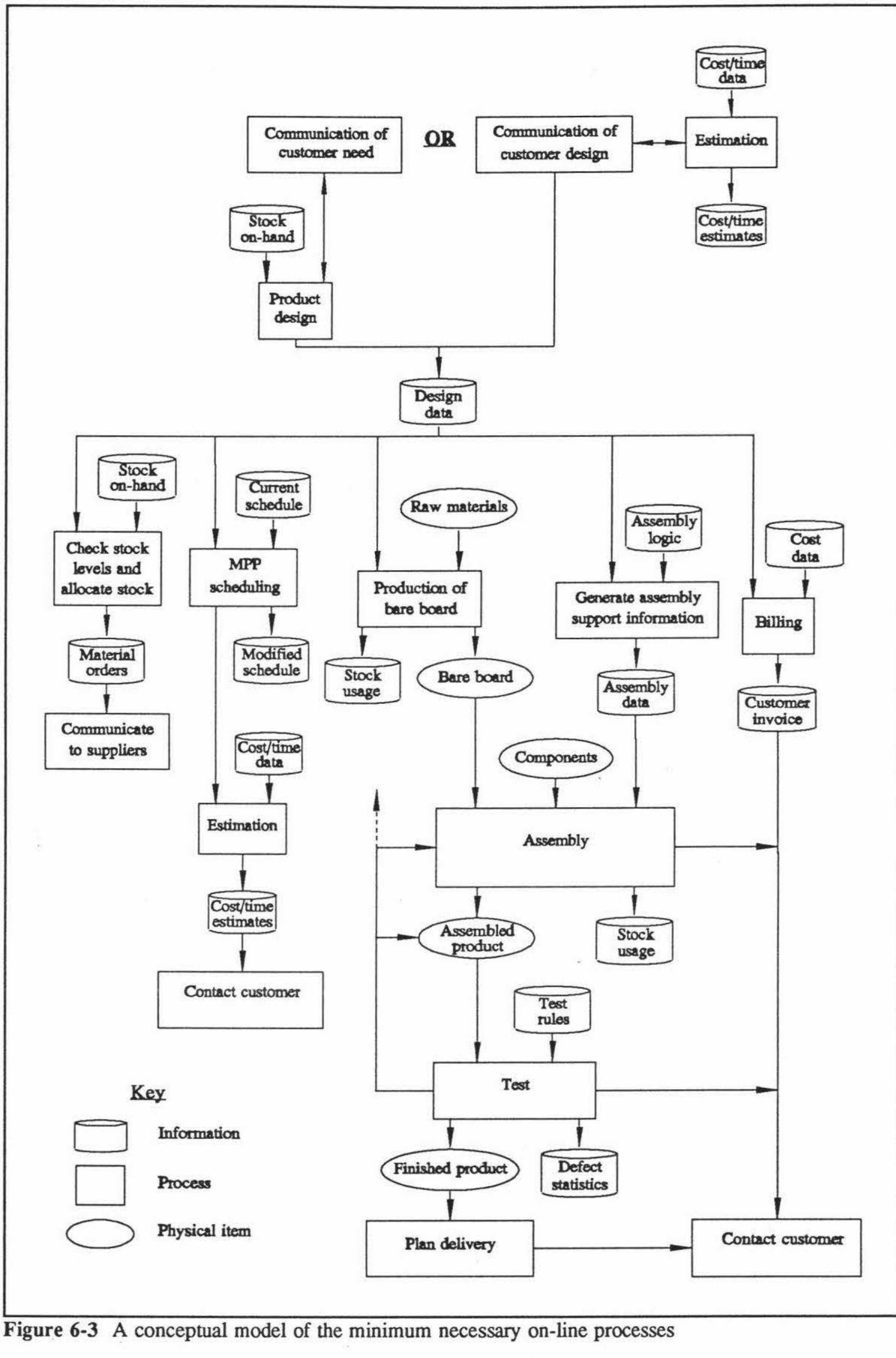

Figure 6-3 A conceptual model of the minimum necessary on-line processes

be slow.

The design process is complete when the design is approved by the customer.

6.5.1.3 Checking Stock Levels and Allocating Stock

The objectives of this process are to determine the impact on stock levels by the production of the order, to allocate stock to a particular order, and to prepare to take the necessary action to obtain components that may be required urgently.

The stock level checking system must perform the following tasks:

- maintain levels of frequently used stock to avoid stockouts,
- by-pass normal supply channels for urgently required components, and
- time the dispatch of orders for components according to the degree of urgency.

With regard to standard components the stock control system is aimed at replenishment after use rather than delivery before use for two main reasons:

- the cost associated with carrying stock is anticipated to be lower than the cost of frequent deliveries of many components in small quantities from multiple suppliers. This is especially true for low value components, and
- typical component delivery lead times are long, unless more expensive delivery procedures are used.

The stock control system highlights the need for systems to be designed according to predetermined and consistent objectives. In the MPP, rapid response takes precedence over low cost.

6.5.1.4 Scheduling and Estimation

The objectives of this process are to provide the customer with a realistic delivery date, and to provide some structure to the activities within the MPP.

The scheduling of an order takes place after the stock level checking process is complete, since it is necessary to determine when all the components will be available and ready for assembly. At this point it is possible to contact the customer and give an accurate estimate, or quotation, of the cost and delivery date.

If a contract between the customer and the MPP does not exist, this would be the point where the customer would make the final decision. If the customer decides to accept the services of the MPP, the orders for urgently required components would be dispatched immediately.

One of the key factors of the scheduling process is that it must apply to the Wet Line as well as to the CAS system and should be based on the cell with the least available capacity. Separate schedules may be required, but they should not be independent. This coordination between the systems ensures that the bare board is always completed before assembly is scheduled to begin. Failure to establish this link may lead to an unnecessary increase in the customer inconvenience time.

As the Wet Line and the CAS system are essentially two semi-connected cells or mini flow-lines, scheduling operations within the cell is unnecessary. This allows a degree of independence within the cells.

6.5.1.5 Production of the Bare Board

A detailed description of the Wet Line is beyond the scope of this discussion except to say that the objectives of the Wet Line must be derived directly from the overall objectives of the MPP, as with the CAS system.

6.5.1.6 Generation of Assembly Support Information

The objective of this process is to extract from the design data information about the product that may be combined with information about the production system, to produce sufficient information to drive the assembly assistance system.

6.5.1.7 Assembly

The objectives of the assembly process are to produce a product that matches the design, with a short overall assembly lead time, and at a competitive cost.

Inspection(s) during the assembly process ensure that defects are discovered and remedied quickly, and are not allowed to progress through production, as corrective measures may become more complicated and costly to perform.

Although the stock level checking process described in Section 6.5.1.3 (p.93) may also be used to generate data regarding stock usage, the advantage in producing this data during assembly is that the data represents *actual* usage in real time, rather than anticipated usage.

6.5.1.8 Testing

The objective of this process is to test the functional performance of the product(s), repairing those that fail the test(s). This ensures that 100% of the products released to the customer function correctly.

The testing process must incorporate mechanisms to correct the product, and, where necessary, to update the information about the production system to ensure that the error is not repeated.

Statistical data may be gathered during testing for immediate or subsequent analysis.

6.5.1.9 Billing

The objectives of the billing process are to provide the customer with an invoice that accurately reflects the cost of production, and to provide information regarding means of payment. Because of the high variety nature of production, it is necessary to charge on a product by product basis.
The mechanism of this process may also be used for producing an estimate or quotation.

6.5.1.10 Planning Delivery

The objectives of this process are to package the product(s) for delivery, and to arrange prompt and reliable transportation from the MPP to the customer. The product must reach the customer in the same condition as when it left the MPP.

6.5.1.11 Contacting the Customer

The objective of this process is to keep the customer informed of progress.
Contact may occur at any time during design, production or assembly, if it would benefit either the customer or the MPP.

Informing the customer of the completion of the order allows the customer to make preparations for the expected delivery of the product. In addition, this type of service cultivates a reputation that the MPP is genuinely concerned with, and committed to providing customer satisfaction.

6.5.2 Conceptual Models of Off-Line Processes

Figure 6-4 (p.96), and Figure 6-5 (p.96) depict a series of models of support processes and functions, referred to as off-line processes. The processes represented in the figures are discussed below.

6.5.2.1 Stock Ordering

The objective of this process is to generate and release purchase orders to ensure that used stock is replaced.

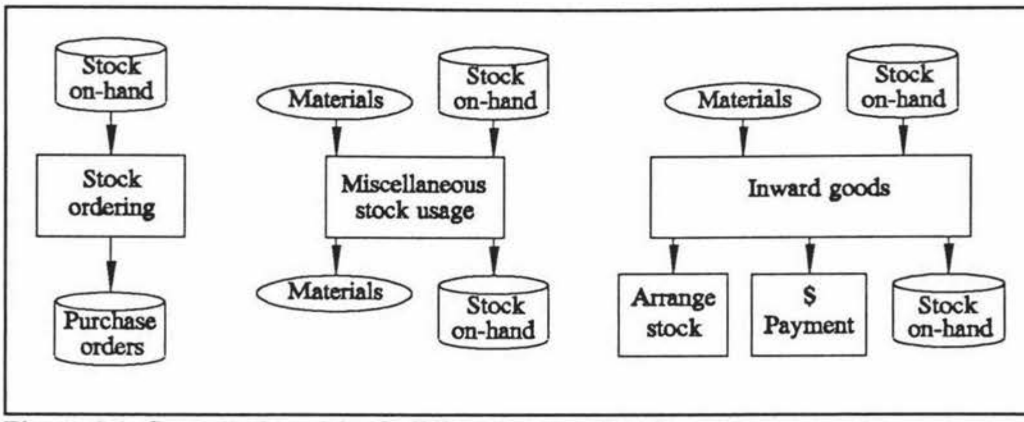

Figure 6-4 Conceptual models of off-line processes, Part I

6.5.2.2 Miscellaneous Stock Usage

The objective of this process is to ensure that a simple procedure is in place allowing stock to be withdrawn from the store(s) for use other than in assembly, and that a record of the transaction is generated.

6.5.2.3 Inward Goods

The objective of this process is to make the transition from "materials received" to "materials available for production" as rapid and simple as possible. In addition, stock records must be updated rapidly.

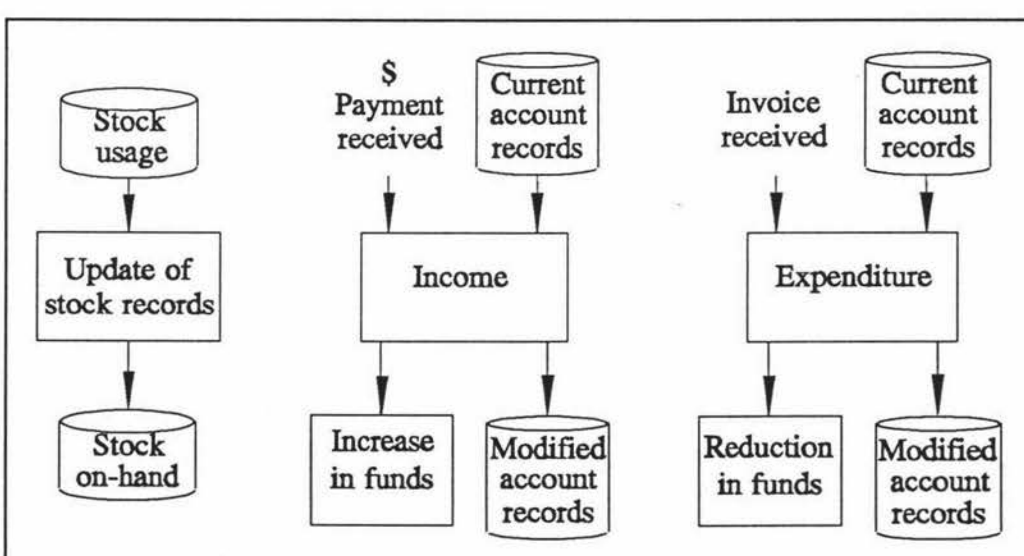

Figure 6-5 Conceptual models of off-line processes, Part II

6.5.2.4 Update of Stock Records

The objective of this process is to ensure that current records detailing on-hand stock levels accurately reflect the actual levels. This is necessary to ensure that enquiries made of current stock levels result in the return of accurate information, thereby allowing sound decisions to be made.

6.5.2.5 Income

The objective of this process is to ensure that payment received is rapidly converted into a more usable form.

6.5.2.6 Expenditure

The objective of this process is to ensure that bills are paid on time, thereby maintaining good relationships with suppliers.

6.5.3 Ranking Processes on the Basis of Importance

This stage in the design process has involved defining the production system at a conceptual level, or, defining *what* the system must do. It has been purely a theoretical exercise. Stage 5 involves defining the production system at a functional level, or, defining *how* the system will work. It is the beginning of the implementation process.

The shift from theory to application will not be successful without an appropriate transition process. It is the purpose of this section to present such a process.
The transition process involves determining what processes are important and why, and ranking them accordingly.

The benefit of ranking processes according to importance is that it ensures that in the implementation stages the most important processes are defined first, together with the interactions between these processes and other processes, and then that the less important processes are defined. In short, the structure of less important processes must be governed by the structure of the more important processes. If the reverse was to occur, the design of the more important processes might be impeded or constrained by the already established structures of less important processes.

Furthermore, the identification of the relative importance of processes provides guidance on how and where to allocate limited resources. This leads to a structured, objective approach to system design and implementation.

The concept of ranking the processes that make up the production system on the basis of importance applies also to the elements making up a single process.

Two methods for classifying processes on the basis of importance will be discussed:

- the identification of the critical path, and
- the identification of the core processes.

6.5.3.1 Identification of the Critical Path

The critical path consists of the minimum necessary operations, executed sequentially, making up the link from the initial contact with the customer to the delivery of the finished product. This has been referred to as the customer inconvenience time.

The sequential operations making up the critical path are:

- communication of customer requirements,
- design,
- checking of stock levels and the ordering of urgently required components,
- scheduling and estimation or quotation,
- production of the bare board,
- assembly,
- testing,
- planning delivery,
- contacting the customer, and
- shipment.

Operations that are not part of the critical path may be referred to as parallel operations as there is a degree of flexibility as to when they may be performed. The significance of this is twofold: first, it ensures that the customer inconvenience time is not unnecessarily long, and second, distinguishing between the two types of operations - sequential and parallel - allows system designers to focus resources and efforts on improving the efficiency of critical path operations, before focusing on improving the efficiency of parallel operations.

The parallel operations are:

- the generation of assembly support information, occurring after design but prior to assembly,
- billing, occurring after the completion of production, and
- off-line processes, including stock ordering, miscellaneous stock usage, the update of stock

records, inward goods, income, and expenditure. These processes occur as required, or when the necessary resources are available.

Parallel operations may be ranked on the basis of the "degree of flexibility" of when they may be executed. Clearly, the generation of assembly support information is a high priority operation in that it is a vital link between design and assembly, and must be executed between those two operations. Another factor that limits the timing of parallel operations is the availability of resources. If parallel operations require the same resources as sequential operations, the parallel operations may interrupt the sequential operations, and will therefore effectively become sequential operations.

The off-line processes are typically parallel operations. Where there are generalisations, however, there are also exceptions: situations will arise where parallel operations, such as the update of stock records, and the ordering and delivery of urgently required components, are temporarily critical path operations.

6.5.3.2 Identification of the Core Processes

Core processes are those that are directly related to the basic objectives of the production system. They are the key value-adding, or revenue-generating steps in the production process. It is these core processes that are of concern to the customer.

The core processes of the MPP are:

- initial contact with the customer: the critical step of winning customers,
- design: the abstract process of devising a solution,
- production of the bare board: the first stage in the construction of the solution,
- assembly: the second stage in the construction of the solution, and
- testing: the verification of functional performance.

It is not sufficient merely to distinguish between core processes and non core processes. Non core processes must be examined and ranked according to the impact they have, or the degree of support they provide to the core processes.

The next most important processes are those with a direct impact on the performance of the core processes. They include:

- the generation of assembly support information: the link between design and assembly,
- checking stock levels: ascertaining whether the product can or can not be assembled with current stock on-hand,

- stock ordering: generating and releasing purchase orders to replenish stock levels,
- inward goods: the transition from "goods received" to "goods available for production" which must be efficient, reflecting the urgency with which the goods are required,
- miscellaneous stock usage: the use of stock for miscellaneous purposes must be recorded to assure the validity of subsequent stock level checks, and
- update of stock records: the delay between the actual addition or withdrawal of stock and the update of stock records must be appropriately short to assure the validity of subsequent stock level checks.

The next most important processes are those that have little impact on the core processes, but have a significant impact on the perception customers have of the performance of the core processes. These processes are:

- scheduling: where estimates must be realistic to ensure that delivery dates are met with few exceptions,
- planning delivery: where delays must be minimal, and protection against handling damage substantial,
- contacting the customer: where customers must be kept informed of progress, in particular, the completion of production and subsequent delivery, and the unpopular but necessary task of informing customers of the consequences of unforseen and unavoidable delays or problems when they occur, and
- billing: where bills must be accurate and consistent, and the method of payment simple.

The outcomes of these processes are clearly apparent to customers. Genuine commitment in these areas contributes significantly to a reputation of professional, responsive service. This is of great importance when operating in a market with many repeat customers. A sound reputation attracts new customers, and helps to generate customer loyalty.

The next most important processes are those with an indirect, or delayed impact on the performance of core processes and include:

- income: where income not received may affect cashflow to a point where core processes are denied essential resources, and
- expenditure: where failure to settle accounts creates tensions between the MPP and suppliers, to the extent where the latter may suspend further supplies until the situation is corrected.

6.5.3.3 Overall Ranking

The first grouping consists of the most important processes. This group includes:

- the initial contact with the customer,
- design,
- production of the bare board,
- ordering and delivery of urgently required components,
- assembly, and
- testing.

This list is made up primarily of core processes which also appear in the critical path.

The next grouping consists of processes that are closely linked to the processes listed in the first grouping. This group includes:

- the generation of assembly support information,
- checking stock levels,
- stock ordering
- the update of stock records,
- inward goods, and
- miscellaneous stock usage.

The internal mechanisms of each of these processes must be related to, and compatible with the internal mechanisms of the processes in the first grouping.

The final grouping consists of the remainder of the processes. This grouping is characterised by two types of processes: those which are, strictly speaking, not considered part of the traditional "production processes", and those which have a significant impact on the perception the customer has, or gains, of the MPP. This group includes:

- scheduling,
- estimation of cost and delivery date,
- billing,
- planning delivery,
- contacting the customer,
- shipment, and
- income and expenditure.

Although the ranking of processes in order of importance has provided guidance on where to place emphasis in the remaining design stages, it is important to recognise that all necessary processes are to some extent important. This is because no process is totally independent. The output of any process, and therefore the internal mechanisms of that process, effect the performance of other processes.

This ranking has, however, provided a method of approaching the next stage in the design process which involves the development of models of how the system functions.

Chapter 7

Implementation of the CAS System

7.1 Introduction

The objective of this chapter is to apply the final stages of the Generic Manufacturing System Design Methodology (GDM) to the design of a system for the assembly of Printed Circuit Boards (PCBs). This system, referred to as the Component Assembly System (CAS), is an integral part of the Manufacturing Pilot Plant (MPP), which offers three services:

- PCB design,
- bare board production, and
- PCB assembly[6].

The MPP is aimed at a market characterised by the demand for the prompt delivery of high quality, special purpose PCBs in low volumes.

The final stages of the GDM are:

- Stage 5: define the system at a functional level, that is, define *how* the system must function to fulfil the objectives. This requires the specification of the physical properties of the system.
- Stage 6: implement the design.

---

[6] In this chapter, the term "production" will not only refer to the production of the bare board. Instead, for brevity, this term will also refer to the total process of PCB manufacture.

This chapter is divided into two sections. Each section focuses on one stage of the GDM.

7.2 Stage 5: Develop Functional Models

The fifth stage of the GDM is to define the manufacturing system at a functional level, that is, to define *how* the system concepts are implemented. This stage is the beginning of the implementation phase, since physical elements of the system must be specified.

This stage is divided into two sections.

The first section is an overview of the functional properties of the CAS system. It is necessary to present such an overview to gain an understanding of the system as a whole.

The second section is the detailed design of the CAS system.

7.2.1 Overview of the CAS System

In this section, the basic framework, or overall functional properties of the CAS system are presented.

From a production viewpoint, the MPP consists of two distinct, but closely linked and compatible computer-based systems:

- the Wet Line, for the production of the bare board, and
- the CAS system, for the assembly of PCBs.

These systems must be linked and compatible as they are both driven by the same design data, and together provide the capability to produce a complete product.

It has been stated above in Chapter 6, Section 6.4.2.1(iii) (pp.88-89), that, while high levels of automation are inappropriate in the MPP, the application of some technology in the support of production and manual assembly operations is appropriate.

The rapid response capabilities of the MPP are achieved through the use of integrated computer systems, in particular, IBM, or IBM compatible Personal Computers (PCs). This choice of computer system is based on the need to satisfy four conditions:

- the computer systems used in design and production must be compatible, without the need for interfaces,

- the computer systems used in production must be flexible and programable,
- the computer systems must allow integration with other technical systems, and
- the computer systems must be low cost, and widely used.

Clearly, the PC satisfies all conditions.

The linked, compatible computer systems used in the core processes of the MPP form the foundation of the manufacturing system. Computer-based support systems are incorporated into this system to provide the full manufacturing capability.

The CAS system functions as a design data driven, closed loop system.

The CAS system is design data driven in that the design data is the primary data input, remaining in computerised form, for processes including the key value adding production processes, production support processes, and administration. The secondary data input for these processes is the CAS Database - a source of information that is production system oriented.

The CAS system is a closed loop system in that the data output of the production processes is one of the key data inputs to the CAS Database.

These two aspects of the CAS system are illustrated in Figure 7-2 (p.110), which will be discussed in detail in Section 7.2.2 (pp.109-120).

While the computer plays a significant role in the CAS system, it is restricted to two categories of activities, namely, the rapid manipulation of data, and the control of technical equipment, in effect, a form of automation.

The implementation of the concept of a computer assisted manual assembly system takes the following form.

- Information aspect: the design data is combined with the relevant data from the CAS Database to provide the vital information link between design and production. This information is referred to as assembly support information.
- Technical aspect: the assembly process is divided into stages, with each stage performed at a separate workstation. Each workstation is comprised of a PC and an electronically controllable storage device, consisting of a number of bins, each uniquely identifiable, both by the electronic controller, and the assembler.
- The combined system: at each workstation the assembler is presented with a graphic image of the PCB on the computer screen, and is informed of what component to insert, and where. Simultaneously, the computer activates the storage device to present the correct component to the assembler.

The computer also keeps a record of components used, thereby providing the information to update the CAS Database.

Although the computer controls the technical elements of the system and the order of assembly, the assembler determines the rate of assembly, and has ultimate control over the computer system.

7.2.1.1 CAS System Hardware and Software

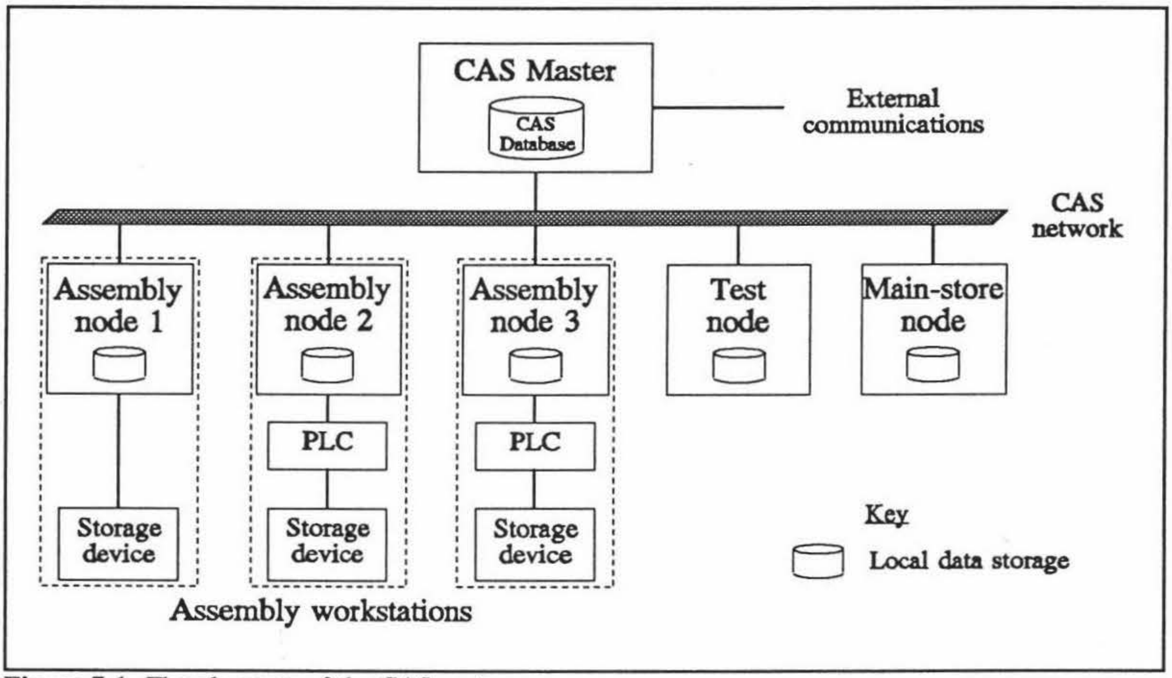

Figure 7-1 The elements of the CAS system

Figure 7-1 (p.106) represents the basic structure of the CAS system at a technical level. The CAS system consists of three types of subsystems:

- the central management system, referred to as the CAS Master,
- assembly systems, referred to as Assembly Workstations, and
- systems for other functions, such as the Main Store and test nodes, referred to as Support Systems.

Each will be considered below.

(i) The CAS Master

The CAS Master consists of a PC with connections to a Local Area Network (LAN) and external communications such as the telephone system.

The tasks of the CAS Master are to:

- provide the means to exchange information with suppliers and customers,
- convert design data into assembly support information,
- communicate with Assembly Workstations and Support Systems,
- maintain the CAS Database,
- may include PCB design software, and
- may act as an Assembly Workstation or Support System.

(ii) Assembly Workstations

Typically, the Assembly Workstations consist of three elements: a PC, a Programable Logic Controller (PLC), and an electronically controllable storage device. The PLC links the PC to the storage device, thereby enabling the PC to control the storage device, while the LAN links the workstation PC to the CAS Master.

A PLC is not required if the storage device has built-in facilities for communications with a PC.

The tasks of the Assembly Workstations are to:

- facilitate the assembly process, and
- record stock usage.

Each workstation is a semi-independent module. The module is integrated with the CAS Master for the communication of information, but may also operate as a stand-alone system. For example, assembly support information may be down-loaded to a workstation from the CAS Master, after which the workstation may operate as a stand-alone assembly station. At the completion of assembly, stock usage data may be up-loaded to the CAS Master.

The added benefit of a modular approach to workstation design is that workstations may be added or removed without the need for extensive modifications.

Workstation software may be grouped into two categories: common software and unique software. Common software is that which is not dependent on the physical characteristics of the storage device, and is therefore common to all workstations. Unique software is that which is dependent on the physical characteristics of the storage device, and is therefore unique to a particular workstation. Unique software is typically restricted to hardware control and communication, and has no impact on the user interface. Consequently, consistency is achieved as the software systems at each workstation will appear identical to the assembler.

An added benefit of this approach is that, when editing the common software, only one version requires editing, and may be distributed to each workstation. The objective in designing the software is that the amount of unique software be kept to a minimum.

(iii) Support Systems

Other functions, such as Main Store control and testing, consist of a PC with a connection to the LAN.

The task of each of these systems is to display, accept, and communicate data.

In the case of the Main Store control node, the software required is that which displays and accepts data regarding stock on-hand, and stock transactions. Little data processing is required. Connection to the LAN is essential.

In the case of the test node, the minimum software required is that which displays and accepts data. The test node may also include systems for data analysis. Connection to the LAN is optional.

7.2.1.2 Advantages and Limitations of a Computer-Based System

The most obvious advantages of correctly designed and implemented computer-based systems are greater speed, flexibility, and efficiency. These, and other benefits are discussed more fully in Chapter 5, in particular Section 5.2.2.3 (p.37).

One of the key points to remember when implementing modern systems is that the system does not solve problems by itself. Technology is a tool, and the right tool must be used in the right application. The GDM endeavours to reveal the characteristics of this application (the CAS system), and to develop the correct tools, such that the benefits of computer systems can be realised.

One of the prime limitations of computer systems is that they only operate efficiently when subject to the conditions for which they were designed. Undesirable, or unpredictable events or outcomes, or failure to function, may result when the system is subject to a set of conditions that it is not designed to accommodate.

Consequently, the effort put into developing computer-based processes must be in proportion to the importance of the process, the range of anticipated design conditions, and the severity of the consequences of non-design conditions. In this instance also, the GDM provides guidance on recognising the important processes and developing effective systems.

Excellently designed computer systems may perform well at the time of installation, however performance may diminish as conditions or needs change. To overcome this it is necessary to institute a program of on-going improvement, such that the system is improved at a pace that allows it to remain at a high level of functionality. A failure to improve the system inevitably results in the abandonment of the system as it becomes more of a hindrance than a help.

The improvement program is based in part on the assumption that the design of computer systems, particularly software, never ends. This approach encourages the development of a permanent, cooperative relationship between system designers and system users.

In summary, the CAS system is based on higher volume, automated assembly systems such as the Unisys plant discussed in Chapter 6, Section 6.4.2.1 (pp.86-89), as well as low volume, conventional manual assembly systems, such as the system discussed in Chapter 6, Section 6.4.2.2 (p.90). This combination forms the basis of a rapid response PCB assembly system.

7.2.2 Detailed Design: On-Line Processes

The discussion of the on-line processes is based on Figure 7-2 (p.110). This figure is a basic model, and is comprised only of major features. The details of the processes are discussed in the sequence in which a typical customer order would progress through the production system. Before discussing the processes, however, the CAS Database will be discussed.

7.2.2.1 The CAS Database

The CAS Database must be a central data source that is able to provide the vital information link between design and production.

Consequently, the database must contain the following type of information for each component:

- component identification,
- workstation locations,
- quantity on-hand, reorder quantity and reorder level for the Main Store and the workstation,
- component details including height, fragility, cost, and polarity, and
- supplier details including delivery performance.

Although the CAS Database plays a critical role in the CAS system, as is evident in Figure 7-2 (p.110), it is essential to remember that it is not the core of the production system, but simply an instrument or tool of production.

To remain an effective and trustworthy data source, the database management system must be robust, with carefully designed data processing procedures. Where possible, data input, output, and communication should be automated, however, where this is not possible, and manual data entry is required, the user must recognise the need for precision and accuracy.

7.2.2.2 Initial Contact with the Customer

The initial contact with the customer is critical, particularly with potential or uncommitted

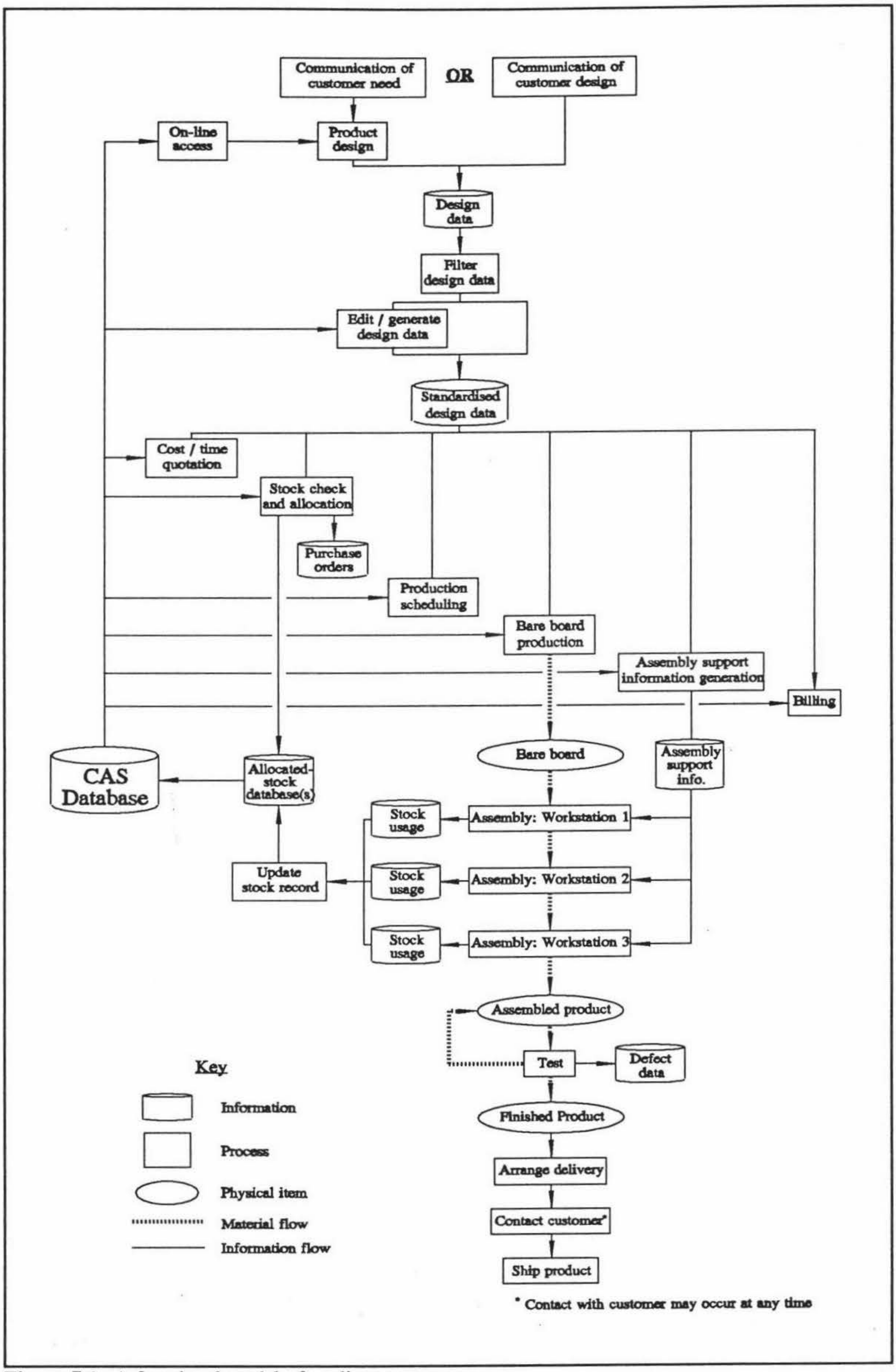

Figure 7-2 A functional model of on-line processes

customers. From the viewpoint of the customer, the initial contact will establish the first impressions, which will have a significant bearing on the overall perception the customer has of the MPP. From the viewpoint of the MPP, the initial contact is the period in which the customer-manufacturer relationship will be developed, establishing the requirements and expectations of both parties.

The requirements of a customer may involve design, production, and/or assembly of PCBs. Consequently, the information exchanged, and the method of communication will differ.

The type of information exchanged may include: a problem definition, product specification, or actual design data; the quantity of PCBs required; and an estimation of the cost and/or time.

Several methods of communication may be required, including: meetings, telephone conversations, data exchange via modem, and written information.

Although marketing philosophies are beyond the scope of this discussion, one point must be noted: customers and potential customers must be made aware that the MPP is a computer-based production system, and as such, requires that the design data be in computerised form.

7.2.2.3 Product Design

To enable in-house designers to design PCBs that can be produced with minimal delays, they must have access to production information while designing the product. Information of particular value is that which details stock on-hand, or the availability of stock not on-hand, including sources and their delivery performance. With computer-based stock records, it may be possible to provide on-line access to the CAS Database. This may be achieved by developing a memory resident program that, when invoked at any time during design, accesses the database, and displays the data in a scroll-able list. Additional search facilities must be included since the number of components in the database may become large.

The advantages of computer-based on-line systems over paper-based systems are significant. Principal advantages include:

- the information is easy to manipulate, and, if it is not a cumbersome system, the likelihood that designers adopt the system and use it regularly is greater,
- the information is totally up-to-date, and
- the information is derived from a single source.

An added benefit of the on-line system is that designers would be able to use as many standard components, that is, those currently held in stock, as possible.

The system suggested so far is a "one way" system in that information would be passed from the production system to the designer. A logical extension to such a system would be to convert it into a "two way" system. A "two way" system would allow the designer to edit the CAS Database, in particular, to add new components to the database. Components added in this way would require a special identification flag so that information, such as workstation locations, may be entered when convenient.

The second important feature of the "two way" system is that it would allow the designer to order components that are either not available in sufficient quantities, or are not listed in the CAS Database. This feature may shorten the overall customer inconvenience time since components may be ordered during the design process, or towards the completion of design where few changes will be made, to be delivered in time for production.

A further extension to the system would be to allow system designers to request the allocation of production time to a specific order. Such a system would, however, require careful design and cautious use. Requests by designers should not be assigned a high priority if the design is not complete, as allocating time to an order that is not subsequently used may result in lost production time, and therefore lost income.

7.2.2.4 Design Data Requirements

Three types of design data would be required for a computer-based assembly assistance system:

- data defining the graphic overlay of the PCB and components,
- data identifying each component individually and uniquely, and
- data linking each component to a position on the PCB.

This requirement poses two problems. Firstly, not all CAD packages produce the component location data. Secondly, the format of the output of each package may differ from that of other packages.

The first problem may be overcome by providing a facility to produce the missing component location data. This facility could present to the user an image of the PCB, derived from the graphic overlay data, allowing the user to select components, and to enter the appropriate identification data. The computer could then automatically generate the required component location data. The generator must have access to the CAS Database so that a selected component may be identified correctly, without the need to type in data.

The key disadvantage of such a system is that it would be labour intensive, and therefore somewhat time consuming for large PCBs. This is not an ideal situation as it is in conflict with the rapid response objective of the MPP.

A logical extension to the system would be to enable it to read all the design data in the CAS system standard format. In this way, the system would also act as an editor, allowing minor changes to the design data.

The solution to the second problem consists of two parts. Firstly, it may be possible to construct simple systems, using the built-in macro programming language of the CAD package, that customise the design data output to a standard format for that particular package. Such systems could be located at the premises of repeat customers, and potential repeat customers, to minimise difficulties and delays between design and production, and also to promote customer loyalty. Secondly, data conversion programs may be constructed that convert the data into a standard format for the CAS system.

7.2.2.5 Quotation of Cost and Delivery Date

This process may only be implemented if the customer specifically asks for a quotation of the cost and delivery date, and supplies the necessary design data.

Determining the exact cost of production would involve determining the cost of the components and other raw materials, and the cost of labour. Delivery costs may be included if necessary. If the design data is available in computerised form, a computer-based system could calculate the cost very quickly.

Determining the production time could be achieved with a computed estimation, if a reliable computer model can be constructed. Provided that the design data is in the standard format for the CAS system, or can automatically be converted to that format, the automated quotation process would be very rapid. This would allow the MPP to respond rapidly to customer enquiries.

An alternative solution would be to construct scatter diagrams, based on, for example, the actual assembly times, the number of components per board, and the number of boards assembled in a batch. The resulting diagrams may reveal trends, or may simply provide a visual method of determining the limits within which the actual production time is likely to fall. While this process is more time consuming than the computerised system, the primary advantages are that the model can be constantly updated using the *actual* production times, the design data need not be in computerised form, and a visual presentation of a considerable amount of data combined with experience may result in accurate estimations of production time.

The delivery date could then be determined in conjunction with the current production schedule.

7.2.2.6 Checking Stock Levels and Allocating Stock

The purpose of this process is to compare component requirements, based on the standardised design data, with available stock, and to generate the necessary orders to ensure that unavailable stock is ordered, thereby avoiding stockouts. A computer system could perform this process very quickly, and without error, if the design data is available in computerised form.

The sophistication of the system may be greatly increased by introducing a product-specific element to the system. With this addition, stock may be allocated to a specific order. The benefits of this are significant, and include:

- the ability to determine what action is required before a specific order can enter production,
- assurance that subsequent stock checking calculations are not based on erroneous data, and
- the elimination of the need to constantly update the CAS Database as assembly proceeds.

Such a system should consist of several parts.

A list would be required of Work In Progress (WIP). For each order in the list, a database, referred to as the allocated-stock database, would exist detailing the components allocated to the order.

The allocation of stock would occur only at the information level. Stock would be allocated by "shifting" stock out of the CAS Database, into the allocated-stock database.

In the situation where the order is terminated prior to production, or major design changes are made, it must be possible to merge the allocated-stock database back into the CAS Database with no negative consequences.

Clearly, such a system requires careful design such that unusual circumstances may be dealt with easily, and without major intervention from the user, or a reduction in the integrity of the CAS Database.

7.2.2.7 Scheduling

Accurate scheduling requires that the production time be accurately estimated. Production time estimation has been discussed in Section 7.2.2.5 (p.113).

A computer-based scheduling system may be developed, that calculates production and assembly times and schedules orders.

Alternatively, a simple manual system, such as a whiteboard, may be used. This form of schedule is simple, flexible, and inexpensive. In addition, it does not require that other resources, such as computers, be free. This is important as it is necessary to have easy access to such information when responding to customer enquiries.

7.2.2.8 Generation of Assembly Support Information

The purpose of the assembly support information is threefold: it must be sufficient to control equipment, it must simplify the assembly process, and it must be sufficient to provide a suitable interface between the technical systems and the assembler.

Each is considered in turn.

The information required for the control of the technical elements of the system is minimal. For each component, there must be information describing which workstation it is located at, and which bin in the workstation.

The basic approach to PCB assembly, namely, the automatic presentation of the components, and guidance for the assembler on the exact location of the component, is itself a simplification of the assembly process, since the assembler is not required to search for components, or to search unaided for the position the component occupies on the PCB.

There is, however, an additional simplification that may be achieved by building a degree of "intelligence" into the CAS system. By including component-specific data in the CAS Database, it becomes possible to structure the order of assembly about specific factors. Factors to consider include:

- component height: it is advantageous to insert short components before tall components, and to solder components of a similar height simultaneously,
- fragility: it is advantageous to insert and solder fragile components last, and
- lead length: it is advantageous to insert and solder all components with short leads first.

While a predetermined assembly order may impose restrictions over the assembly process, it may also provide a consistent and methodical approach to assembly. This is not provided with conventional assembly methods where it is up to each assembler to determine what assembly method to use for each new product. While this is not a major problem where product variety is low, it becomes increasingly irritating as variety increases and product volumes decrease. This problem intensifies with increasing product size or complexity.

The interface between the technical system and the assembler may be provided by a graphic prompting system. This prompting system would make use of the graphic overlay data produced by CAD packages for plotters. This data, which defines the outline of the PCB and of each component, is expressed in HPGL instructions and coordinates, but must be filtered for two reasons:

- to eliminate unnecessary information, and
- to convert the data into instructions and coordinates for use by the graphics system of the

computer programming language in which the prompting system is written.

These elements are essential especially for large, complex PCBs where the computer may frequently re-draw the image of the PCB during assembly. Minimising computer processing time during re-drawing ensures that the system is not perceived as being sluggish.

The system has the potential to inform the assembler of a variety of information, which is either component specific, such as polarity, or product specific, such as recommendations of when to solder components.

The purpose of a computer assisted assembly system would be to improve product quality, to reduce assembly time, and to reduce the learning time for users who are unfamiliar with PCB assembly. These goals are consistent with the overall objectives of the MPP, such as high product quality, and a short assembly time.

7.2.2.9 Production of the Bare Board

Detailed discussion of the production of the bare board is beyond the scope of this discussion, however, since it is a crucial part of the MPP several comments may be made:

- processes such as the drilling of holes may be computer controlled, and driven by the design data, however, this will require information additional to that described in Section 7.2.2.4 (pp.112-113),
- the production of the bare board is represented in Figure 7-2 (p.110) as a single process, but in reality consists of many stages,
- the number of different materials required by the Wet Line is small, and control of these materials may be served more adequately by a unique, but linked database rather than the CAS Database, and
- the time required to produce the bare board is a function of the size and number of boards produced, and is therefore easy to determine for estimation and scheduling purposes.

7.2.2.10 Assembly

The assembly process should be divided into 4 stages. Each stage will involve the placement, or insertion of similar types of components. This approach allows each workstation to be tailored to the requirements of the component grouping.

(i) Stage 1: Surface Mount Components

This stage will involve the placement of surface mount components, using a computer assisted

Assembly Workstation.

Following placement, the components should be soldered in place with an infra-red reflow machine.

Each product must be inspected by the assembler for substandard work, including mis-placed, crooked, or poorly soldered components.

(ii) Stage 2: Small Through-Hole Components

This stage will involve the insertion of small, through-hole components, such as resistors, small capacitors, and diodes, using a computer assisted Assembly Workstation.

Following insertion, the components should be manually soldered, after which the leads may be clipped short.

Each product must be inspected by the assembler for substandard work.

(iii) Stage 3: Large Through-Hole Components

This stage will involve the insertion of larger, through-hole components, such as large capacitors, integrated circuits, and switches, using a computer assisted Assembly Workstation.

Following insertion, the components should be manually soldered and the leads clipped short.

Each product must be inspected by the assembler for substandard work.

(iv) Stage 4: Uncommon Components

This stage will involve the addition of uncommon components, but is not computer assisted. Three reasons account for this:

- uncommon components may not be registered in the CAS Database,
- the allocation of very large components to a workstation may not be justified since the number which fit may be small, and
- some components, such as battery clips, can not be inserted with automatic insertion machines. Consequently, the component location data is not included in the design data.

These components should also be manually soldered.

While all products follow the same path through each of the stages, not all will require assembly at every stage.

Although tasks such as lead clipping, and checking for crooked components may seem trivial, it is necessary to perform them carefully, since the visual appearance of the product ultimately reflects the attitude of the assembler to the customer. Consequently, attention to detail helps to portray an accurate image of a professional, top-class service, which provides high quality products.

This may be achieved through the training of the assembler in the objectives of the MPP. For example, rapid response must be interpreted by the assemblers as being efficient, non-wasteful, well-managed work, rather than hasty, careless work.

7.2.2.11 Updating the CAS Database

The timing of the update of the CAS Database will depend on the type of process that generated the stock usage data. Data resulting from inward goods, miscellaneous stock usage, stock transfers, or stock take, to be discussed in Section 7.2.3.1 (pp.120-121), must be transmitted back to the CAS Database with minimum delays to ensure that subsequent calculations involving the CAS Database are correct. Data resulting from assembly operations, however, will not require immediate transmission to the allocated-stock database, since the stock has been allocated and is no longer associated with the CAS Database. One of the benefits of this approach will be that the number of transactions is kept to a minimum.

For simplicity, the format of stock usage files should be identical for all processes involving stock movement, however, the system must be able to distinguish between the different types of files so that the correct database is updated.

7.2.2.12 Testing

The thoroughness of this operation will be dependent on:

- the degree of information provided with the design data regarding expected performance of the product, and
- the level of skill and understanding of the tester.

For the testing operation to be successful it is essential that the tester understand that testing is not simply about checking whether a particular product functions correctly. The tester must recognise that defects may arise from poor design, in which case similar products may exhibit similar problems; or may arise from the production processes, in which case similar features or elements of different products may exhibit a specific problem. Under this approach, data collected during testing may be examined, and provide significant benefits for the MPP. In particular:

- data concerning defects may be used as the basis for the improvement of in-house design and production processes, and
- data concerning excellence allows a library of "best practice" to be established.

In addition, non-confrontational liaison with designers, where design is done externally to the MPP, may allow the MPP to recommend certain design practices, or to suggest alternatives for others, to improve future production or product quality.

Product-dependent data will be most use in the short term: while the product is still in production.

Process-dependent data, while equally important, will be of most use in the long term, since it is used for gaining a quantitative perspective on the performance of design and production operations. It will allow trends to be revealed, and will point to areas requiring improvement. It will also assist in identifying whether previous changes (frequently loosely termed "improvements") have produced any real benefits.

While it is possible to construct a simple manual system for the recording of defect data, such a system may not be as well disposed to thorough analysis as a computer-based system. A computer-based system must be product-oriented for data entry and on-line analysis of a specific product, but must also be non product-oriented for general analysis. This may be achieved by generating a database for individual products or orders, and creating a temporary database into which all product databases may be merged for analysis purposes.

7.2.2.13 Planning Delivery

With regard to delivery, one of two events may take place: either the customer will arrange for the collection of the order, or the MPP will make such arrangements.

In each case, the MPP must organise the timing of the collection to minimise the delay between the completion of production and collection.

Since the product must arrive in the same condition as when it left the MPP, it must be packaged to eliminate handling damage. The ideal packaging would consist of a tough exterior material, and a softer, supportive inner material.

Delivery services must be found who operate according to similar objectives as the MPP.

7.2.2.14 Contacting the Customer

Contact with the customer must be considered a priority. Specifically, contacting the customer when the order is almost complete is essential, as it allows the customer to make preparations for the anticipated delivery of the order. While such an activity has no effect on the real lead time or on the product itself, it affects the perceived lead time since the customer has knowledge based on facts of the progress of the order.

Such a service elevates the perception the customer has of the MPP if such a service is not normally provided.

Equally importantly, if the promised delivery date can not be met, the customer must be contacted promptly and informed of the delay. Also, if a promise is made to contact the customer, it must be carried out. Customer loyalty can not be generated or sustained if the MPP has a casual approach to customers.

7.2.2.15 Billing

The billing process may be considered as part of the on-line processes, where the invoice would be produced immediately, and would accompany the product.

An alternative method would be to convert it into an off-line process, and send the invoice at a later date.

In the case where a quotation has been provided, the quotation may also serve as the invoice.

In the case where a quotation has not been provided, the invoice may be generated in the same manner as the quotation, except that:

- actual figures would be used for labour costs rather than estimates, and
- the presentation, or format would differ.

7.2.2.16 Shipment

While the handing over of the product to the deliverer is a straight forward operation, it is nevertheless important to carry this operation out in a manner consistent with all other stages of design and production. The deliverer must be provided with clear, detailed instructions on the destination, and, where advantageous, the name of the recipient.

In addition, the details of payment of the deliverer must be established at the outset to avoid confusion and conflict.

7.2.3 Detailed Design: Off-Line Processes

The discussion in this section is based on Figure 7-3 (p.121). This figure is a basic model, and is comprised only of major features.

7.2.3.1 Off-Line Stock Transfers

Off-line stock transfers involve the transfer of stock into, out of, or within the CAS system; and the recording of details about such transfers. Included in this group are: inward goods,

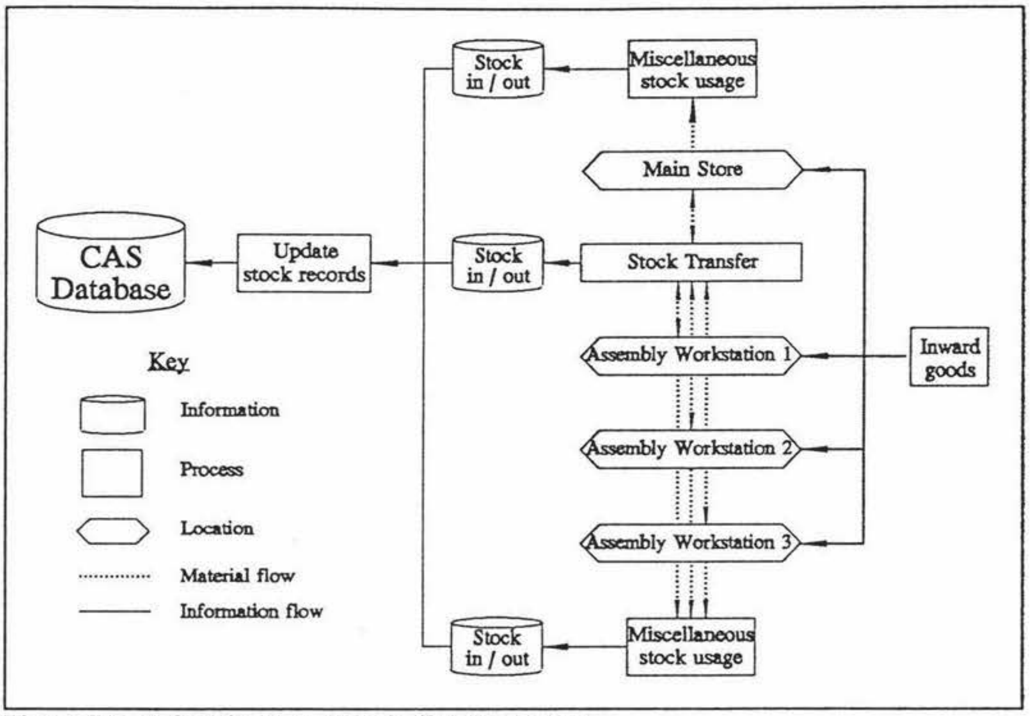

Figure 7-3 A functional model of off-line processes

miscellaneous stock usage, the transfer of stock from the Main Store to the workstations, and the less usual case of the transfer of stock from a workstation back to the Main Store. In addition, this facility must provide for stock take procedures.

For total, integrated stock control it is necessary to locate a PC at the Main Store enabling automatic recording of stock withdrawals and deposits.

With this type of system, the user may focus on the task of withdrawing and/or depositing components, without being concerned with the recording of the transaction details.

7.2.3.2 Income and Expenditure

A computer-based accounting system may be developed which is linked to the scheduling, estimation, and billing procedures. The key feature of such a system is that it be well managed, or, more specifically, that customers are billed appropriately, and that suppliers are paid on time. An alternative system would be a simple manual system.

7.3 Stage 6: Implement the Design

The sixth stage of the GDM is to implement the design. This section details the progress of the development of the CAS system to date.

While the system is not yet complete, those elements that do exist allow the system to function as a computer assisted, manual assembly system.

Figure 7-4 (p.123) represents the closed-loop, on-line part of the CAS system. It represents the processes that currently exist, and the order in which they are implemented for a typical customer order.

Appendix A (pp.170-174) provides an in-depth discussion of:

- the structure of the CAS Database,
- the significance of file names and extensions,
- the configuration file, and
- the standard format for data files.

7.3.1 The CAS Database

The CAS Database provides the vital information link between design and production. Specifically, it enables design data to be used to generate assembly "instructions", referred to as assembly support information.

The database contains one record for every component. The data fields include:

- 3 identification descriptions,
- the workstation location number,
- 3 workstation addresses to identify the exact bin location,
- the quantity on-hand, reorder level, and reorder quantity for the workstation,
- the quantity on-hand, reorder level, and reorder quantity for the Main Store, and
- the polarity, cost, height, and fragility of the component.

7.3.2 Graphic Overlay Data Filter

Location: CAS Master

Filename: BUILDOVL.EXE

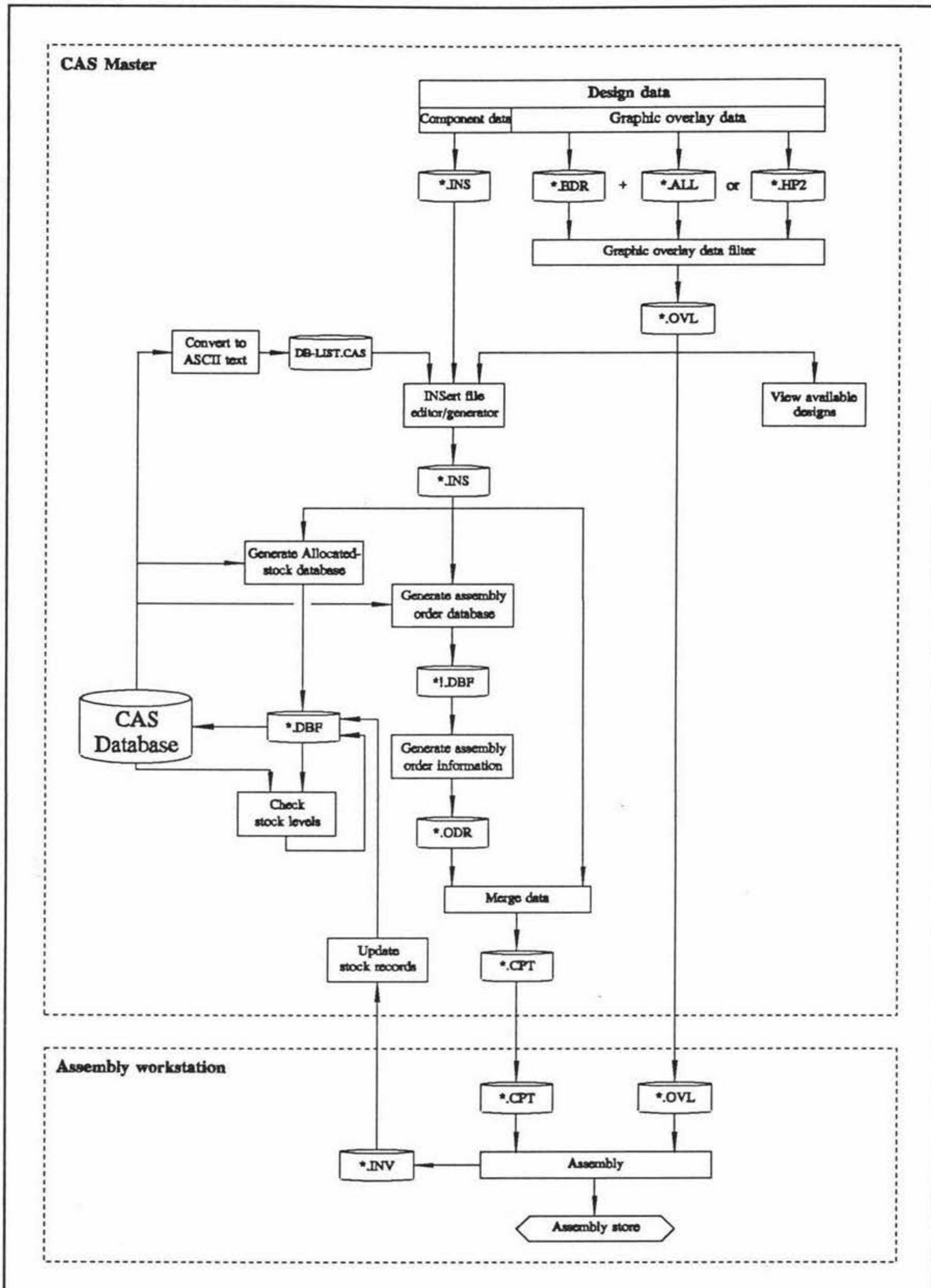

Figure 7-4 The implementation of on-line processes

Language: Turbo Pascal

Input files: <PCB>.BDR and <PCB>.MAP, or <PCB>.HP2

Output file: <PCB>.OVL

The first operation involves the conversion of the raw graphic design data produced by the CAD package. This data must be automatically converted from HPGL instructions and coordinates into instructions and coordinates for use by Turbo Pascal graphics procedures. The converted data provides the image of the PCB for the assembly prompting system. The prompting system is a fundamental element of the CAS system, therefore, the conversion system must be robust, and able to cope with variation.

Appendix B (pp.175-178) provides an in-depth discussion of:

- the operation of the filter,
- commonly used HPGL instructions,
- graphics procedures available in Turbo Pascal, and
- the characteristics of the output file produced by the filter.

7.3.2.1 Functional Properties of the Filter

The filter is designed to perform four key tasks.

(i) Task 1: Offset Data to New Origin

The filter must identify the location of the origin of the data, typically at the lower left corner of the board. The X-coordinate of the origin must then be subtracted from all other X-coordinates, while the Y-coordinate of the origin must then be subtracted from all other Y-coordinates. This is to ensure that all coordinate values are positive.

(ii) Task 2: Scale Data

Having made the adjustment to the new origin location, the filter must multiply all data by a scaling factor, equal to 1/1.016, to convert the scale from HPGL plotter units to thousandth of an inch (mils). This is necessary since the unit of measure used in the <PCB>.INS file, which details component locations, is mils.

Because the factor is close to 1, the effect of scaling on resolution is minimal.

(iii) Task 3: Identify and Interpret HPGL Instructions

This is the key task. It involves identifying relevant HPGL instructions, and converting them for use by Turbo Pascal graphics procedures. The conversion process reduces the graphic information to lines and arcs.

Although the entire conversion process is discussed in Appendix B (pp.175-178), an overview will be provided in this section.

In Turbo Pascal, three graphics procedures are utilised:

- *lineto*(X,Y),
- *moveto*(X,Y), and
- *arc*(X,Y,Θ_1,Θ_2,R).

The output file consists of pairs of 32-bit integers, which are coded to communicate the associated Turbo Pascal procedure. The code is based on combinations of positive and negative numbers on the X and Y coordinates, where:

- *lineto* is identified by the combination +X,+Y,
- *moveto* is identified by the combination -X,+Y, and
- *arc* is identified by the combination +X,-Y. The X,Y coordinates are followed by two integer pairs, consisting of: the two angles, the radius, and a padding number.

(iv) Task 4: Identify Border Data

To present a realistic graphic image of the PCB to the user, the outline of the PCB is drawn first, then the board is coloured dark green. Finally, the components are displayed (please refer to Exhibit 7-4 (p.139)).

Two methods exist for identifying the border data.

In the first method, the border data is distinguished from the remaining data because of particular characteristics of the input file(s).

One of two options may be used with this method:

- Option 1: two data files are used, with the border data in one file (<PCB>.BDR), and the remaining data in another file (<PCB>.MAP).
- Option 2: only one data file is used (<PCB>.HP2). The border data appears first, followed by the remaining data. The two sets of data are separated by "PG;".

A second method exists for identifying the border data, however, this is achieved by modifying the output file, and is discussed in Section 7.3.3 (pp.125-126).

7.3.3 Graphic Overlay Viewer / Editor

Location: CAS Master

Filename: FINDBRDR.EXE

Language: Turbo Pascal

Input files: <PCB>.OVL

Output file: <PCB>.OVL

This operation is automatically implemented immediately after the graphic overlay data filter. This system will perform one of two actions. If the border data is distinguishable from the remaining data, the system will display the complete PCB. Otherwise the system will allow the user to identify the border, and will then display the complete PCB. Each is considered below.

7.3.3.1 Graphic Overlay Viewer

If the border data is distinguishable from the remaining data, the system will display the complete PCB with a dark green background.

7.3.3.2 Graphic Overlay Editor

If the border data is not distinguishable from the remaining data, the system will sequentially implement each instruction in the <PCB>.OVL file under the control of the user. Typically, the border data is located at the beginning of the file. Consequently, the user advances through the file until the complete border is drawn on the screen. At this point the user confirms the existence of the border. The editor then colours the area inside the border dark green, draws the remaining overlay data, and rewrites the <PCB>.OVL file, including a -1,-1 in the file at the correct place.

7.3.4 INSert File Editor / Generator

Location: CAS Master

Filename: BUILDINS.EXE

Language: Turbo Pascal

Input files: <PCB>.INS (optional), <PCB>.OVL and DB-LIST.CAS

Output file: <PCB>.INS

The second operation, which in some cases may be by-passed, involves generating or editing the information regarding the identification and location of any or all components. This system will not be required if the CAD package is able to produce the appropriate data in a format recognisable to the CAS system. This is one of the few operations requiring manual data entry.

It is therefore potentially error prone and time consuming. The system includes facilities, however, that will minimise the process time, and the occurrence of errors.

The editor is a mouse-driven system allowing the user to select known or unknown components and to enter or modify data regarding the identification or location of the component.
A graphic representation of the PCB, produced from the data generated by the graphic overlay data filter, is presented to the user. This is shown in Exhibit 7-1 (p.128).

Appendix C (pp.179-182) provides an in-depth discussion of:

- the operation of the editor,
- the characteristics of the <PCB>.INS file, and
- the magnification and navigation facilities,

The editor offers several features, which are discussed in Section 7.3.4.1 (pp.127-130), and may be operated in two modes, which are discussed in Section 7.3.4.2 (pp.130-131). In this way, the editor provides flexibility, and the ability to perform well in different circumstances.

7.3.4.1 Functional Properties of the Editor

The key features of the editor are: access to a listing of the CAS Database, and total control of the editor through the mouse.

(i) Database Listing

When entering or modifying the descriptions of a specific component, the user may select a component from a pop-up pick-list displaying the description fields of all components in the CAS Database. The key benefits of this are that it is less time consuming, and the incidence of data entry errors is reduced. Once the user has become proficient with the system, the time spent using the system will be short.

The pick-list includes a search facility, whereby the user types in a letter or group of letters, and the editor searches for and displays the first component for which the first letters of the first description field match the letters typed by the user.
The pick-list is shown in Exhibit 7-1 (p.128).

(ii) Mouse Control

When the graphic image of the PCB is displayed, the editor is fully controllable with the mouse. Components on the PCB may be selected using the mouse in a number of ways.

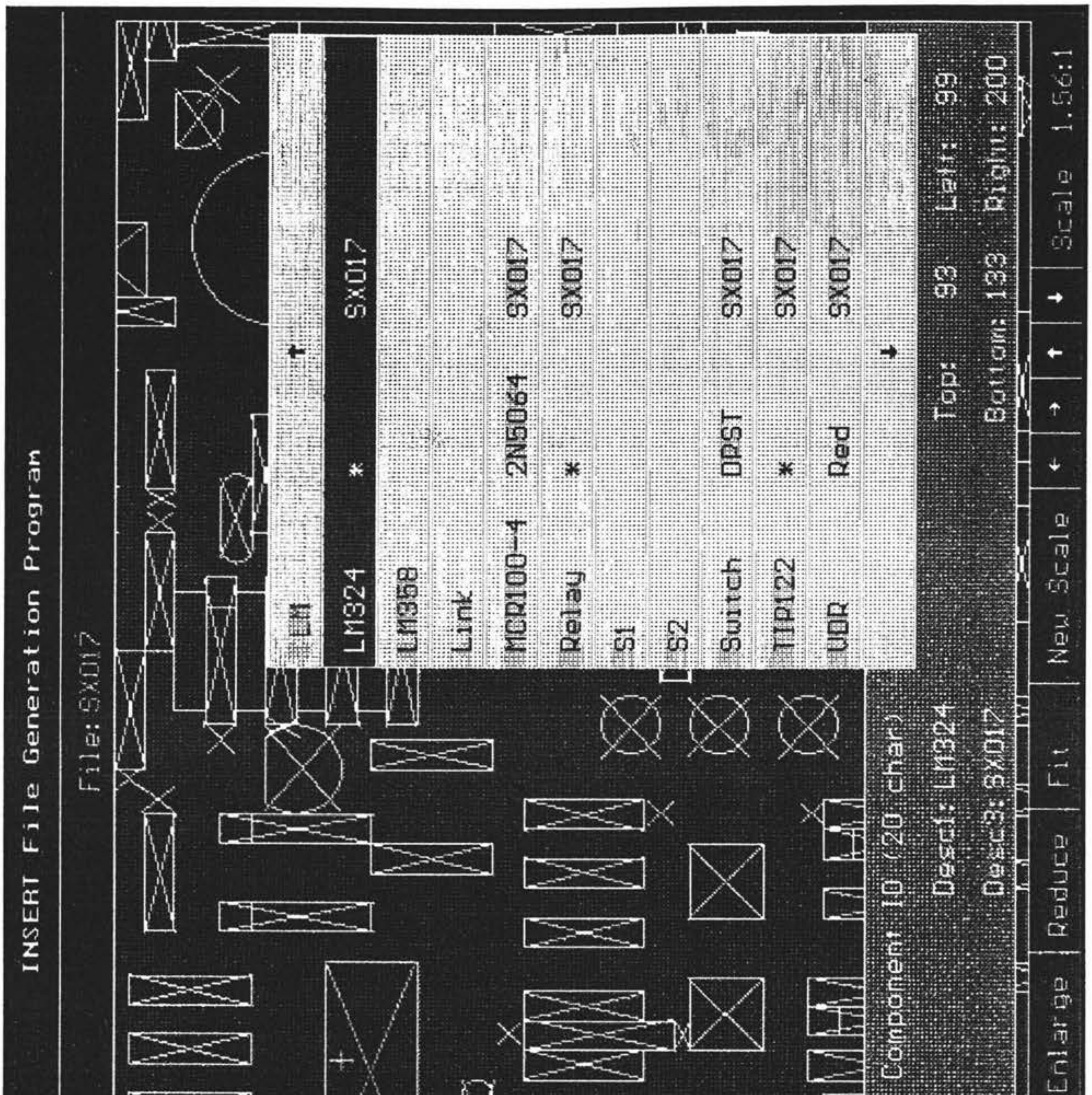

Exhibit 7-1 <PCB>.INS file editor

Consider first the functions of the left button.

Components on the graphic overlay that are not listed in the <PCB>.INS file may be selected by positioning the mouse cursor within the bounds of the component and pressing the left button. From that position on the screen, the editor searches for the boundaries of the component. When all four boundaries have been located, a box is drawn around the component. If the box envelops the component to the satisfaction of the user, the user may press the left button again, or the enter key to confirm the component boundary. If not, the user may press the right button, or the escape key. A situation requiring care is that involving round components. In this case, the user must locate the mouse cursor close to the centre of the component.

The editor has a built-in safety device. If the user attempts to select a component that is not fully within the viewing window, the boundary search performed by the editor will fail.

This method may not be considered appropriate, however, for polarised components such as diodes, where there is an extra band at the cathode end. In such cases an alternative method is required. The solution involves the right mouse button and is discussed below.

Existing components may be identified simply by pressing the left button while the mouse cursor is within the bounds of the component. The editor searches through the data detailing the component boundaries until one is found that encloses the mouse cursor.

Consider also the function of the right mouse button.

The right button allows the user to identify new components and features that are not on the graphic overlay, or listed in the <PCB>.INS file. To achieve this, the user must position the mouse cursor at one corner of the component or feature and press the right button. A box appears with one corner fixed at where the right button was pressed, and the diagonally opposite corner at the mouse cursor. As the mouse cursor is moved, the box is continually re-drawn. The user then moves the mouse cursor until the correct shape is achieved and then presses the left button. The user-defined box may be discontinued either by pressing the right button again, or the escape key.

It is advantageous to enlarge the image of the PCB such that individual components occupy a significant proportion of the viewing window. This is because the editor reverse-scales the coordinate data from pixel units (typically in the region of 65 units per inch) to mils (one thousand units per inch). Consequently, greater accuracy is achieved with a large image size.

(iii) Edit-Able Data

The items of data associated with a particular component that may be edited are:

- the reference description,
- the three identification descriptions, and

- the left and right, and upper and lower boundary coordinates.

7.3.4.2 Modes of Operation

The editor may be operated in two modes: the random selection mode, and the step-through mode.

The random selection mode allows any new or existing component to be selected for the entry or modification of data.

The step-through mode allows all known components to be highlighted sequentially, simultaneously displaying the data associated with the component. This allows the user to check that the data for each component is correct.

(i) Mode 1: Random Selection

This is the default, or normal mode of operation. In this mode all existing components are highlighted with a yellow "X", as in Exhibit 7-1 (p.128).

The user has three options available.

Option 1: selecting a new component. A new component may be selected either by using the left or right mouse button. A listing of the database is then displayed, allowing the user to select component descriptions. If the correct component is not listed, the user may press escape and enter the data manually. If auto-referencing, discussed in Appendix C1 (p.179), is disabled, the user will also be required to enter a reference description.

Option 2: selecting an existing component, as shown in Exhibit 7-1 (p.128). If the user presses the left mouse button while the mouse cursor is situated within the bounds of a known component, a dialogue box will appear at the bottom of the screen showing all edit-able data, and the selected component will be highlighted with a light green "X". The user may then edit any of the fields, or, by pressing the left button inside the dialogue box, may invoke the database listing. This allows the description fields to be modified with a minimum of manual data entry.

Option 3: invoking Mode 2 operation. This may be achieved by pressing F10, or the "+" or "-" key.

(ii) Mode 2: Step-Through

In this mode, there is always one "current component" that is highlighted with a light green "X". Preceding components, that is, those between the first component in the list and the current component, are highlighted with a yellow "X". Subsequent components are not highlighted.

If this mode is invoked by the F10 or "+" key, the current component will be the first component in the list of known components, and will be the only component highlighted. If this mode is invoked by the "-" key, the current component will be the last component in the list of known components. It will be highlighted by a light green "X", while all other known components will be highlighted with a yellow "X".

In addition to the light green highlight, an information box is displayed at the bottom of the screen displaying the reference description and three descriptions of the component.

As in mode 1, the user has three options available.

Option 1: stepping through each component sequentially. The user may press either the "+" or "-" key to step through the list of known components, where the "+" key advances through the list, and the "-" key steps backwards through the list. While stepping through the list, the current component is always highlighted with a light green "X", while the preceding components are highlighted with a yellow "X".

The current part may be edited by pressing the left button while the mouse cursor is within the bounds of the current component, or by pressing enter.

Option 2: jumping to a specific component. At any point during the step-through process, the user may position the mouse cursor within the bounds of an existing component and press the left button. This option is similar to Option 2 in Mode 1, since the editor will highlight the newly selected component with a light green "X" and will display the dialogue box, allowing the user to edit the information, and, if required, to invoke the database listing. Once edited, the selected component becomes the current component, and those components that were skipped are highlighted with a yellow "X".

Option 3: returning to Mode 1 operation. This may be achieved by pressing escape.

This mode requires an additional capability. While stepping through the components, it is likely that there will be instances where the next component to be highlighted is not presently visible to the user. When this situation is encountered, and the "+" or "-" key is pressed, the editor re-draws the PCB such that the next component appears in the middle of the screen.

7.3.5 Setting an Order in Progress

Location: CAS Master

Filename: CASMAIN.EXE

Language: Clipper

The third operation is fundamental in terms of the objective of achieving a responsive, computer integrated system. It is the critical link in which the design data is transformed into assembly "instructions".

This operation is split into a number of procedures performed consecutively.

Appendix D (pp.183-191), in particular Appendix D2.2 (pp.186-188), provides an in-depth discussion of the operation of this program.

This program allows the user to set a new product into production. Through the Assembly Planning System, the user may select a <PCB>.INS file, enter the order quantity, the description of the product, and the due date, and add it to the list of WIP. When this is done, the program performs two procedures: it determines the impact the order has on stock levels (Section 7.3.5.1 (pp.132-134)), and it generates the assembly support information (Section 7.3.5.2 (pp.134-135)).

Before considering these two functions it is necessary to introduce two product-specific databases.

The program creates two special purpose databases: one for the stock level checking and allocation procedure, referred to as the allocated-stock database, and one for the generation of assembly support information, referred to as the assembly order database.

The Allocated-Stock database contains one record for every *different* component in the <PCB>.INS file. It details how many of each type of component there are on a single PCB, the total number required for the order, and the impact the order has on stock levels. Stock is allocated to the order by being "removed" from the CAS Database.

This database includes a "Status" field. If there are sufficient components at the workstation to complete the order, this field is set to true for the component. If some action is required *before* assembly can begin, such as the purchase or transfer of components, this field is set to false.

The structure of the database is given in Table D-3, Appendix D2.2(ii) (p.188).

The Assembly Order database contains one record for *every* component in the <PCB>.INS file. It is used for the generation of the <PCB>.ODR file.

The structure of the database is given in Table D-2, Appendix D2.2(i) (p.187).

7.3.5.1 Stock Level Checking and Allocation Procedure

Input files: PARTS.DBF and <PCB>.DBF

Output file: <PCB>.DBF

The stock level checking and allocation system is an automated process designed to determine what measures must be taken, if any, to ensure that:

- the production system is able to complete the new order, and
- the production system will be able to complete subsequent orders.

Consequently, action can be taken to keep the supply of components in a perpetual state of readiness.

(i) Functional Properties of the System

The stock analysis system operates on the allocated-stock database, and performs the following tasks for each component in the database.

Task 1: Find Component Match

The first task is to match the component in the allocated-stock database to a component in the CAS Database.

If a match is not found, the Exception field is set to true, and the Status field is set to false.

If a match is found, the program continues by checking stock levels.

Task 2: Check Stock Levels

The next task is to check stock levels, and to allocate stock to the order. This task is comprised of several steps.

The first step is do determine whether there are sufficient components at the workstation to complete the order. If there are, the Status field is set to true, otherwise it is set to false.

Then the required quantity of components are "removed" from the CAS Database.

Finally, stock level checking begins. If the workstation store quantity (StnQty) is below the workstation reorder level (StnROL), a quantity equal to the workstation reorder quantity (StnROQ) must be transferred from the Main Store to the workstation. Consequently, the Transfer field is set equal to the workstation reorder quantity.

Next, the Main Store level (StoreQty) is checked. If the Main Store level minus the transfer quantity is below the purchase reorder level (PurchROL), a quantity of components equal to the purchase reorder quantity (PurchROQ) must be purchased. Consequently, the Purchase field is set equal to the purchase reorder quantity.

While this type of stock control system is simple, it allows a flexible stock system to be created. Consider first, common, or low value components. The Main Store quantity, and purchase reorder quantity may both be set high to ensure that stockouts are avoided. This type of stock control would emulate the traditional reorder point stock control system in which a supply of components is always on-hand.

Consider also, rarely used components. The Main Store quantity and purchase reorder quantity may be set very low. This type of stock control, while still a reorder point system, would, to a degree, emulate the more modern just-in-time stock control system in which components are ordered only as required.

Clearly, other factors must be considered when setting the Main Store and workstation stock and reorder levels, such as: delivery lead times, component costs, transport costs, and the size of the workstation storage bin.

Task 3: Inform User of Results

The program then generates a report that lists those components which: are not recognised, require transfer, or require purchasing. In addition, the Status field is listed for each component. If components must be purchased or transferred from the Main Store to a workstation *before* assembly can begin, the Status field displays "Problem", otherwise it is left blank. This immediate feedback provides the user with a complete picture of the present capability of the production system. The user is informed of critical stock shortages, and is able to take action to obtain this stock promptly, but is able to delay action to obtain non-critical stock until assembly is complete, or until a suitable opportunity arises. Consequently, the assembly lead time is not lengthened unnecessarily.

A printout of this report may also be obtained.

7.3.5.2 Assembly Order Information Generation Procedure

Input files: <PCB>!.DBF

Output file: <PCB>.ODR

The assembly order information generation system is an automated process designed to generate the production "instructions", or assembly support information. This is a simple but critical step in which the order of assembly is determined. This feature of the CAS system is very important as it eliminates the need for the assembler to devise a new order of assembly for each new product. This feature is of most use where product variety is high, as in the CAS system, as it reduces the difficulties normally associated with the introduction of new products into production.

Appendix E (p.192) contains a sample of the output file.

(i) Functional Properties of the System

The assembly order information generation system performs two tasks.

Task 1: Assembly Order Determination

The first task involves determining the order in which the PCB is assembled.

At present, the order of assembly is determined on the basis of: workstation number, component height, component fragility, and the workstation addresses. The workstation addresses are included so that, in the case where a series of components are to be inserted with equal height and fragility, the movement of the presentation system is optimised.

Task 2: Output File Generation

Next, the assembly support information is generated. This information is produced as a text file containing the following information for each component:

- the component reference description,
- the workstation number,
- workstation addresses X, Y, and Z, and
- a polarity flag.

The assembly order file does not include components that were not recognised.

7.3.6 Merge Data

Location:	CAS Master
Filename:	BUILDCPT.EXE
Language:	Turbo Pascal
Input files:	<PCB>.INS and <PCB>.ODR
Output file:	<PCB>.CPT

The fourth operation is to merge the <PCB>.ODR and <PCB>.INS files. This is an automated process in which the assembly support information is combined with the design data to form a single file. This data, together with the processed graphic overlay data, is sufficient to drive the assembly system.

Appendix F (p.193) provides an in-depth discussion of the operation of the data merger.

7.3.6.1 Functional Properties of the Data Merger

The data merger performs the following task.

The system begins by reading the input files. The data for each component is stored in memory as a Turbo Pascal record, with multiple records forming a link-list. The <PCB>.ODR file is stored in a link-list of records containing all the data fields for both input files, referred to as the part list. The <PCB>.INS file, however, is stored in a link-list of records containing only the data fields of the insert file, referred to as the insert list.

The merging process begins with the first component in the part list. The program searches the insert list to find a matching reference description. When found, the part list fields are updated to include the data from the insert list. The program continues until all parts have been matched. If a match is not found, the program will stop, and report the error.

Finally, the output file is created. The output file is formatted as a file of records. The order of the records matches the order of components in the part list.

7.3.7 Production of the Bare Board

A detailed discussion of the processes required to produce the bare board are beyond the scope of this discussion.

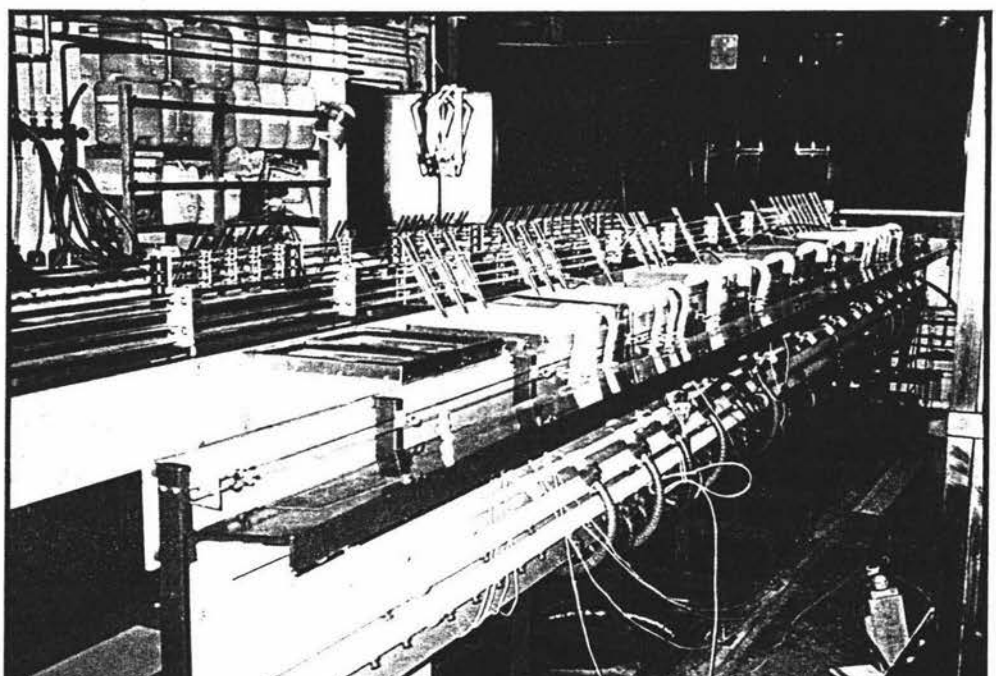

Exhibit 7-2 The Wet Line

The chemical processes of the Wet Line are shown in Exhibit 7-2 (p.136).

7.3.8 Assembly

Location:	Assembly Workstations
Filename:	ASSEMBLY.EXE
Language:	Turbo Pascal
Input files:	<PCB>.OVL and <PCB>.CPT
Output file:	<PCB>.INV

The fifth operation is assembly. This is the key value-adding step.

Assembly may begin if all required stock is available, the data processing operations were successful, and the production of the bare board is complete.

If the design data is complete, and in a recognisable format, the data processing operations that must be executed before assembly can begin are very rapid. For example, for a complex PCB with 435 components, the data processing is complete in approximately 1 minute.

The assembly system is the core of the CAS system. Combined with the other elements of the CAS system it provides a rapid response service, with short assembly times, and short setup or changeover times. Furthermore, it has the potential to improve product quality by increasing consistency and product "correctness". These are the primary objectives of the CAS system.

Appendix G (pp.194-195) provides an in-depth discussion of:

- the operation of the assembly system, including menu options, and
- the magnification facility.

The assembly system performs 3 operations:

- it presents to the user a graphic image of the product, and highlights the location of the component(s) to be inserted, as in Exhibit 7-4 (p.139),
- it activates the storage device to present the correct component to the user, and
- it keeps a record of stock usage.

7.3.8.1 The Stages of Assembly

The assembly process is broken into 4 key stages. These stages are for: surface mount components, small through hole components, large through hole components, and miscellaneous components.

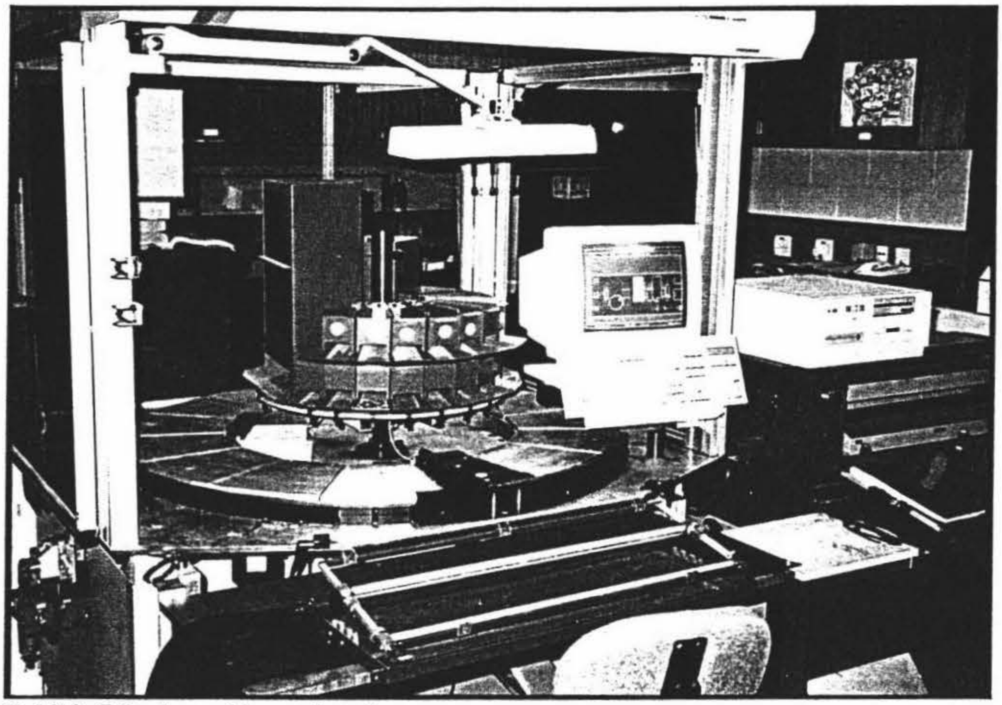

Exhibit 7-3 Assembly workstations

The Assembly Workstations are shown in Exhibit 7-3 (p.138). The Jacob's Ladder part presentation system (Stage 2) is partially shown on the right, and the ISM part presentation system (Stage 3) is shown on the left.

7.3.8.2 Functional Properties of the Assembly System

The assembly system embodies the following features.

(i) Basic Operation

The assembly prompting system is displayed in Exhibit 7-4 (p.139). The current component(s) to be inserted are highlighted as shown, and the component identification and workstation location is displayed at the bottom of the screen. Additional information provided includes the current magnification of the PCB, and the angle of rotation.

To acknowledge that a component, or group of components, has been inserted the user presses the space bar or the enter key.

To assist the insertion process, the program masks those components that have already been inserted. Components inserted at a previous workstation are masked with light green, while those already inserted at the current workstation are masked in yellow. This is shown in

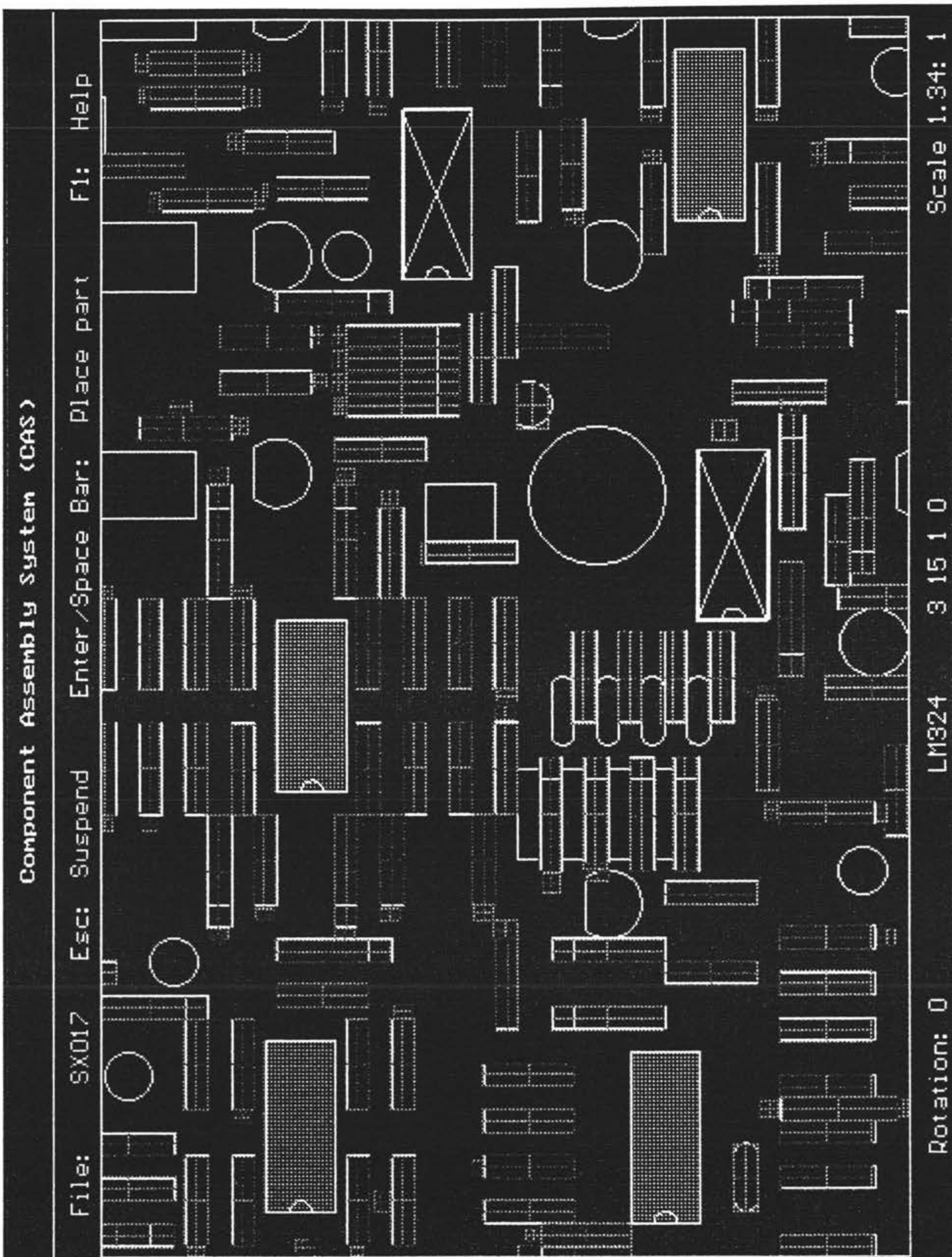

Exhibit 7-4 Assembly prompting system

Exhibit 7-4 (p.139).

(ii) Interpretation of Highlight Colours

To maximise system flexibility, the colour of the highlight can be changed to communicate additional information effectively.

At present, two colours are used:

- for polarised components, the highlight colour is light red, as in Exhibit 7-4 (p.139), while
- for non-polarised components, the highlight colour is yellow.

Highlighting polarised components in light red serves to remind the assembler to ensure that the component is correctly oriented.

An important feature of the highlight is that it must not obscure the features of the component shown in the graphic overlay data, such as the extra band at the cathode end of polarised components.

Although the possibility exists to increase the number of colours used, the danger in doing so is that too many colours will be used, and the meaning or significance of each will diminish, or be forgotten.

(iii) Multiple Components

In many instances, a single component will appear more than once on the PCB. Because of the procedures used for generating the assembly order file, these components are inserted consecutively. In such cases, it is frustrating to the user if the system highlights only one component at a time. This is overcome by highlighting up to 5 components simultaneously. This introduces a problem, namely, that of ensuring that all highlighted components are visible on the screen. The solution to this problem is discussed in Section 7.3.8.2(iv) (pp.140-141).

(iv) Re-Drawing, Auto-Centring, and Auto-Scaling

Consider first the case where only one component is to be inserted next. In this case, once the current component has been inserted, the system determines whether the entirety of the next component to be inserted is currently visible to the user. If not, the PCB is re-drawn such that the next component appears in the centre of the screen. This feature allows the user to magnify the PCB significantly to aid assembly.

In the case where more than one component is highlighted, the system must take a different approach. In this case the system calculates the size of the area enclosing all the components to be highlighted. The PCB will then be re-drawn such that the centre of the area enclosing the components is positioned at the centre of the screen. A special case exists, however, where the area enclosing the components is larger than the screen. In this case, the PCB will be reduced in size until all components can be displayed. Following the placement of the components, the system will return the PCB to the size it was previously. This is the case in Exhibit 7-4 (p.139).

(v) Rotation

This feature allows the graphic image of the PCB to be rotated clockwise or anti-clockwise in steps of 90° to match the orientation of the mounted PCB.

Rotation is accomplished by pressing the "+" key for anti-clockwise rotation, and the "-" key for clockwise rotation.

(vi) Recording of Stock Usage

As assembly progresses, a record is kept of the stock used, if this option has been enabled. With each placement, data is passed to an output file with the generic filename <PCB>.INV. The data is written to disk with each placement to ensure that hardware or power failures do not cause the loss of data.

Upon completion of assembly at each workstation the assembler is requested to advance the PCB(s) to a specified workstation for further assembly, or is informed that assembly is complete.

7.3.9 Stock Management

Location:	Main Store and Assembly Workstations
Filename:	STRCNTRL.EXE
Language:	Turbo Pascal

The stock management system is a generic system designed to operate at the Main Store and on all Assembly Workstations.

As the stock records are all computer-based, it is essential that a computer-based stock management system be designed, capable of performing all the functions required to maintain an effective stock system.

The system facilitates and records the results of the following modes of operation:

- stock transfers within the MPP,
- inward goods,
- miscellaneous stock usage, and
- stock take.

Appendix H (pp.196-198) provides an in-depth discussion of:

- the operation of the stock management system, including the screen format for each mode of operation,
- the facility for manual control of the storage device, and
- the contents of output files.

7.3.9.1 Component Pick-List

In each of the modes of operation, the user is presented with a pick-list of components at the current workstation location. The pick-list consists of one line per component, with the component descriptions, and other data, depending on the mode of operation. The user navigates about the list to select the required component, and enters the data required. In each mode, only one number, a positive number, is required. The number entered may always be positive since the mode of operation determines whether stock is deposited or withdrawn. Consequently, the system alters the sign of the transaction quantity accordingly, freeing the user from the concern of whether the stock is in-coming or out-going.

The primary benefits of this system are that:

- the user has easy access to the components, and
- the user is required to enter only a single, positive number.

7.3.9.2 Stock Transfer Between Stores

Input files: DB-LIST.CAS, *.INV, *.STK and *.TRN

Output files: *.STK and *.TRN

This mode facilitates the transfer of stock from the Main Store to a workstation, or from a workstation back to the Main Store.

This mode is illustrated in Figure 7-5 (p.143).

Whether this mode involves transfer of stock from the Main Store to a workstation, or the reverse, the procedure is essentially the same.

Consider the case where stock is transferred from the Main Store to a workstation.

Having selected a component from the pick-list, the details of which are discussed in Appendix H1.1 (p.197), the user is prompted to enter the quantity of components removed from the store. This process is repeated for each component requiring transfer.

At the completion of this exercise, the program generates a single MAIN2STN.TRN file.

At the destination, the user again selects the first entry of the menu, but in this case is presented

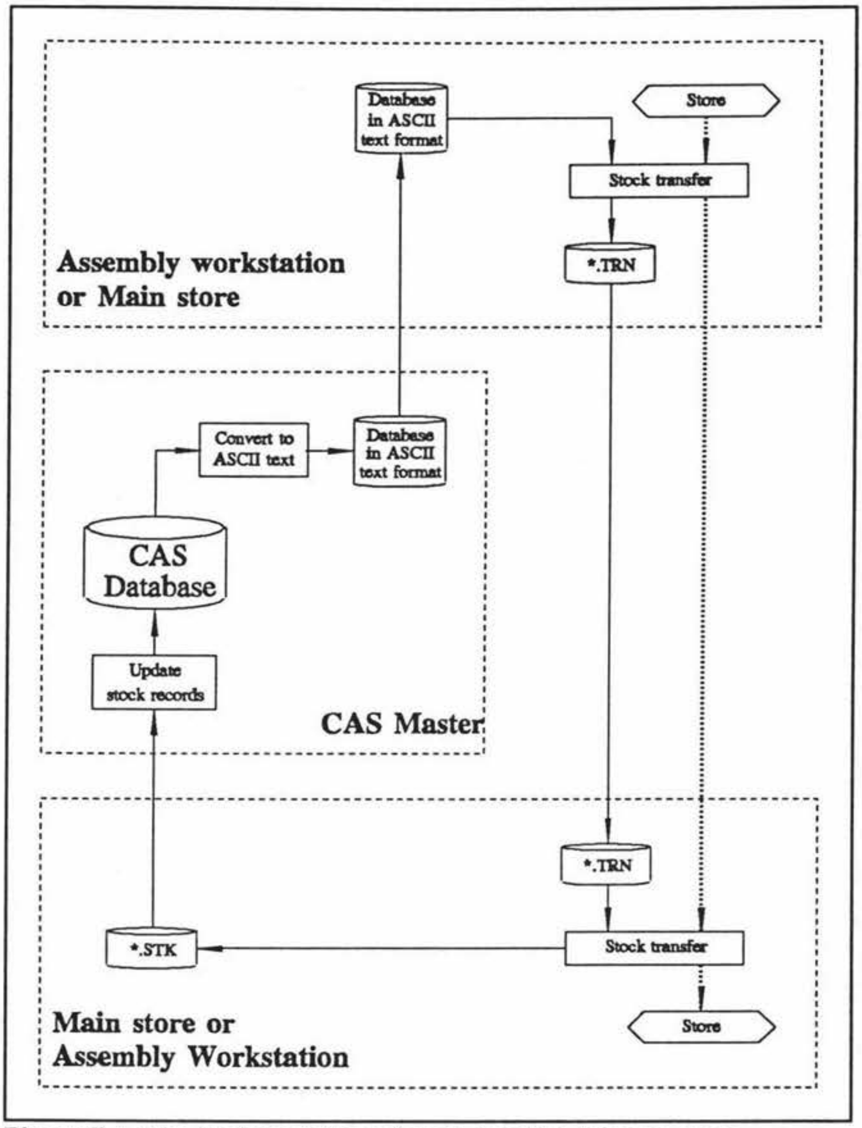

Figure 7-5 The implementation of stock transfers between stores

with a pick-list consisting only of those components listed in the MAIN2STN.TRN file that are located at the workstation to which the components are being transferred. The user selects each component from the pick-list and either confirms that the correct quantity of components is deposited, or enters the actual quantity deposited.

At the conclusion of this process a *.STK file is generated which treats the stock that has been deposited as inward goods. In this way, the stock transaction is reported only once to the CAS Database. If all the components in the file are added to the workstation in the correct quantity, the *.TRN file is deleted. If not, the file is re-created, containing only those components not added to the store.

In the case where components are transferred from a workstation to the Main Store, the user selects menu option 2, and the file detailing the transaction has the name STN2MAIN.TRN.

7.3.9.3 Inward Goods and Miscellaneous Stock Usage

Input files: DB-LIST.CAS, *.INV, and *.STK

Output file: *.STK

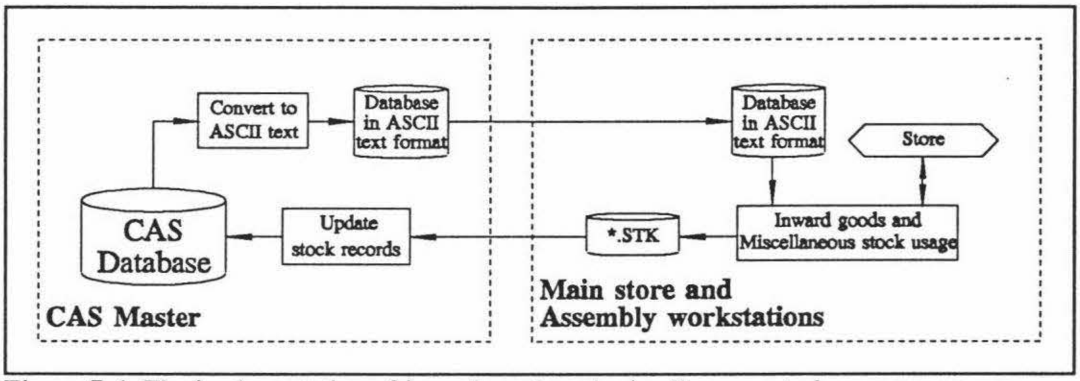

Figure 7-6 The implementation of inward goods and miscellaneous stock usage processes

This mode facilitates the deposit or withdrawal of stock from a store, but not including stock transferred between stores.

This mode is illustrated in Figure 7-6 (p.144).

Having selected a component from the pick-list, the details of which are discussed in Appendix H1.2 (p.197) and Appendix H1.3 (p.197), the user is prompted to enter the quantity of components deposited or withdrawn. This process is repeated for each component.

At the conclusion of the process a *.STK file is generated.

7.3.9.4 Stock Take

Input files: DB-LIST.CAS, *.INV, and *.STK

Output file: *.STK

This mode facilitates the update of the current stock on-hand levels.

This mode is illustrated in Figure 7-7 (p.145).

Having selected a component from the pick-list, the details of which are discussed in Appendix H1.4 (p.197), the user is prompted to enter the total number of components in the store. The system then calculates the difference between theoretical and actual stock levels. This process is repeated for each component for which the stock level is checked.

At the conclusion of the process a *.STK file is generated. Discrepancies between theoretical and actual stock levels are treated as positive or negative quantities.

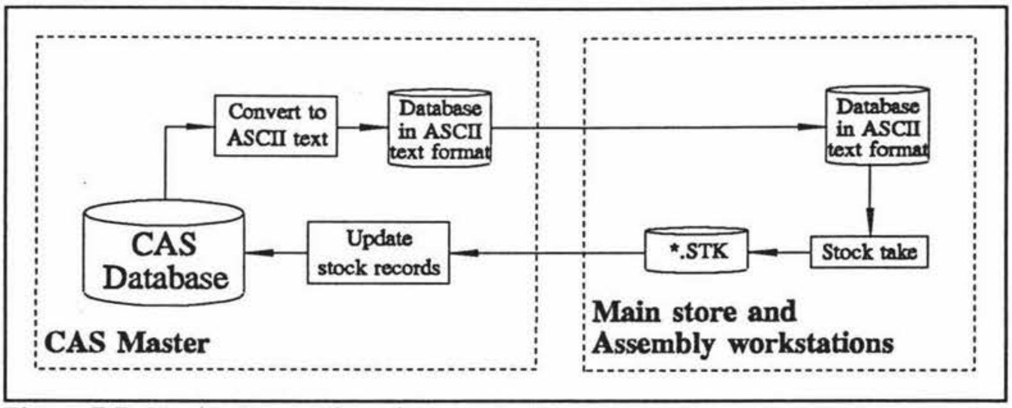

Figure 7-7 The implementation of stock take

7.3.10 Updating the Databases

Location: CAS Master

Filename: CASMAIN.EXE

Language: Clipper

Input files: PARTS.DBF and/or <PCB>.DBF, <PCB>.INV and *.STK

Output file: PARTS.DBF and/or <PCB>.DBF

The update of the database stock levels is a generic feedback system for stock transactions as well as for assembly operations.

This is possible since the two operations produce files with the same format, but different file name extensions.

The stock level update system is fully automated, and is not activated by the user. The system is embedded in CASMAIN.EXE, and is triggered when CASMAIN.EXE is activated. The system searches for *.STK and *.INV files, and updates the correct database as described below.

7.3.10.1 Updating the CAS Database

In this case, the system updates the CAS Database (PARTS.DBF), with the contents of the *.STK file(s) (please refer to Figure 7-5 (p.143)). The Main Store quantity (StoreQty) field and/or the workstation quantity fields (StnQty) are adjusted according to the quantity listed in the file.

The timing of this operation is critical since the validity of subsequent calculations involving the CAS Database is dependent on the accuracy of that database.

7.3.10.2 Updating the Allocated-Stock Database

In this case, the system updates the <PCB>.DBF file with the contents of the <PCB>.INV file (please refer to Figure 7-4 (p.123)). The quantity-allocated field is decreased by the quantity listed in the file.

The timing of this process is not critical, since the stock has already been allocated and does not effect subsequent stock level checking operations.

7.3.11 Completion of an Order

Location: CAS Master

Filename: CASMAIN.EXE

Language: Clipper

The final operation involves removing an order from the list of WIP.

Appendix D (pp.183-191), in particular Appendix D2.3 (pp.189-189), provides an in-depth discussion of the operation of this program.

When an order is removed from the list of WIP, the allocated-stock database is merged back into the CAS Database. If the number of PCBs produced equalled the order quantity, then for each component the quantity-allocated field would equal zero. In this case, the CAS Database would not be modified.

In the case where fewer PCBs are produced, the quantity-allocated field would be greater than zero. To ensure the CAS Database remains valid, these components must be "de-allocated", that is, the workstation quantity field (StnQty) must be increased by the quantity remaining in the quantity-allocated field (QtyAlloctd).

In the case where more PCBs are produced, the quantity-allocated field would be less than zero. In this case, the workstation quantity field must be reduced by the amount in the quantity-allocated field.

This is a robust system that is able to cope with order quantity changes, and cancellations without a loss of data integrity.

Finally, the <PCB>.ODR, <PCB>!.DBF, and <PCB>.DBF files are deleted, and the order is deleted from the list of WIP.

7.3.12 The CAS Shell

Location: Cas Master and all workstations

Filename: CAS.EXE

Language: Turbo Pascal

All the programs constituting the CAS system may be executed from within a single program. This program offers a menu to the user with the following entries:

- PCB file name:
- Begin assembly
- Build/edit insert file (*.INS)[7]
- Build assembly order file (*.ODR) (Database system)[7]
- Build overlay file (*.OVL)[7]
- Build component file (*.CPT)[7]
- Build assembly input files and begin assembly[7]
- Stock control system
- View all PCB overlay files (*.OVL)
- Exit to DOS

Each is considered below.

PCB file name. This option allows the user to enter a generic file name. Alternatively, the file name may be included in the command line, and is then posted automatically.

If the file name is entered, the file name pick-lists are always by-passed, and subsequent operations automatically operate on files with the same generic file name.

Begin assembly. This option executes the ASSEMBLY.EXE program and allows the user to begin assembly.

Build/edit insert file (*.INS). This option executes the BUILDINS.EXE program and allows the user to generate or edit a <PCB>.INS file.

Build assembly order file (*.ODR) (Database system). This option executes the CASMAIN.EXE program and provides the user with full access to the CAS Database, and the Assembly Planning System.

Build overlay file (*.OVL). This option executes the BUILDOVL.EXE program and allows the user to convert HPGL files into files for use by the CAS system programs.

---

[7] Available only on the CAS Master.

Build component file (*.CPT). This option executes the BUILDCPT.EXE program and allows the user to merge the <PCB>.INS and <PCB>.ODR files.

Build assembly input files and begin assembly. This option executes the BUILDOVL.EXE, BUILDCPT.EXE and ASSEMBLY.EXE programs consecutively and allows all assembly input files to be generated, and assembly to commence in a single step.

Stock control system. This option executes the STRCNTRL.EXE program and allows the user to implement any of the store control or stock transaction procedures.

View all PCB overlay files (*.OVL). This operation executes the VIEWALL.EXE program that allows the user to view all the *.OVL files.

Exit to DOS. This option allows the user to exit quit the CAS system and to return to DOS.

The menu displayed at workstations does not include the options that are only available on the CAS Master.

The menu options are selected by moving a highlight bar using the arrow keys.

If the executable file can not be found, or there is insufficient memory to execute the program, the user is informed, and is returned to the menu.

7.3.13 CAS Configuration

Location:	Cas Master and all workstations
Filename:	CASSETUP.EXE
Language:	Turbo Pascal
Input files:	CONFIG.CAS
Output file:	CONFIG.CAS

The CAS setup program allows the customisation of basic system settings. Each workstation must have a configuration file.

Basic system settings that can be altered are:

- the Workstation identification number,
- the CAS Master identification number,
- a flag that determines whether stock usage is recorded during assembly,
- the full path to inventory files,
- the full path to design files,
- the full path to assembly files,

- the full path to database files,
- the full path to Clipper executable files, and
- the full path to Turbo Pascal executable files.

The setup program can not be executed from the CAS Shell.

Chapter 8

Analysis of the CAS System

8.1 Introduction

To determine whether the Component Assembly System (CAS) outperforms conventional manual assembly methods, an experiment was devised in which the two systems were observed performing actions with similar outcomes.

The experiment required the assembly of small Printed Circuit Boards (PCBs) in batches ranging from 1 to 4 units.

8.2 Scope of Experiment

The experiment was designed to gather data regarding the performance of the two manufacturing systems in key areas of PCB assembly, namely, stock level checking, setup, assembly, soldering and lead clipping.

The experiment was not designed to gather extensive data concerning the performance of two commercially viable assembly systems in every area. Two reasons account for the decision to adopt this approach:

- the CAS system lacked several key features at the time the experiment was conducted, and
- the CAS system was not designed to replace an existing manual assembly system within the

Manufacturing Pilot Plant (MPP). Consequently, it was necessary to simulate an appropriate manual system.

Any conclusions drawn from this experiment must reflect these points.

8.3 Hypothesis

The objective of the experiment was to test the following hypothesis.

> The CAS system outperforms conventional manual assembly methods not only in terms of the quality of the product, but also in terms of the effectiveness and efficiency of the system used to produce it.
>
> Furthermore, differences in the performance of the two systems are most perceptible as the batch size approaches a single unit.

8.3.1 Basis of Hypothesis

Consider first the product itself. The CAS system is designed to present to the assembler the correct component at the correct time, indicating also where the component is to be placed. In addition, it informs the assembler of additional information, such as whether the component is polarised. These factors serve to reduce the first-pass defect rate, since the incidence of component placement errors will be reduced.

Conventional assembly methods do not incorporate such features, and rely totally on the abilities and awareness of the assembler.

Consider also the production system. The production system must regularly and repeatedly perform a fixed set of tasks. To maintain an acceptable level of overall system performance in the long term, it is essential to maintain an appropriate level of effectiveness of the elements of the system. For example, the stock control system can be considered reliable only if previously generated data is accurately and correctly recorded and used.

Providing that the product design is correct, the data input to the CAS Database is correct, the supplied components are "pure", and that the system is used as it ought, the value of the output of the CAS system will remain of a consistently high quality.

Conventional assembly methods, however, consist entirely of manual processes, including repetitive data processing tasks, which are inherently error prone.

Finally, consider the influence of batch size. The difference in performance between the CAS system and the conventional assembly method is expected to be most perceptible as the batch size approaches a single unit. This is based on the expectation that the time spent performing non value-adding activities, such as stock level checking, and setup, are to a degree independent of batch size. Consequently, for small batches, the proportion of time spent performing non value-adding activities is greater than for large batches.

With the CAS system, these operations are computer assisted, and in some instances fully automated. They are therefore very short. Consequently, it is anticipated that the impact of non value-adding activities on the total production lead time will be less with the CAS system than with conventional assembly methods.

This is represented graphically in Figure 8-1 (p.152).

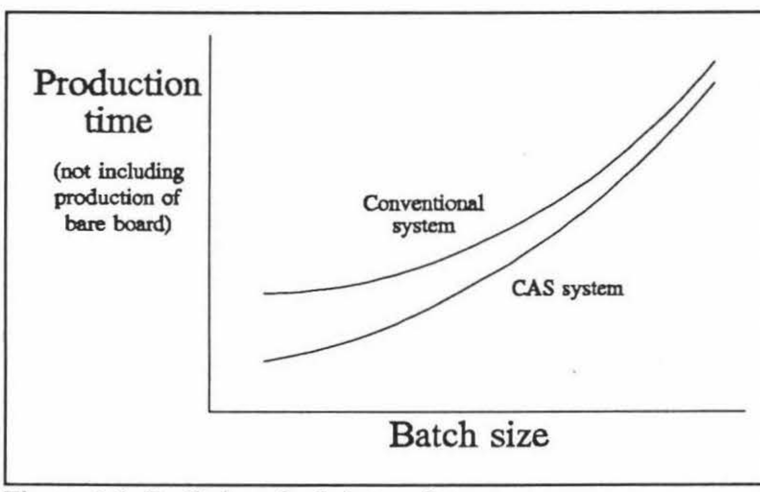

Figure 8-1 Prediction of relative performance

This figure may be represented alternatively by converting the Y-axis to "the CAS system production time as a fraction of the conventional method production time". The resulting curve would approach the Y = 1.0 line asymptotically from below.

8.4 Structure of the Experiment

8.4.1 Constitution of the Product

The product to be assembled consisted of the following components:

- 7 capacitors,

- 7 diodes,
- 1 display,
- 6 integrated circuits,
- 31 resistors,
- 1 transistor, and
- 2 wire links.

A detailed Parts List is provided in Appendix I1 (p.199).

The participants were not required to insert the display or the integrated circuits, since the necessary equipment was not available.

8.4.2 Setup

The experiment consisted of the following elements.

- Main Store: the Main Store contained only those components required to assemble the product. The layout of the Main Store corresponded with the order of components listed in the Main Store Records. The Main Store Records are provided in Appendix I2 (p.200).
- CAS system: workstations 2 and 3 were set up with all the required components, except those requiring loading during the experiment.
- Conventional assembly system: the conventional assembly system included storage bins with blank labels attached.
- Equipment: each participant was equipped with a jig in which to mount the PCB(s), soldering equipment, and a sample of a completed PCB.
- Recording of results: participants were provided with data sheets upon which to fill in start and finish times for each activity on the data sheet provided. A sample of the data sheet is provided in Appendix I3 (p.201).

8.4.3 Experiment Execution and Expected Results

The experiment consisted of 7 stages. Each stage will be considered, outlining the activities to be performed in both the CAS system and the conventional assembly method. In addition, the anticipated difference in performance between the two systems will be outlined.

8.4.3.1 Stage 1: Stock Level Checking

The first stage involved checking stock levels to determine what action was required before assembly could begin.

(i) The CAS system. Participants were required to execute the database program (CASMAIN.EXE) and select the appropriate design file. The purpose of this program is to generate a file detailing the order of assembly. This program is discussed extensively in Chapter 7, Section 7.3.5 (pp.131-135).

(ii) The Conventional Assembly Method. Participants were required to analyse the product Parts List, and determine whether component levels in the Main Store, based on the Main Store Records, were sufficient to fulfil the order.

Where the store quantity fell below the reorder level, participants were required to fill out a Component Order Form. A sample Component Order Form is provided in Appendix I4 (p.202). For each participant, the store quantity fell below the reorder level for 4 components.

(iii) Expected Results. One of the strengths of a computerised system is the ability to process large amounts of information very quickly, without error. It was expected that the CAS system would outperform the conventional assembly method in terms of time and accuracy.

8.4.3.2 Stage 2: Setup

Next, the participants were required to set up the work area for assembly.

(i) The CAS System. Participants were required to execute the stock control program (STRCNTRL.EXE) and collect the appropriate quantities for 5 different components: 2 for workstation 2, and 3 for workstation 3. This program is discussed extensively in Chapter 7, Section 7.3.9 (pp.141-144).

(ii) The Conventional Assembly Method. Participants were required to label each bin and gather the exact quantity of each component from the Main Store.

(iii) Expected Results. As the CAS system required only 5 different components to be loaded, and as each workstation has a simple controller, it was again expected that the process time for the CAS system would be the shortest.

8.4.3.3 Stage 3: Assembly (1)

The first assembly stage involved the insertion of the wire links, diodes, and small resistors; a total of 37 components per board.

(i) The CAS System. Participants were required to execute the assembly program (ASSEMBLY.EXE) and assemble the PCB(s) by following the prompting. This program is

discussed extensively in Chapter 7, Section 7.3.8 (pp.137-141).

(ii) The Conventional Assembly Method. Participants had no option but to devise their own methodic assembly system, and had 3 basic options:

- working down the Parts List provided, matching reference descriptions with those on the bare board,
- copying from the completed PCB provided, or
- systematically emptying each bin and locating components either from the Parts List, or the completed PCB provided.

(iii) Expected Results. It was expected that the assembly time for the CAS system would be the lowest. However, as the time to insert each component was a significant proportion of the total assembly time, the difference between these times consisted not only of the effect of the system used, but also on the ability of the participant to perform intricate tasks. Consequently, variance due to the performance of individual assemblers was expected to be high, and could only be minimised with a large number of trials of the experiment.

8.4.3.4 Stage 4: Soldering (1)

It is standard practice to solder the short components before inserting the taller components to ensure that the shorter ones do not fall out of the board when soldering the taller components.

Although this activity is not affected by the type of assembly system used, it was nevertheless advantageous to measure this time since it provided some insight into the relative performance of the participants.

The first soldering stage consisted of 74 solder points.

(i) Expected Results. Ideally, the soldering time data should be similar and consistent for both systems.

8.4.3.5 Stage 5: Assembly (2)

The second stage of assembly progressed in a similar manner as the first stage except the components to be inserted were the capacitors, large resistors, and the transistor; a total of 11 components per board.

8.4.3.6 Stage 6: Soldering (2)

The second soldering stage consisted of 24 solder points.

8.4.3.7 Stage 7: Lead Clipping

Lead clipping was the final stage. It was similar to the soldering stages in that it provided an indication of the relative performance of the participants, not only in terms of time, but also in terms of the quality of the work.

After the experiment was completed, the products were inspected by a technician.

8.5 Results and Analysis

Unfortunately, circumstances only allowed two trials of the experiment to be conducted. The results for each trial are presented and discussed below.

In the first trial, 8 untrained students participated. In the second trial, a single, trained assembler conducted the entire trial. Consequently, it was anticipated that the results for Trial 2 would be more consistent than the results for Trial 1.

8.5.1 Trial 1

The complete results for Trial 1 are provided in Appendix I5, Table I-1 (p.203).

Table 8-1 Average process-time results for Trial 1

	CAS: Average	Conv. method: Average
Stock check	1:00	2:25
Setup	6:20	11:50
Assembly (1)	28:45	25:30
Soldering (1)	15:25	17:15
Assembly (2)	9:40	8:25
Soldering (2)	7:00	8:10
Lead clipping	7:10	9:00
TOTAL	**75:20**	**82:35**

Note: all times shown in minutes

Table 8-1 (p.156) provides a summary of the results. For both systems the average of the process times for each stage is given.

The conclusions of inspection are provided in Table 8-2 (p.157).

Figure 8-2 (p.158) displays the complete results for Trial 1 graphically.

Table 8-2 Errors made during Trial 1

Batch Size	System	Error
1	Conventional	Diodes D1 and D3 incorrectly oriented
1	CAS	Resistor R15 not soldered
1	CAS	Transistor Q1 not in far enough
2	CAS	Leads not clipped properly
3	CAS	Resistor R38 not inserted
4	Conventional	Transistor Q1 not inserted
General	CAS	R12 not inserted (input file error)

With regard to the results a number of observations may be made:

- stock level checking and setup processes are far less time consuming for the CAS system as expected,
- assembly, soldering and lead clipping process times are similar for both systems,
- the total process time for the CAS system is lower than for the conventional assembly method,
- the variation between participants is clearly apparent in Figure 8-2 (p.158),
- there is no apparent trend for either system across the batches,
- most of the errors made with the CAS system did not arise from the system itself
- errors made with the CAS system may show consistency, as in the case where the input file contains an error. Although such errors are not acceptable, correction is a simple task as all products contain the same error,
- the CAS system is an assembly *assistance* system, not a control system. Consequently, there is no guarantee that the assembler will follow the instructions, and
- the quality of work, such as component alignment and soldering, is operator-dependent, rather than production system-dependent.

Further analysis is performed in Section 8.6 (p.161).

8.5.2 Trial 2

This trial was conducted entirely by a single, trained assembler. This approach allowed the wide variations between the participants in Trial 1 to be eliminated.

The complete results for Trial 2 are provided in Appendix I6, Table I-2 (p.203).

Table 8-3 (p.159) provides a summary of the results. For both systems the average of the process time for each stage is given.

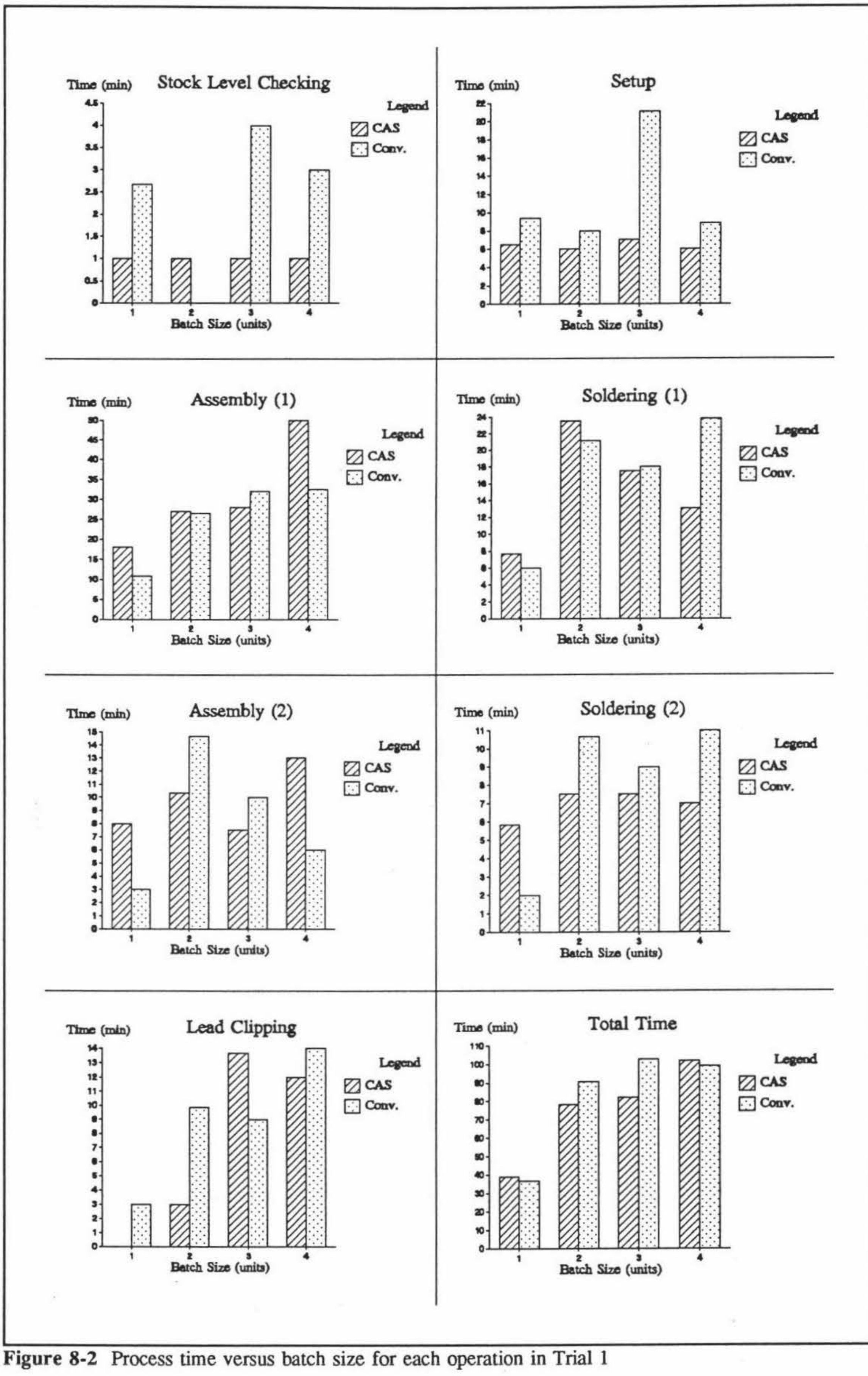

Figure 8-2 Process time versus batch size for each operation in Trial 1

Table 8-3 Average process-time results for Trial 2

	CAS: Average	Conv. method: Average
Stock Check	0:20	2:15
Setup	2:45	6:55
Assembly (1)	13:20	18:10
Soldering (1)	6:35	7:30
Assembly (2)	3:45	4:35
Soldering (2)	2:55	3:25
Lead clipping	3:50	4:20
TOTAL	33:30	47:10

Note: all times shown in minutes

Table 8-4 Errors made during Trial 2

Batch Size	System	Error
1	Conventional	Stock Check: 200 k 1% resistor not ordered
1	Conventional	Assembly 1: 200 k 1% resistor misplaced
4	Conventional	Setup: 2 spare 910 k 1% resistors
4	Conventional	Assembly 2: C5 not inserted.

The conclusions of inspection are provided in Table 8-4 (p.159).

Figure 8-3 (p.160) displays the complete results for Trial 2 graphically.

With regard to the results a number of observations may be made:

- stock level checking and setup processes are far less time consuming for the CAS system as expected, and are relatively independent of the batch size for the CAS system,
- assembly process times are significantly less time consuming for the CAS system,
- the total process time for the CAS system is significantly lower than for the conventional assembly method,
- there is considerable uniformity across the batches, as revealed in Figure 8-3 (p.160),
- the assembler was consistently quicker at the soldering and lead clipping activities with the CAS system. This may be attributed to the fact that the assembler conducted all the trials on the conventional system first, to eliminate any increase in knowledge of the product that may otherwise be gained from the CAS system, and
- all errors were made with the conventional system.

Further analysis is performed in Section 8.6 (p.161).

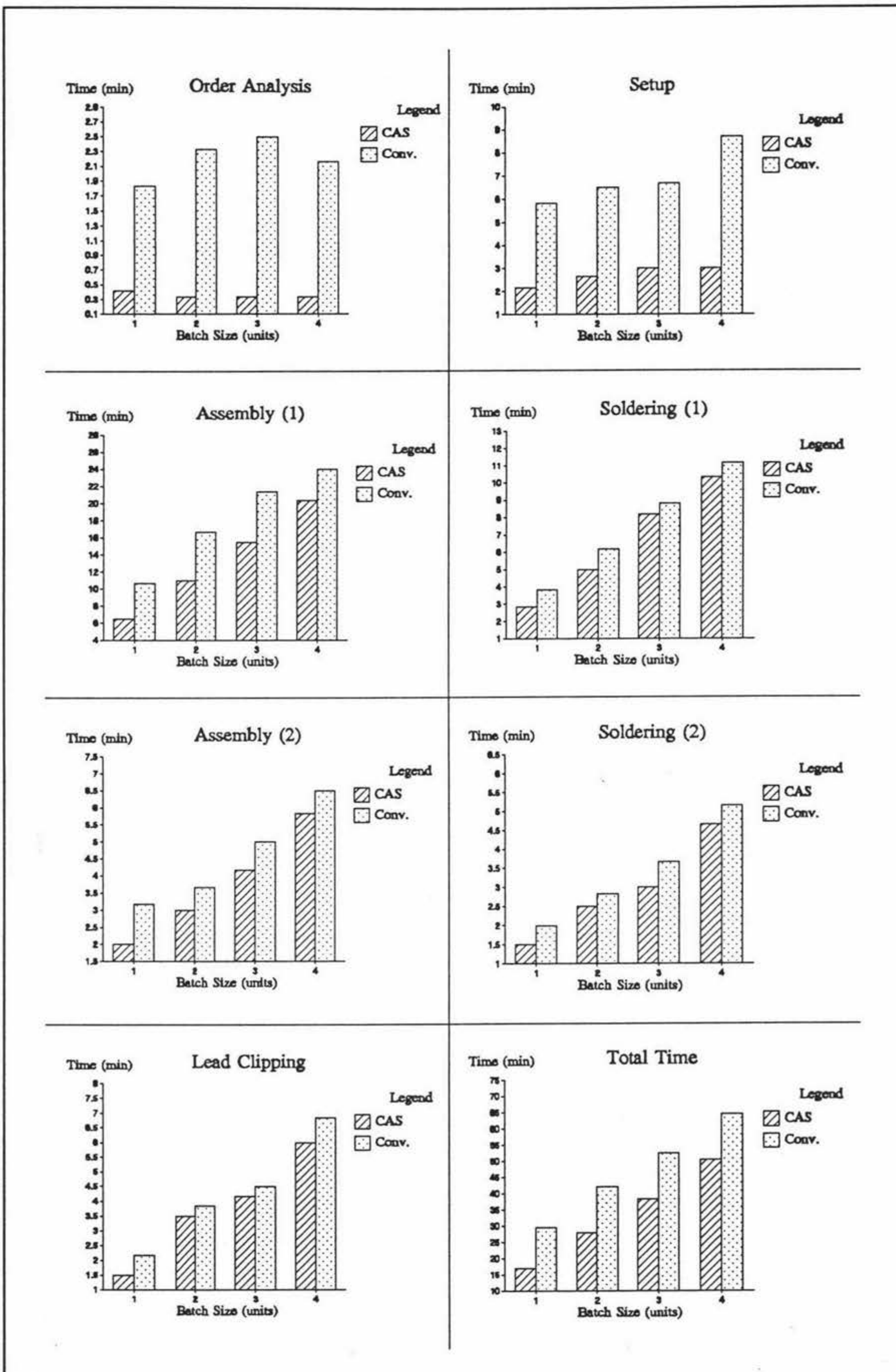

Figure 8-3 Process time versus batch size for each operation in Trial 2

8.6 Further Analysis of Results

An alternative method of examining the data is to consider the value-adding process times as a fraction of the total production time. The formula for this is:

$$X = \frac{\text{Total assembly time}}{\text{Total time}}$$

The results of this are given in Table 8-5 (p.161).

Table 8-5 Assembly time as a percentage of production time

	CAS Assembly					Conventional Assembly				
Trial	1	2	3	4	Av.	1	2	3	4	Av.
Trial 1	0.46	0.48	0.43	0.62	0.51	0.38	0.45	0.41	0.39	0.41
Trial 2	0.5	0.5	0.51	0.52	0.51	0.47	0.48	0.5	0.47	0.48

The data does not show a trend on the basis of batch size, but does reveal that the value-adding time is maximised under the CAS system.

Finally, it is necessary to express the total production time of the CAS system as a fraction of the total production time of the conventional assembly method. The formula for this is:

$$X = \frac{(\text{Total Assembly Time})_{CAS}}{(\text{Total Assembly Time})_{Conv.}}$$

The results of this are given in Table 8-6 (p.161).

Table 8-6 Relative assembly times

	Batch Size			
Trial	1	2	3	4
Trial 1	1.06	0.86	0.80	1.03
Trial 2	0.79	0.78	0.81	0.86

The results for Trial 2 do support the theory that the difference in performance between the CAS system and the conventional assembly method is most perceptible as the batch size approaches a single unit.

8.7 Conclusions

Based on the results of the experiment, a number of conclusions may be drawn:

- the CAS system outperforms the conventional assembly method,
- the difference in performance between the systems is most perceptible as the batch size approaches a single unit, and
- the CAS system reduces the incidence of assembly errors.

These conclusions must be qualified with the following:

- the number of trials performed was insufficient upon which to draw numerically definitive conclusions,
- the conventional assembly method was simplistic in that the Main Store and stock records included only those components required for assembly of the test product,
- the range of batch sizes was too narrow for the purposes of extracting batch-size dependent trends, and
- variation due to the differences in participants significantly affected the results for Trial 1.

Despite the above restrictions, the experiment has shown that the CAS system outperforms a conventional system in the key areas of stock level checking, setup, and assembly. It is anticipated that the performance of the CAS system would be even more superior than the performance of conventional manual assembly system if the above restrictions were not present.

Chapter 9

Summary and Conclusions

9.1 Summary

The objective of this research project was to design and develop a rapid response, computer integrated Printed Circuit Board (PCB) assembly system. This system, referred to as the Component Assembly System (CAS), forms an integral part of a commercially viable manufacturing system, the Manufacturing Pilot Plant (MPP), for the design, production, and assembly of high quality, special purpose PCBs in low volumes.

In Chapter 2, the characteristics and weaknesses of conventional PCB manufacturing systems were discussed. A vision was then presented that outlined the MPP as a modern, computer integrated PCB production and assembly system. This vision represented the intuitive phase of design process, and provided the necessary guidance for the analytic phase that followed.

In Chapter 3, a variety of existing manufacturing system design methodologies were investigated. From these methodologies, a Generic Manufacturing System Design Methodology (GDM) was derived. The GDM consisted of two parts. The first part was the structured design process, and consisted of 6 distinct stages. The second part consisted of general considerations, each providing a unique, but essential perspective on the design process.

Although the GDM was intended for the design of the CAS system, it is also applicable to the design of other manufacturing systems.

The GDM formed the analytic phase of the design process.

In Chapter 4, the relationship between market demands and the selection and management of processes and resources was investigated.

This relationship was represented by the Product-Process matrix, in which three generic types of manufacturing system were identified, namely: jobbing, batch production and mass production. These systems were referred to as Traditional Manufacturing Systems.

Each system was examined to identify: the characteristics of the market requirements, the selection and management of resources, and common problems and potential solutions.

In each case, the total system was examined. This ensured that individual elements of the systems could be seen in the correct context.

In Chapter 5, philosophy-driven manufacturing systems were investigated. These systems were distinct from the Traditional Manufacturing Systems as they could not be defined by a specific location in the Product-Process matrix. This was because some systems overlapped with other systems, and collectively the systems did not cover the full spectrum as the Traditional Manufacturing Systems did.

The following systems were considered: Integrated Manufacture and Computer Integrated Manufacturing (CIM), Just in Time (JIT), Group Technology (GT), and Material Requirements Planning (MRP) and Manufacturing Resource Planning (MRP II). These systems were referred to as Modern Manufacturing Systems.

Each system was examined to identify: characteristics, objectives and benefits, development motivation, application, implementation, and common problems.

In each case, the total system was examined. This ensured that individual elements of the systems could be seen in the correct context.

In Chapter 6, the first 4 stages of the GDM were applied. These stages were:

- Stage 1: define the characteristics of the market in which the MPP operates. This starting position ensured that the design process was correctly focused from the outset.
- Stage 2: formulate a strategy for the MPP in the form of a set of objectives, based on the outcome of the market analysis performed in Stage 1. This ensured a consistent approach to design regardless of the level of detail.
- Stage 3: examine existing manufacturing systems, identifying areas of strength and applicability, and areas of weakness or incompatibility. This allowed the MPP to be based on relevant principles proven in other manufacturing systems.
- Stage 4: define the system at a conceptual level, that is, define *what* the system must do to fulfil the objectives. This defined the necessary internal mechanisms of the CAS system at a conceptual level.

  In addition, a distinction was made between critical and non-critical elements of the system.

In Chapter 7, the final stages of the GDM were applied. These stages were:

- Stage 5: define the system at a functional level, that is, define *how* the system must function to fulfil the objectives. This defined the necessary internal mechanisms of the CAS system at a functional level.
- Stage 6: implement the design. This was the constructive process of building the systems.

In Chapter 8, the CAS system was tested against a conventional assembly system. The objective of the experiment was to test the hypothesis that the CAS system could outperform a conventional assembly system in key areas of production including: stock level checking, setup, assembly, soldering, and lead clipping. The results were presented and analysed, and indicated that the hypothesis was correct.

9.2 Conclusions

In Chapter 6, Section 6.3 (pp.74-78) the objectives of the MPP were discussed. Principal objectives focused on: commercial viability, rapid response, high quality, and low volume - high variety production.

Each will be considered below.

9.2.1 Commercial Viability

There is no numerically definitive data to prove that the MPP is capable of operating as a commercially viable manufacturing system. However, based on the performance characteristics of the system determined in the experiment in Chapter 8, it is expected that, with good management, the MPP will achieve *major* gains in the quality of the product and the standard of service, particularly the customer inconvenience time. Over time, the MPP will establish a market niche, made up of a significant proportion of repeat customers.

9.2.2 Rapid Response

The CAS system has rapid response capabilities in two key areas, namely, pre-assembly operations and assembly.

The pre-assembly tasks include:

- converting the graphic overlay data produced by CAD packages into graphic data for use in the CAS system,
- allocating stock to the order,
- determining the impact the allocation of stock has on stock levels and producing a status report that details: the identification and quantity of components that must be purchased or transferred from the Main Store to a workstation, and the identification of unrecognised components. Furthermore, the system makes a distinction between components for which action is required *before* assembly can begin, and those for which action can be delayed, and
- producing assembly instructions that contain sufficient information to inform the assembler of where each component is located, the order of assembly, and other user information, as well as information to control the workstation hardware.

The status report provides the user with a complete account of what action must be taken, if any, before assembly can begin.

To quantify this responsiveness, consider, for example, an order for a complex PCB with 435 components. The tasks listed above can be completed in approximately 1 minute on a relatively high performance Personal Computer (PC).

If these tasks were to be performed manually, it would take considerably longer, and errors would almost certainly be made.

The second area of responsiveness is in assembly. If all the required components are on-hand and are available in sufficient quantities at the workstations, assembly can begin *immediately* after the data processing is complete. This is because each workstation incorporates a buffer store, eliminating the need to make up kits.

The responsiveness of the CAS system is derived primarily from the use of integrated computer technology. This integration crosses the functional boundaries between design, production, assembly, and administration, and in doing so, obscures these boundaries.

9.2.3 High Quality

The CAS system contributes significantly to the quality of the assembled product. Greater consistency can be achieved, not only between products within a batch, but also between batches. Furthermore, the potential exists to reduce the occurrence of insertion errors.

The capabilities of the Wet Line and the CAS system contribute to the production of consistently high quality PCBs.

9.2.4 Low Volume - High Variety Production

The CAS system is best suited to low volume, high variety production. The hardware and software used in the CAS system provide flexibility, and allow it to cope effectively with variety, while the use of manual assembly operations make the CAS system unsuitable for high volume assembly.

The strength of the CAS system, relative to conventional low volume, high variety manufacturers, is derived from the use of low cost, flexible technology.

9.3 Future Work

The CAS system is at present a basic functioning system. Although it has the required capability to operate as a computer integrated assembly system, performance can be enhanced through the development of the systems briefly described in the following sections.

9.3.1 Supply of Components

With regard to the supply of components, the CAS system can be improved with the incorporation of:

- supplier information such as contact numbers, delivery performance, and a preference rating,
- information that links components in the CAS Database with a supplier, and
- systems for communicating with suppliers, such as for requesting information or sending purchase orders.

9.3.2 Design

With regard to design, the CAS system can be improved with the incorporation of:

- on-line access for designers to the CAS Database and stock ordering and scheduling systems,
- a facility allowing designers to select alternative components that are known to be on-hand, or that satisfy other requirements,
- a suite of CAD data conversion programs,
- incorporating a facility in the INsert file generator/editor that generates the required information to drive the Computer Numerical Control (CNC) drill, and
- incorporating a facility in the INsert file generator/editor that allows the graphic overlay data to be edited.

9.3.3 Assembly

With regard to assembly, the CAS system can be improved with the incorporation of:

- on-line and off-line systems for defining and displaying component-specific information during assembly, such as insertion hints or warnings,
- on-line and off-line systems for defining and displaying product-specific information during assembly, such as recommendations when to solder, or other timely information that may be provided to improve the assembly process, and
- incorporating a facility in the assembly system that allows the assembler to suspend assembly, and to save a file that details assembly progress. This file could later be restored so that assembly could resume from the point at which it was suspended.

9.3.4 General

At a more general level, the CAS system can be improved with the incorporation of:

- hardware and software for a Local Area Network (LAN), including modem facilities,
- extensive on-line help systems for the CAS software,
- an increase in the number of system settings that can be altered by the user, coupled with a log-in system allowing frequent system users to define personal preferences for system settings,
- systems for cost and time estimation, and scheduling,
- systems for billing and accounting,
- an improvement in the robustness of data processing systems, and file management systems,

- development of a database and analysis system for PCB testing,
- a detection system that automatically checks the CAS Database for missing or erroneous data, and other faults,
- a system that allows new components to be added to the CAS Database from the stock control system,
- a system for assigning workstation addresses to new components,
- an improvement in error detection systems during data processing, and
- a system for optimising workstation addresses for components such that the order in which the components are located at the workstation reflects the assembly order rules, which are based on component height, fragility and workstation location. This will ensure that the travel distances between successive components for insertion is minimised.

9.3.5 The Benefits of Manufacturing Experience

The GDM used in the design and development of the CAS system has allowed the development of a functional manufacturing system. The environment in which this system operates, however, will change due to factors such as changes in customer requirements and competitor capabilities, and changes in product and process technology. Furthermore, through experience with the system, the flaws and weaknesses of the system will be exposed. Consequently, the CAS system must be subject to an on-going cycle of observation and development to ensure that the system remains effective.

Further development of the system must be guided by the objectives of the MPP unless the objectives are found to be groundless.

Appendices

Appendix A General Characteristics and Standard Features of the CAS System

This appendix contains the general characteristics, and standard features of the Component Assembly System (CAS).

In particular, the following aspects will be discussed:

- the structure of the CAS Database,
- the significance of file names and extensions,
- the configuration file, and
- the standard format for data files.

A1 The CAS Database

Filename: PARTS.DBF

The CAS Database is a centralised source of data providing the information link between design and production.

The structure of the database is shown in Table A-1 (p.171).

The description fields (Desc1, Desc2, and Desc3) may contain both upper and lower case characters. This allows the user to employ the correct nomenclature for component descriptions. For character string comparisons, however, all strings are converted temporarily to upper case characters, as the character string comparison operations are case sensitive.

Table A-1 The structure of the CAS Database

Field	Type	Width	Description
Desc1	Character	20	Description 1 (eg 10k)
Desc2	Character	20	Description 2 (eg 0.5W)
Desc3	Character	20	Description 3 (eg 0.5-In)
StnNo	Character	1	Identification code of workstation at which component is located
StnLocX	Character	2	Address 1 locating component on workstation
StnLocY	Character	2	Address 2 locating component on workstation
StnLocZ	Character	2	Address 3 locating component on workstation
StoreQty	Numeric	4	Quantity of components on-hand in Main Store
PurchROL	Numeric	4	Quantity of components below which more components are purchased from suppliers to the Main Store
PurchROQ	Numeric	4	Purchase reorder quantity
StnQty	Numeric	4	Quantity of components on-hand at the workstation
StnROL	Numeric	4	Quantity of components below which more components are transferred from the Main Store to the workstation
StnROQ	Numeric	4	Workstation reorder quantity
Height	Numeric	4,1	Component height in millimetres, measured from the base of the board to the top of the component
Fragility	Numeric	1	Fragility of component, where 0 is least fragile, and 9 is most fragile
Polarity	Logical	1	Polarity. True for capacitors, transistors, ICs
Cost	Numeric	6,2	Purchase cost per component

A2 File Names and Extensions

Data files may be classified as belonging to one of two groups, namely, those which relate to a specific product, and those which relate to the production system.

For simplicity, the MS-DOS file naming terminology has been adopted [99 p.69]. The following terms are defined:

- the term "filename" refers to the entire name of the file, up to 12 characters long,
- the term "file name" refers to the first 8 characters of the filename, and

- the term "extension" refers to the last 3 characters of the filename.

In addition, the term <PCB> refers to the generic file name of a specific product.

The file name and/or extension identifies the nature of the contents of the file. The list below relates filenames to file contents.

Basic design files:

- **<PCB>.INS**: the INSert file contains the raw design data regarding the identification and location of all components for a specific product,
- **<PCB>.BDR, <PCB>.MAP**: these files are graphic overlay data files detailing the appearance of the PCB, in Hewlett Packard Graphics Language (HPGL). The first file contains the BorDeR data, while the second file contains a MAP of the contents of the PCB, and
- **<PCB>.HP2**: this file contains the same data as the <PCB>.BDR and <PCB>.MAP files, except that all information is in a single file.

Databases linking the design data to the CAS Database:

- **<PCB>.DBF**: this is the allocated-stock database. It details the quantity of each component required for the quantity of products ordered. It also contains the results of the stock checking operation, and
- **<PCB>!.DBF**: this is the database that results from the extraction of part of the data from the <PCB>.INS file. Each component has a record. This database is used to create the <PCB>.ODR file.

Assembly order information and workstation presentation system control file:

- **<PCB>.ODR**: this file contains the assembly OrDeR data. This is the data defining the order in which the components are inserted, together with information detailing the exact location of the component in the production system.

Assembly support information files:

- **<PCB>.CPT**: this file contains the data that results from the merger of the <PCB>.INS and <PCB>.ODR files, and
- **<PCB>.OVL**: this file contains the processed graphic OVerLay data.

Assembly stock usage data file:

- **<PCB>.INV**: this file is an INVentory file. It details the use of stock as a result of assembly operations. It is used to update the allocated-stock database.

Stock transfer data files:

- TRNSACTN.STK: this file details the deposit and withdrawal of components at the Main Store or a workstation and is used to update the CAS Database. This does not include stock transfers between the Main Store and workstations,
- MAIN2STN.TRN: this is a temporary file detailing the TRaNsfer of stock from the Main Store to workstations.
- STN2MAIN.TRN: this is a temporary file detailing the TRaNsfer of stock from workstations to the Main Store.

A3 The Configuration File

Location: Main Store and all workstations

Filename: CONFIG.CAS

The configuration file contains the following details:

- the identification number of the workstation at which the file is located,
- the identification number of the CAS Master,
- a logic code (0 or 1) signifying whether to record the usage of stock during assembly (1 = true),
- the location (drive and directory) of the inventory files,
- the location (drive and directory) of the design, or input files,
- the location (drive and directory) of the assembly files,
- the location (drive and directory) of the database data files,
- the location (drive and directory) of the Clipper executable files,
- the location (drive and directory) of the Turbo Pascal executable files.

The following workstation identification numbers are used:

- 0 denotes the Main Store,
- 1 denotes the DIMA SMD Pick and Place machine,
- 2 denotes the Jacob's Ladder part presentation machine, and
- 3 denotes the ISM part presentation machine.

A4 Standard Format for Data Files

Most data files are coded in American Standard Code for Information Interchange (ASCII) text. This ensures that:

- programs written in different languages can access the same data files, and
- the user may view or edit the data files using standard text file editors if the need arises.

The exceptions to this are:

- databases, and
- files used exclusively by programs written in one language, where writing to, and reading from the file is simpler, or more efficient with a special format file rather than with an ASCII text file.

The CAS Database is a special case. A copy of the database is generated upon exit of CASMAIN.EXE. This file, with the name DB-LIST.CAS, is an ASCII text file, delimited with commas, and is used by Turbo Pascal programs.

Appendix B Graphic Overlay Data Filter

This appendix consists of the details of the graphic overlay data filter.

In particular, the following aspects will be discussed:

- the operation of the filter,
- commonly used HPGL instructions,
- graphics procedures available in Turbo Pascal, and
- the characteristics of the output file produced by the filter.

B1 Operation of the Filter

When the filter is activated, it searches for pairs of <PCB>.BDR and <PCB>.MAP files. Those which are found are presented to the user in a pick-list. The user either selects a pair, or presses escape. If the user presses escape, the filter searches for <PCB>.HP2 files, presenting these in a similar manner. Again, the user has the choice of selecting an entry, or pressing escape. Pressing escape at this point terminates the program.

If the selection of an input file is successful, the filter checks if an output file exists. If a file does exist, the user is asked to confirm replacement of the file.

If confirmation is given, the filter processes the input file(s), and produces the required output file without further user intervention.

B2 Commonly Used Instructions in Hewlett Packard Graphics Language

B2.1 The *Input Window* Instruction

Syntax: IWX1,Y1,X2,Y2;

This instruction sets the boundaries of the plotting area. X1,Y1 sets the lower left corner, while X2,Y2 sets the upper right corner.

B2.2 The *Pen Up* Instruction

Syntax: PU;

This instruction raises the pen.

B2.3 The *Pen Down* Instruction

Syntax: PD;

This instruction lowers the pen.

B2.4 The *Plot Absolute* Instruction

Syntax: PAX,Y;

This instruction moves the pen from the current position to the new position given by X,Y.

B2.5 The *Arc Absolute* Instruction

Syntax: AAX,Y,Θ_1,[Θ_2];

This instruction draws an arc centred on X,Y. The arc angle is given by Θ_1, and the starting position of the arc is given by the current position of the pen. If Θ_1 is positive the arc is drawn counter clockwise. The smoothness of the arc is optionally given by the cord angle, Θ_2. The default value of the cord angle is 5°.

B2.6 The *Circle* Instruction

Syntax: CIR,[Θ_1];

This instruction draws a circle at the current pen position with a radius given by R, and a chord angle optionally given by Θ_1.

This instruction automatically raises and lowers the pen during implementation.

B3 Turbo Pascal Graphics Procedures

Before discussing the graphics procedures available in Turbo Pascal it is necessary to define several Turbo Pascal data types.

B3.1 Data Types in Turbo Pascal

The following data types are defined.

- integer: a 16-bit whole number in the range -32768 to 32767,
- word: a 16-bit whole number in the range 0 to 65535,
- longint: a 32-bit whole number in the range -2147483648 to 2147483647.

B3.2 The *MoveTo* Procedure

Syntax: *moveto*(X,Y: integer).

The *moveto* procedure moves the current pointer, the equivalent of the cursor in text mode, from the present location to a new location given by X,Y.

The *moveto* procedure is used when the pen is up (PU) and a plot absolute (PAX_{HPGL},Y_{HPGL}) instruction is given.

B3.3 The *LineTo* Procedure

Syntax: *lineto*(X,Y: integer).

The *lineto* procedure draws a line from the present location of the current pointer to a new location given by X,Y.

The *lineto* procedure is used when the pen is down (PD) and a plot absolute (PAX_{HPGL},Y_{HPGL}) instruction is given.

B3.4 The *Arc* Procedure

Syntax: *arc*(X,Y: integer; Θ_1,Θ_2,R: word).

The *arc* procedure draws an arc from the start angle, Θ_1, to the finish angle, Θ_2. The radius of the arc is given by R, and the centre point by X and Y. Θ_1 and Θ_2 are defined according to the standard polar coordinate system.

The *arc* procedure is used when an arc absolute ($AAX_{HPGL},Y_{HPGL},\Theta_{1HPGL},[\Theta_{2HPGL}]$) instruction is given.

The *arc* procedure is also used in the special case where a circle ($CIR_{HPGL},\Theta_{1HPGL}$) instruction is given. In this case, $\Theta_1 = 0$, and $\Theta_2 = 360$.

B3.5 The *FloodFill* Procedure

Syntax: *floodfill*(X,Y: integer; BorderColor: word);

The *floodfill* procedure fills a region of the screen, starting at point X,Y, the seed, and bounded by the colour BorderColor. The pattern and colour used by the *floodfill* procedure is determined by the *setfillstyle* procedure.

B4 Characteristics of the Output File

The output file is divided into two sections. The first section consists of 5 special purpose longints. The second section of the file consists of pairs of longints.

B4.1 Section One: Five Special Purpose Longints

The first number is a logic flag, taking on the value of 0 or 1. If the border data is distinguishable from the remaining data, this number set to 1. This flag enables or disables the use of the *floodfill* procedure during drawing of the PCB.

The following 4 numbers represent the minimum and maximum values of the board in the X (horizontal) and Y (vertical) directions. In many cases the values for minimum X and Y will be 0. These numbers are used for scaling purposes.

B4.2 Section Two: Pairs of Longints

This is the main part of the file, and consists of pairs of longints.

The *moveto*, *lineto*, and *arc* procedures described in Appendix B3 (pp.176-177) require 2 or 5 coordinates. In the latter case, 6 coordinates are passed to the output file, where the sixth number is a padding number.

Identifying which procedure each number pair belongs to is achieved by using combinations of positive and/or negative numbers. The convention developed is:

- -X,+Y denotes *moveto*,
- +X,+Y denotes *lineto*,
- +X,-Y denotes *arc*, and
- -1,-1 denotes the end of the border data.

In the case where there are two input files, or a single input file, the end of the border data will be indicated either by an end of file marker, or "PG;" respectively. At this point, a -1,-1 is inserted in the output file. This indicates when the *floodfill* procedure must be executed.

Appendix C INSert File Editor / Generator

This appendix contains the details of the INSert data file editor / generator.

In particular, the following aspects will be discussed:

- the operation of the editor,
- the characteristics of the <PCB>.INS file, and
- the magnification and navigation facilities,

C1 Operation of the Editor

When the editor is activated, it searches for all <PCB>.OVL files. A pick-list is presented to the user, who may then select a file, or press escape. If escape is pressed the user may either enter the name of a file including the drive and directory, or may press escape to terminate the program.

If the selection of an input file is successful, the editor checks if a <PCB>.INS file exists. If a file does exist, the user is asked to confirm replacement of the file.

If confirmation is given, the editor will read in the <PCB>.OVL file, the <PCB>.INS file, if it exists, and DB-LIST.CAS.

Assuming the operation is successful, the user will be presented with a menu. The menu will allow certain parameters to be changed, such as mouse sensitivity, magnification and navigation step factors, and the enabling or disabling of the auto-referencing facility.

If auto-referencing is disabled, the user must enter component reference descriptions manually, such as R*n* for resistors, where *n* is a positive integer. If auto-referencing is enabled, reference descriptions are automatically assigned to new components. The disadvantage with auto-referencing is that, at this stage, the generic reference assigned to all components is Cpt*n* (the abbreviated form of Component *n*), where *n* is a positive integer. The reference description, therefore, has no bearing on the component, nor to the standard reference descriptions generated by CAD packages, and will therefore not match the reference descriptions printed on the bare board.

The editor includes a facility which ensures that different components do not share the same reference description.

The user is then presented with an image of the PCB, including all the known components. Please refer to Exhibit 7-1 (p.128).

C2 Characteristics of the Output File

The sample <PCB>.INS file shown below has been broken into 3 segments. Each segment is discussed.

Segment 1

```
%************************************************************
%                                                           *
%                   PC-INSERT FILE                          *
%                                                           *
% PC-INSERT Version 4.50                                    *
% Date       :  AUG 17 1991                                 *
% Time       :  03:46 PM                                    *
% File In    :  PT123.PCB                                   *
% File Out   :  PT123.INS                                   *
%                                                           *
%************************************************************
```

This segment of the file contains miscellaneous details.

Segment 2

```
$FORMAT
 REFDES  CENTX  CENTY ANGLE   TYPE  EXT1X  EXT1Y  EXT2X  EXT2Y
     VAL
$UNITS
   MIL
$BOARD-EXTENT
         -50    -150    2900     -900
$BOARD-ORIGIN
          50    -750
```

The second segment defines the format of the file, and the PCB.

Data types are:

- REFDES: the reference description of the component,
- CENTX: the centre of the component in the X-axis,
- CENTY: the centre of the component in the Y-axis,
- ANGLE: the angle in the X-Y plane at which the component lies,
- TYPE: the component type,
- EXT1X: the minimum extremity of the component in the X axis,

- EXT1Y: the minimum extremity of the component in the Y axis,
- EXT2X: the maximum extremity of the component in the X axis,
- EXT2Y: the maximum extremity of the component in the Y axis,
- VAL: The value of the component.

The VAL field represents description 1, while the 2 lines below are for descriptions 2 and 3 (Desc1, Desc2, and Desc3 in the CAS Database respectively).

Next, the unit of measure is given. The unit mil represents one thousandth of an inch.

The four figures for board extent represent the board extremities, specifically, minimum X, minimum Y, maximum X, and maximum Y.

The board origin defines the offset to the origin of the board.

<u>Segment 3</u>

```
$TARGET
$THROUGH-TOP
    C2   400   100    0    CASE-AA   270   230   530   -30
     4u7


    D1   2600  250    180  D05       2560  450   2640  50
     1N4148


    R1   1400  250    0    RC05      1365  450   1435  50
     470K


$THROUGH-BOTTOM
$SMD-TOP
$SMD-BOTTOM
$END
```

This is the main data segment, and includes data for four types of components:

- through-hole components on the top side of the board,
- through-hole components on the under side,
- surface-mount components on the top side, and

- surface-mount components on the under side.

C3 Magnification and Navigation Facilities

To aid the task of identifying and selecting components, the size of the image of the PCB can be altered, and the image can be moved vertically and horizontally.

Five scaling functions are included:

- the page up key enlarges the PCB by a specific factor,
- the page down key reduces the PCB by a specific factor,
- the home key returns the PCB to the original size, a scale of 1:1,
- the end key scales the PCB such that it fits exactly into the viewing window, and
- the insert key allows the user to enter any scale factor.

These functions may also be executed with the mouse.

The current magnification scale is displayed at the lower right corner of the screen.

In the case where the PCB is displayed at such a size that it does not fit within the viewing window, it is necessary to be able to traverse, or navigate around the PCB to access any area. This is accomplished either with the up, down, left and right arrow keys, or the on-screen, mouse driven navigation functions.

When selecting new components, the user is recommended to enlarge the image such that components occupy a significant portion of the screen. This is because the editor must convert the coordinate data from pixel units (typically in the region of 65 units per inch) to mils (one thousand units per inch). Consequently, greater accuracy is achieved with a large image size.

Appendix D Operation of CASMAIN.EXE

This appendix details the operation of CASMAIN.EXE, the CAS Database management system written in Clipper.

Before this program presents the menu to the user, it updates all databases by reading the files detailing stock usage during assembly, and stock transfers.

The program searches for existing *.STK and <PCB>.INV files. The *.STK files are used to update the CAS Database, while each <PCB>.INV file is used to update the associated <PCB>.DBF file. In this way, the outcome of any subsequent operations performed with the CAS Database will be accurate.

The user is then presented with a menu with the following choices:

- Stock System
- Assembly Planning System
- Utilities
- Exit

Each will be considered below.

D1 Stock System

The stock system is the means by which the user may add new components to the database, modify the details of any component in the database, or extract other useful information from the database.

The user is presented with a menu with the following entries:

- Add new component
- Modify existing component
- Delete existing component
- Display CAS Database
- Print WStn loading report
- Return to Main Menu (Esc)

D1.1 Add New Component

This option allows the user to add a new component to the database. The user may edit all fields.

By pressing F1, the user is able to activate the on-line help facility. This facility provides an explanation for each field. The details presented depend on the location of the cursor when F1 was pressed.

By pressing F10, the user is able to view the workstation loading report, discussed in Appendix D1.5 (p.185). If the station number field (StnNo) is blank, the user must select a workstation from the menu that appears. If the field is not blank, the menu is by-passed, and the correct loading report is displayed.

D1.2 Modify Existing Component

This option allows the user to update any field for any component. A pick-list of all components is presented to the user, from which the required component is selected. The pick-list includes a search facility. The user presses a key and the system will display the first component for which the key pressed matches the first letter of Desc1.

By pressing F1, the user is able to activate the on-line help facility. This facility provides an explanation for each field. The details presented depend on the location of the cursor when F1 was pressed.

By pressing F10, the user is able to view the workstation loading report, discussed in Appendix D1.5 (p.185). If the station number field (StnNo) is blank, the user must select a workstation from the menu that appears. If the field is not blank, the menu is by-passed, and the correct loading report is displayed.

D1.3 Delete Existing Component

This option allows the user to delete any component from the database. A pick-list of all components is presented to the user, from which the required component is selected. This pick-list also includes a search facility. The user is presented with all the details of the component and prompted to confirm deletion.

D1.4 Display CAS Database

This option allows the user to view the entire contents of the database. A second menu is shown with the following choices:

- Index on Description (Screen)
- Index on Addresses (Screen)
- Index on Description (Printer)
- Index on Addresses (Printer)

This menu allows the user to direct the output to the screen or the printer. The CAS Database is indexed either on the descriptions (Desc1 + Desc2 + Desc3), or on the workstation addresses (StnNo + StnLocX + StnLocY + StnLocZ).

D1.5 Print WStn Loading Report

The following menu is presented to the user:

- Workstation 1
- Workstation 2
- Workstation 3

After selecting a workstation the program prints a table that shows how many components are located at each workstation location. This table assists in allocating workstation addresses to new components.

D1.6 Return to Main Menu (Esc)

This option allows the user to return to the main menu. This option may also be activated by pressing escape.

D2 Assembly Planning System

The assembly planning system is the means by which the design data is converted into production assistance data, and the user is informed of what action must be taken before assembly can commence.

The user is presented with a menu with the following entries:

- View Work In Progress (WIP)
- Activate new PCB
- De-activate PCB
- Display partial PCB data
- Display complete PCB data
- Print partial PCB data
- Print <PCB>.ODR file
- Return to Main Menu (Esc)

D2.1 View Work In Progress (WIP)

This option accesses the database listing the orders currently in progress (ACVTPCBS.DBF). The structure of the database is shown in Table D-1 (p.186).

Table D-1 Structure of the Work In Progress (WIP) database

Field	Type	Width	Description
FileName	Character	8	Generic name of PCB files.
Descriptn	Character	35	Description of PCB or order.
QtyToAsble	Numeric	3	Order quantity.
Status	Character	10	Status of order.
DueDate	Character	8	Date order is due.
Date	Character	8	Date file was processed.
Time	Character	5	Time file was processed.
Cost	Numeric	6,2	Cost of product.

The Status field contains the number of components for which the workstation quantity is insufficient for production.

D2.2 Activate New PCB

With this option, the user may add a PCB to the list of WIP.

The user is presented with a list of <PCB>.INS files. The list excludes those for which the file name matches the FileName field in the list of orders already in progress. Consequently, each product can be activated only once, unless the files are duplicated, and given a different name.

Having selected a file, the user is able to enter the quantity of PCBs to assemble, a description of the product, and the due date for the order.

Following this, the system generates two databases, checks the stock levels, produces the assembly order information, and adds the order to the list of WIP. These operations are entirely automatic, however, the user is constantly informed of progress.

(i) The Assembly Order Database

Filename: <PCB>!.DBF

This database contains one record for *every* component listed in the <PCB>.INS file. This database is used for generating the <PCB>.ODR file.

The structure of the database is shown in Table D-2 (p.187).

Table D-2 Structure of the Assembly Order database

Field	Type	Width
Comp_Side	Character	2
RefDes	Character	8
Desc1	Character	20
Desc2	Character	20
Desc3	Character	20
Height	Numeric	4,1
Fragility	Numeric	1
StnNo	Character	1
StnLocX	Character	2
StnLocY	Character	2
StnLocZ	Character	2
Polarity	Logical	1

(ii) The Allocated-Stock Database

Filename: <PCB>.DBF

The second database, referred to as the allocated-stock database, contains one record for every *different* component. The system calculates how many of each component are on a board, as well as the total quantity required to complete the order. This database is used for calculating the effect the order has on stock levels.

The structure of the database is shown in Table D-3 (p.188).

(iii) Stock Level Checking

The system allocates stock to the order by reducing the workstation quantity (StnQty) field in

Table D-3 Structure of the Allocated-Stock database

Field	Type	Width	Description
Desc1	Character	20	Description 1
Desc2	Character	20	Description 2
Desc3	Character	20	Description 3
QtyPerPCB	Numeric	4	Number of components per PCB
QtyAlloctd	Numeric	4	Total number of components required for order
StockOK	Logical	1	True *only* if sufficient components are available at the workstation to complete order
Purchase	Numeric	4	Number of components to purchase
Transfer	Numeric	4	Number of components to transfer from the Main Store to the workstation
Exception	Logical	1	True if the component is not recognised
Cost	Numeric	6,2	Total cost for this component
StnNo	Character	1	Station number at which component is located

the CAS Database by the quantity shown in the quantity allocated to the order (QtyAlloctd) field in the allocated-stock database. It then determines the effect the order has on the workstation store and Main Store stock levels. If components must be transferred from the Main Store to the workstation, the Transfer field is set equal to the workstation reorder quantity (StnROQ). If components must be purchased, the Purchase field is set equal to the Main Store reorder quantity (PurchROQ).

While the stock checking process is in operation, a record is kept of the number of components either, not recognised, or for which the workstation quantity is insufficient for production.

(iv) Assembly Order Information Generation

Next, the system generates the <PCB>.ODR file. This is produced from the <PCB>!.DBF database, which is indexed on workstation number (StnNo), Height, Fragility, and the three workstation locations (StnLocX, StnLocY, StnLocZ).

(v) Add Order to List of WIP

If all operations are successful, the order is added to the list of WIP. The Status field is updated as follows:

- if all components are recognised, and the quantity of each component at the workstation is sufficient for production the field will be set to "All OK", otherwise
- the field will be set to "*x* not OK", where *x* is the number of components either not recognised, or not available in sufficient quantities at the workstation for production.

Finally, the program displays a partial listing of the allocated-stock database. This listing is discussed fully in Appendix D2.4 (p.189).

D2.3 De-activate PCB

With this option, the user may remove a PCB from the list of WIP. This is normally done when the order is complete. The user is presented with a pick-list of the orders from which one is selected. The user is asked to confirm removal. If confirmation is given, the allocated-stock database described in Appendix D2.2(ii) (p.187) is de-allocated. The stock is de-allocated by adding the QtyAlloctd field to the StnQty field in the CAS Database. If the correct quantity of PCBs was assembled, the QtyAlloctd would equal 0. Finally, the two databases, <PCB>.DBF and <PCB>!.DBF, are deleted.

There is no short-cut for re-validating the orders in the list of WIP. The user must first de-activate the order, and then re-activate it. This method is considered more robust than the re-validation method, since all databases and output files are recreated, thereby ensuring they are fully up-to-date.

D2.4 Display Partial PCB Data

With this option, the components in the allocated-stock database (<PCB>.DBF) that: are not recognised; are not available in sufficient quantities for production; require transfer from the Main Store to the workstation; or require purchasing are displayed.

The data displayed includes:

- the component descriptions,
- the quantity of components per PCB,
- the status of the availability of the component: "√" if the component is available in sufficient quantity, "Problem" if not, or if not recognised,
- the quantity of components that must be purchased. This will either equal zero, or the PurchROQ field in the CAS Database,
- the quantity of components that must be transferred from the Main Store to the workstation. This will either equal zero, or the StnROQ field in the CAS Database, and

- whether the component is not recognised: "Yes" if not recognised, "-" if recognised.

D2.5 Display Complete PCB Data

With this option, all components in the allocated-stock database (<PCB>.DBF) are displayed.

The data displayed includes:

- the component descriptions,
- the quantity of components per PCB,
- the status of the availability of the component: "√" if the component is available in sufficient quantity, "Problem" if not, or if not recognised,
- the quantity of components that must be purchased. This will either equal zero, or the PurchROQ field in the CAS Database,
- the quantity of components that must be transferred from the Main Store to the workstation. This will either equal zero, or the StnROQ field in the CAS Database, and
- whether the component is not recognised: "Yes" if not recognised, "-" if recognised.

D2.6 Print Partial PCB Data

This option is identical to the "Display partial PCB data" option, as discussed in Appendix D2.4 (p.189), except that the output is directed to the printer, and not the screen.

D2.7 Print <PCB>.ODR File

This option presents a pick-list to the user of all PCBs listed in the database of WIP (ACVTPCBS.DBF). After selecting a PCB, a printout of the <PCB>.ODR file is produced.

D2.8 Return to Main Menu (Esc)

This option allows the user to return to the main menu. This option may also be activated by pressing escape.

D3 Utilities

The utilities system is the means by which system parameters may be modified, and data files managed.

The user is presented with a menu with the following entries:

- Backup files

- Restore files
- Re-index CAS Database
- Setup
- Return to Main Menu (Esc)

D3.1 Backup Files

This option allows the user to backup data files to a floppy disk.

D3.2 Restore Files

This option allows the user to restore data files from a floppy disk.

D3.3 Re-index CAS Database

This option re-indexes the CAS Database. Although this is performed automatically when necessary, this option may occasionally be used to force a re-index.

D3.4 Setup

This option allows the user to set up the directories. The directories that may be altered include:

- the location of database data files,
- the location of Clipper executable files,
- the location of PCB design files, and
- the location of inventory files.

D3.5 Return to Main Menu (Esc)

This option allows the user to return to the main menu. This option may also be activated by pressing escape.

D4 Exit

This option allows the user to exit the program. Upon exiting, the program will recreate DB-LIST.CAS, a text file containing the CAS Database information, delimited with commas.

Appendix E Assembly Order Information Generation

This appendix contains a sample of the assembly order information file.

```
%*******************************************************************
%                                                                  *
%               PC Placement Order File                            *
%                                                                  *
%                                                                  *
% Date     :  Wednesday 29 June  1994                              *
% Time     :  22:13:04                                             *
% File In  :  EXPT.INS                                             *
% File Out :  EXPT.ODR                                             *
%                                                                  *
%*******************************************************************
$FORMAT
 REFDES  WKSTN  ADDR1  ADDR2  ADDR3  POLAR
    ZD1      2      1     10      0      T
    R14      2      1      1      0      F
     C3      3      4      1      0      F
    IC5      3     10      1      0      T
    IC1      3     12      1      0      T
     C4      3      7      1      0      F
     C2      3     15      1      0      T
$END
```

Appendix F Merge Data

This appendix contains the details of the operation of the data merger.

F1 Operation of Data Merger

When the merger is activated, it searches for pairs of <PCB>.INS and <PCB>.ODR files. Those which are found are presented to the user in a pick-list. The user either selects a pair, or presses escape. If the user presses escape, the program is terminated.

If the selection of input files is successful, the merger checks if an output file exists. If a file does exist, the user is asked to confirm replacement of the file.

If confirmation is given, the program processes the input files and generates the output file automatically. The output file contains the information from both input files, and the order corresponds to the order of the <PCB>.ODR file. The output file is a file of Turbo Pascal records.

Appendix G Assembly

This appendix contains the details of the assembly program.

In particular, the following aspects will be discussed:

- the operation of the assembly system, including menu options, and
- the magnification facility.

G1 Operation of the Assembly System

When the assembly system is activated, it searches for pairs of <PCB>.OVL and <PCB>.CPT files. Those which are found are presented to the user in a pick-list. The user either selects a pair, or presses escape. If the user presses escape, the program is terminated.

If the selection of input files is successful, the program reads the two data files, storing the information in memory. The user is then presented with a menu with the following options:

- begin assembling a new PCB,
- enable or disable the recording of stock usage,
- enable or disable the storage device,
- help, and
- quit the assembly system.

Having chosen to assemble a new PCB, the user is presented with a graphic image of the product, with the first component(s) for insertion highlighted. This is shown in Exhibit 7-4 (p.139).

G1.1 Effect of Menu Options

If the user has enabled the recording of stock usage, then after choosing to begin assembly of a new PCB, the user will be prompted to enter the batch size. Then, assembly will proceed normally.

If assembly is interrupted, for example when assembly is not completed at the end of a day, the system must enable the user to continue assembly at a later date from the point at which it was interrupted, without delay or the generation of erroneous stock records.

This may be achieved by disabling both the storage device and the recording of stock. The user may then step through each of the components already inserted, and then exit to the menu and enable both the storage device, and the recording of stock records. Assembly then proceeds as in the case above.

If the user exits from the assembly system back to the menu, an extra choice is given. This choice allows the user to continue assembly of the current product.

G2 Magnification

To aid the assembly process, the image of the PCB can be scaled up and down. Five scaling functions are included:

- the page up key enlarges the PCB by a specific factor,
- the page down key reduces the PCB by a specific factor,
- the home key returns the PCB to the original size, a scale of 1:1,
- the end key scales the PCB such that it fits exactly into the viewing window, and
- the insert key allows the user to enter any scale factor.

At the lower right corner of the screen, the current magnification scale is displayed.

Magnification is essential as it allows the user to select the most suitable size of the displayed PCB regardless of the actual board size, or of the scaling of the <PCB>.OVL data.

Appendix H Stock Management System

This appendix contains the details of the stock management system.

In particular, the following aspects will be discussed:

- the operation of the stock management system, including the screen format for each mode of operation,
- the facility for manual control of the storage device, and
- the contents of output files.

H1 Operation of the Stock Management System

When the stock management system is activated, a menu is presented to the user allowing the user to operate the system in one of five modes:

- Transfer stock from Store to Workstation, Figure 7-5 (p.143),
- Transfer stock from Workstation to Store, Figure 7-5 (p.143),
- Miscellaneous stock usage, Figure 7-6 (p.144),
- Inward goods, Figure 7-6 (p.144),
- Stock take, Figure 7-7 (p.145), and
- Quit.

If the user selects a choice other than to quit the program, the system reads the DB-LIST.CAS file and stores it in memory.

The system will search for existing output files (*.STK, and *.INV), and will also read these, modifying the data stored in memory as required. In this way, the data presented to the user reflects actual stock levels even though the data in the CAS Database may not be fully up-to-date.

The user may change modes by exiting back to the menu and re-selecting a new operating mode. Each time a mode is exited, an output file is generated detailing the transactions performed.

The data is presented to the user as a pick-list, however, the format of the data depends on the location of the program, and the mode in which the system operates. Common to all, however, is the display of the three component descriptions. For consistency, the Main Store quantity is always displayed before the workstation quantity.

Additional information displayed for each mode will be considered.

H1.1 Stock Transfers Within the Manufacturing Pilot Plant

In this mode, the contents of the pick-list depend on the location.

If the location is the Main Store from which components are transferred to a workstation, the pick-list contains:

- the Main Store quantity on-hand,
- the identification of the workstation at which the component is located,
- the workstation quantity on-hand, and
- the workstation reorder quantity.

If the location is a workstation from which components are transferred back to the Main Store, the pick-list contains:

- the Main Store quantity on-hand, and
- the workstation quantity on-hand.

If the location is the destination of the components the pick-list contains:

- the local store quantity on-hand, and
- the quantity to add to the local store.

H1.2 Miscellaneous Stock Usage

In this mode, the user is presented with a pick-list displaying the local store quantity on-hand.

H1.3 Inward Goods

In this mode, the user is presented with a pick-list displaying the following information:

- the local store quantity on-hand, and
- the local store reorder quantity.

H1.4 Stock Take

In this mode, the user is presented with a pick-list displaying the local store quantity on-hand.

H1.5 General Features of the Pick-List

The pick-list includes a search facility allowing the user to rapidly find a particular component.

Navigation about the pick-list is also possible with the up and down arrow keys, and the page up, page down, home and end keys.

A specific component is selected by pressing the enter key.

When depositing or withdrawing components, the user is always prompted to enter a positive value. This significantly reduces confusion.

The text of components that have been selected is subsequently displayed in a darker colour to ensure the user is fully aware of progress.

H2 Manual Control of Storage Device

The stock management system includes a facility for manual control of the workstation storage devices. By pressing the space bar the user has full control of the device, and may access any storage bin, by pressing the up and down arrow keys, or the left and right arrow keys, depending on the physical characteristics of the workstation.

H3 Characteristics of Output Files

The name of the output file reflects the content of the file, as well as the location at which the file was produced, and the destination of the file.

Two types of files are used: *.STK, and *.TRN.

The format of both files is identical. The data contained in the files includes: the three component descriptions, the quantity added to the Main Store, and the quantity added to the workstation store. In the case of inward goods, miscellaneous stock usage, and stock take, one of the two quantities will always equal zero.

The format of the two files is identical as a single procedure is used to read both files. The data for each component is stored in memory as a Turbo Pascal record. Each record includes logic flags that identify whether the transaction involves stock transfer, inward goods, miscellaneous stock usage, or stock take.

Of the two types of files, only the *.STK files are used to update the CAS Database.

Appendix I Data Sheets for Experiment

This appendix consists of representations of the information and data entry sheets used by participants in the experiment discussed in Chapter 8.

I1 Test Product Parts List

MANUFACTURING PILOT PLANT EXPERIMENT							
Test Product Parts List							
Component Descriptions			**Batch Size**				
Desc. 1	**Desc. 2**	**1**	**2**	**3**	**4**	**Ref. Desc.**	**Stn**
A. Wire Links							
Link		2	4	6	8	LK1,LK2	2
B. Resistors							
180 Ω		1	2	3	4	R14	2
820 Ω		1	2	3	4	R17	2
10 kΩ		2	4	6	8	R5,R13	2
10 kΩ	variable	1	2	3	4	R15	3
68 kΩ	0.67 W	2	4	6	8	R38,R39	3
100 kΩ		3	6	9	12	R11,R12,R36	2
100 kΩ	1%	6	12	18	24	R23-R28	2
200 kΩ	1%	10	20	30	40	R18-R22,R30-R34	2
910 kΩ	1%	1	2	3	4	R29	2
1 MΩ		2	4	6	8	R35,R37	2
4.7 MΩ		1	2	3	4	R16	2
10 MΩ		1	2	3	4	R10	2
C. Capacitors							
1 nF		1	2	3	4	C5	3
0.01 μF		1	2	3	4	C6	3
0.1 μF	yellow	1	2	3	4	C3	3
0.1 μF	blue	1	2	3	4	C4	3
0.15 μF		1	2	3	4	C1	3
1 μF		1	2	3	4	C7	3
2.2 μF		1	2	3	4	C2	3
D. Diodes							
1N4007		4	8	12	16	D1-D4	2
1N4148		2	4	6	8	D5,D7	2
BZX7965V6		1	2	3	4	ZD1	2
E. Integrated Circ.							
4518		0	0	0	0		3
4543		0	0	0	0		3
40106		0	0	0	0		3
LM358		0	0	0	0		3
F. Transistors							
BC337		1	2	3	4	Q1	3
G. Displays							
F2113		0	0	0	0		3

I2 Main Store Records

MANUFACTURING PILOT PLANT EXPERIMENT				
Main Store Records				
Description 1	**Description 2**	**Stock level**	**Reorder level**	**Reorder quantity**
A. Wire Links				
Link		51	50	50
B. Resistors				
180 Ω		30	20	50
820 Ω		32	20	50
10 kΩ		21	10	50
10 kΩ	variable	15	10	50
68 kΩ	0.67W	50	30	50
100 kΩ	1%	43	20	50
100 kΩ	1%	32	30	50
200 kΩ	1%	50	45	100
910 kΩ		20	10	20
1 MΩ		28	15	50
4.7 MΩ		40	10	50
10 MΩ		33	10	50
C. Capacitors				
1 nF		21	10	50
0.01 μF		29	10	50
0.1 μF	yellow	25	10	50
0.1 μF	blue	33	10	50
0.15 μF		25	10	50
1 μF		27	10	50
2.2 μF		29	10	50
D. Diodes				
1N4007		21	20	50
1N4148		46	20	50
BZX7965V6		36	20	50
E. Integrated Circ.				
4518		33	20	50
4543		21	20	50
40106		28	20	50
LM358		40	20	50
F. Transistors				
BC337		35	20	20
G. Displays				
F2113		49	20	50

I3 Data Entry Sheet

MANUFACTURING PILOT PLANT EXPERIMENT

<u>Data Sheet</u>

Name: Batch size:

Experience with PCB assembly:

Assembly method: Manual / CAS

1: Updating stock records

Start:	Finish:	Comment:

2: Kitting

Labelling and filling bins

Start:	Finish:	Comment:

3: Assembly of wire links, small resistors and diodes

Task	Start	Finish	Comment
Assembly			
Soldering			

4: Assembly of capacitors, large resistor, and transistor

Task	Start	Finish	Comment
Assembly			
Soldering			

5: Lead clipping

Start:	Finish:	Comment:

Comments

I4 Component Order Form

MANUFACTURING PILOT PLANT EXPERIMENT

Component Order Form

Batch size:

No.	Description(s)	Quantity Ordered
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

I5 Complete Results for Trial 1

Table I-1 (p.203) contains the complete results of Trial 1.

Table I-1 Complete process-time results for Trial 1

	CAS Assembly					Conventional Assembly				
Batch Size	1	2	3	4	Av.	1	2	3	4	Av.
Stock check	1:00	1:00	1:00	1:00	**1:00**	2:40	-	4:00	3:00	**2:25**
Setup	6:30	6:00	7:00	6:00	**6:20**	9:20	8:00	21:00	8:50	**11:50**
Assembly (1)	10:00	27:00	28:00	50:00	**28:45**	10:50	26:30	32:00	32:30	**25:30**
Soldering (1)	7:40	23:30	17:30	13:00	**15:25**	6:00	21:10	18:00	23:50	**17:15**
Assembly (2)	8:00	10:20	7:30	13:00	**9:40**	3:00	14:40	10:00	6:00	**8:25**
Soldering (2)	5:50	7:30	7:30	7:00	**7:00**	2:00	10:40	9:00	11:00	**8:10**
Lead clipping	-	3:00	13:40	12:00	**7:10**	3:00	9:50	9:00	14:00	**9:00**
TOTAL	**39:00**	**78:20**	**82:10**	**102:00**	**75:20**	**36:50**	**90:50**	**103:00**	**99:10**	**82:35**

Note: all times shown in minutes

I6 Complete Results for Trial 2

Table I-2 (p.203) contains the complete results of Trial 2.

Table I-2 Complete process-time results for Trial 2

	CAS Assembly					Conventional Assembly				
Batch Size	1	2	3	4	Av.	1	2	3	4	Av.
Stock Check	0:25	0:20	0:20	0:20	**0:20**	1:50	2:20	2:30	2:10	**2:15**
Setup	2:10	2:40	3:00	3:00	**2:45**	5:50	6:30	6:40	8:40	**6:55**
Assembly (1)	6:30	11:00	15:30	20:20	**13:20**	10:40	16:40	21:20	24:00	**18:10**
Soldering (1)	2:50	5:00	8:10	10:20	**6:35**	3:50	6:10	8:50	11:10	**7:30**
Assembly (2)	2:00	3:00	4:10	5:50	**3:45**	3:10	3:40	5:00	6:30	**4:35**
Soldering (2)	1:30	2:30	3:00	4:40	**2:55**	2:00	2:50	3:40	5:10	**3:25**
Lead clipping	1:30	3:30	4:10	6:00	**3:50**	2:10	3:50	4:30	6:50	**4:20**
TOTAL	**16:55**	**28:00**	**38:20**	**50:30**	**33:30**	**29:30**	**42:00**	**52:30**	**64:30**	**47:10**

Note: all times shown in minutes

Appendix J CAS System Source Code

A copy of the source code of the CAS system software may be borrowed from:

Dr. Ross R. Nilson

Department of Production Technology

Massey University

Private Bag 11222

Palmerston North

Phone: (06) 356-9099 (Ext. 4084)

References

1 **Skinner, W.**

'The Focused Factory'. *Harvard Business Review*, May-June, 1974. pp.113-121.

2 **Hammer, M.**

'Reengineering Work: Don't Automate, Obliterate'. *Harvard Business Review*, July-August, 1990. pp.104-112.

3 **Stewart, T.A.**

'Reengineering: The Hot New Managing Tool'. *Fortune*, August 23, 1993. pp.25-29.

4 **Young, S.**

'Manufacturing Strategy as a Competitive Weapon'. *Industrial Management and Data Systems*, Volume 91, Number 6, 1991. pp.10-16.

5 **Clark, K.B.**

'What Strategy can do for Technology'. *Harvard Business Review*, November-December, 1989. pp.94-98.

6 **Graham, I.**

'Just-in-Time Management of Manufacturing'. Technical Communications and Elsevier Science Publishers, 1988.

7 **Ashton, J.E. and Cook, F.X.**

'Time to Reform Job Shop Manufacturing'. *Harvard Business Review*, March-April, 1989. pp.106-111.

8 **Bassett, G.**

'Job-shop Operations Reform: Strategies for Achieving Queueless Work Flow'. *International Journal of Operations and Production Management*, Volume 11, Number 7, 1991. pp.55-71.

9 **Pels, H.J. and Wortmann, J.C.**

'Modular Design of Integrated Databases in Production Management Systems'. *Production Planning and Control*, Volume 1, Number 3, 1990. pp.132-146.

10 **Ashton, J.E., Johnson, M.D. and Cook, F.X.**

'Shop Floor Control in a System Job Shop: Definitely not MRP'. *Production and Inventory Management Journal*, Second Quarter, 1990. pp.27-31.

11 **Gunn, T.**

'The Mechanisation of Design and Manufacturing'. An article in 'Capabilities of Group Technology', published by The Computer and Automated Systems Association of SME, 1987. Dearborn, Michigan. pp.31-46.

12 **Hitomi, K.**

'Non-Mass, Multi-Product, Small-Sized Production: The State of the Art'. *Technovation*, Volume 9, 1989. pp.357-369.

13 **Brown, D.H.**

'Production Information Management: The Great Orchestrator'. *Computer-Aided Engineering*, May, 1991. pp.60-66.

14 **Kochan, A.**

'BAe Ambitions are about to be Realised', *The FMS Magazine*, Volume 5, Number 2, 1987. pp.63-67.

15 **Chevalier, P.W.**

'Group Technology: The Connecting Link to Integration of CAD and CAM'. An article in 'Capabilities of Group Technology', published by The Computer and Automated Systems Association of SME, 1987. Dearborn, Michigan. pp.51-64.

16 **Weston, F.C.**

'Functional Goals are Often in Conflict with Each Other'. *Industrial Engineering*, November, 1991. pp.25-29.

17 **Kim, C.**

'Issues on Manufacturing Flexibility'. *Integrated Manufacturing Systems*, Volume 2, Number 2, 1991. pp.4-13.

18 **De Toni, A. and Panizzolo, R.**

'Repetitive and Intermittent Manufacturing: Comparison of Characteristics'. *Integrated Manufacturing Systems*, Volume 3, Number 4, 1992. pp.23-37.

19 **Arn, E.A.**

'Group Technology: An Integrated Planning and Implementation Concept for Small and Medium Batch Production'. Springer - Verlag, Berlin, Heidelburg, New York 1975.

20 **Goldhar, J.D. and Schlie, T.W.**

'Computer Technology and International Competition: Part 1: The Factory of the Future'. *Integrated Manufacturing Systems*, Volume 2, Number 1, 1991. pp.16-22.

21 **Schonberger, R.J.**

'World Class Manufacturing: The Lessons of Simplicity Applied'. The Free Press, 1986.

22 **Ingersoll Engineers.**

'Integrated Manufacture'. IFS (Publications) Ltd, Ingersoll Engineers, 1985.

23 **Warndorf, P.R. and Merchant, M.E.**

'Development and Future Trends in Computer Integrated Manufacturing in the USA'. *International Journal of Technology Management*, Volume 1, Numbers 1&2, 1986. pp.161-178.

24 **Crowe, T.J.**

'Integration is Not Synonymous with Flexibility'. *International Journal of Operations and Production Management*, Volume 12, Number 10, 1992. pp.26-33.

25 **Bessant, J. and Buckingham, J.**

'Implementing Integrated Technology'. *Technovation*, Volume 9, 1989. pp.321-336.

26 **Ebers, M. and Lieb, M.**

'Computer Integrated Manufacturing as a Two-Edged Sword'. *International Journal of Operations and Production Management*, Volume 9, Number 2, 1989. pp.69-92.

27 **Hitomi, K.**

'Strategic Integrated Manufacturing Systems: The Concepts and Structures'. *International Journal of Production Economics*, Volume 25, 1991. pp.5-12.

28 **Benhabib, B., Charania, M., Cupillari, A., Fenton, R.G. and Turksen, I.B.**

'CIM Implementation for Job-Shop Environments'. *Production Planning and Control*, Volume 1, Number 4, 1990. pp.235-250.

29 **Kathawala, Y., Chawla, S. and Elmuti, D.**

'Some Strategic Aspects of Computer Integrated Manufacturing'. *Integrated Manufacturing Systems*, Volume 3, Number 1, 1992. pp.27-34.

30 **O'Rourke, J.T.**

'The Common Sense of CIM'. *Industrial Management and Data Systems*, Volume 90, Number 7, 1990. pp.3-8.

31 **King, W.R. and Ramamurthy, K.**

'Do Organisations achieve their objectives for Computer Based Manufacturing Technology?'. *IEEE Transactions on Engineering Management*, Volume 39, Number 2, 1992. pp.129-141.

32 **Goldhar, J.D. and Schlie, T.W.**

'Computer Technology and International Competition: Part 2: Managing the "Factory of the Future" to Achieve Competitive Advantage'. *Integrated Manufacturing Systems*, Volume 2, Number 2, 1991. pp.22-30.

33 **Aletan, S.**

'The Components of a Successful CIM Implementation'. *Industrial Engineering*, November, 1991. pp.20-22.

34 **Lei, D. and Goldhar, J.D.**

'Computer Integrated Manufacturing (CIM): Redefining the Manufacturing Firm into a Global Service Business'. *International Journal of Operations and Production Management*, Volume 11, Number 10, 1991. pp.5-18.

35 **Tunc, E.A. and Gupta, J.N.D.**

'Is Time a Competitive Weapon Among Manufacturing Firms?'. *International Journal of Operations and Production Management*, Volume 13, Number 3, 1993. pp.4-12.

36 **Vesey, J.T.**

'Meet the New Competitors: They Think in Terms of Speed-to-Market'. *Industrial Engineering*, December, 1990. pp.20-26.

37 **Youssef, M.A.**

'Agile Manufacturing: A Necessary Condition for Competing in Global Markets'. *Industrial Engineering*, December, 1992. pp.18-20.

38 **Higgins, P. and Browne, J.**

'Master Production Schedule: A concurrent Planning Approach'. *Production Planning and Control*, Volume 3, Number 1, 1992. pp.2-18.

39 **Rae, A.**

'A Survey of Independent CIM Centres in the UK'. *The FMS Magazine*, Volume 6, Number 3, 1988. pp.155-158.

40 **Sarkis, J.**

'Production and Inventory Control Issues in Advanced Manufacturing Systems'. *Production and Inventory Management Journal*, First Quarter, 1991. pp.76-82.

41 **Remenyi D.S.J.**

'Introducing Strategic Information Systems Planning (SISP)'. NCC Blackwell Ltd, 1991.

42 **Ptak, C.A.**

'MRP, MRP II, OPT, JIT and CIM - Succession, Evolution or Necessary Combination?'. *Production and Inventory Management Journal*, Volume 32, Number 2, 1991. pp.7-11.

43 **Eidenmuller, B.**

'CIM and Logistics in the Factory of the Future'. *Production Planning and Control*, Volume 1, Number 2, 1990. pp.72-78.

44 **Kidd, P.T.**

'Organisation, People and Technology: Advanced Manufacturing in the 1990s'. *Computer Aided Engineering Journal*, October, 1990. pp.149-153.

45 **Twigg, D., Voss, C.A. and Winch, G.M.**

'Implementing Integrating Technologies: Developing Managerial Integration for CAD/CAM'. *International Journal of Operations and Production Management*, Volume 12, Number 7&8, 1992. pp.76-91.

46 **Hayes, R.H. and Clark, K.B.**

'Why Some factories are more Productive than Others'. *Harvard Business Review*, September-October, 1986. pp.66-73.

47 **Giust, L.**

'Just-in-Time Manufacturing and Material Handling Trends'. *Industrial Management and Data Systems*, Volume 93, Number 1, 1993. pp.3-9.

48 **Arogyaswamy, B. and Simmons, R.P.**

'Thriving on Interdependence: The Key to JIT Implementation'. *Production and Inventory Management Journal*, Volume 32, Number 3, 1991. pp.56-60.

49 **Heiko, L.**

'A Simple Framework for Understanding JIT'. *Production and Inventory Management Journal*, Fourth Quarter, 1989. pp.61-63.

50 **Crawford, K.M. and Cox, J.F.**

'Addressing Manufacturing Problems Through the implementation of JIT'. *Production and Inventory Management Journal*, Volume 32, Number 1, 1991. pp.33-36.

51 **Rao, A. and Scheraga, D.S.**

'Moving from Manufacturing Resource Planning to Just-in-Time Manufacturing'. *Production and Inventory Management Journal*, First Quarter, 1988. pp.44-49.

52 **Goldratt, E.M.**

'What is This Thing Called Theory of Constraints and How Should it be Implemented?'. North River Press, Inc, 1990.

53 **Cheng, T.C.E.**

'Some Thoughts on the Practice of Just-In-Time Manufacturing'. *Production Planning and Control*, Volume 2, Number 2, 1991. pp.167-178.

54 **Voss, C. and Clutterbuck, D.**

'Just-in-Time: A Global Status Report'. IFS Ltd and Springer-Verlag, 1989.

55 **Maskell, B.**

'MRP II or Just-in-Time: Which Way to Productivity? *Management Accounting*, January, 1989. pp.34-35.

56 **Jordan, H.H.**

'Inventory Management in the JIT Age'. *Production and Inventory Management Journal*, Third Quarter, 1988. pp.57-59.

57 **Shingo, S.**

'A Study of the Toyota Production System: From an Industrial Engineering Viewpoint'. Productivity Press, Connecticut, 1989.

58 **Westbrook, R.**

'Time to Forget "Just-in-Time"? Observations on a Visit to Japan'. *International Journal of Operations and Production Management*, Volume 8, Number 4, 1988. pp.5-21.

59 **Safayeni, F., Purdy, L., van Engelen, R. and Pal, S.**

'Difficulties of Just-in-Time Implementation: A Classification Scheme'. *International Journal of Operations and Production Management*, Volume 11, Number 7, 1991. pp.27-36.

60 **Giunipero, L.C. and Law, W.K.**

'Organisational Support for Just-in-Time Implementation'. *The International Journal of Logistics Management*, Volume 1, Number 2, 1990. pp.35-40.

61 **Walleigh, R.C.**

'What's Your Excuse for not Using JIT?' *Harvard Business Review*, March-April, 1986. pp.38-54.

62 **Malley, J.C. and Ray, R.**

'Informational and Organisational Impacts of Implementing a JIT System'. *Production and Inventory Management Journal*, Second Quarter, 1988. pp.66-70.

63 **Johnston, S.K.**

'JIT: Maximising its Success Potential'. *Production and Inventory Management Journal*, First Quarter, 1989. pp.82-86.

64 **Pennucci, N.J.**

'Just-in-Time for a Change'. *Quality Progress*, November, 1987. pp.67-68.

65 **Plenert, G.**

'Three Differing Concepts of JIT'. *Production and Inventory Management Journal*, Second Quarter, 1990. pp.1-2.

66 **Lambrecht, M.R. and Decaluwe, L.**

'JIT and Constraint Theory: The Issue of Bottleneck Management'. *Production and Inventory Management Journal*, Third Quarter, 1988. pp.61-65.

67 **Burnham, J.M.**

'Some Conclusions About JIT Manufacturing'. *Production and Inventory Management Journal*, Third Quarter, 1987. pp.7-11.

68 **Johnson, D. and LaBarre, J.**

'Inventory Control: A Target for MIS Support'. *Production and Inventory Management Journal*, Volume 32, Number 1, 1991. pp.62-65.

69 **Peters T.J. and Waterman, R.H.**

'In Search of Excellence: Lessons from America's Best-Run Companies'. Harper and Row, Publishers, 1991.

70 **Hyer, N.L. and Wemmerlöv, U.**

'Group Technology and Productivity'. An article in 'Capabilities of Group Technology', published by The Computer and Automated Systems Association of SME, 1987. Dearborn, Michigan. pp.3-12.

71 **Fry, T.D., Wilson, M.G. and Breen, M.**

'A Successful Implementation of Group Technology and Cell Manufacturing'. *Production and Inventory Management*, Third Quarter, 1987. pp.4-6.

72 **Guerrero, H.H.**

'Group Technology: II. The Implementation Process'. *Production and Inventory Management*, Second Quarter, 1987. pp.1-9.

73 **Billo, R.E., Rucker, R. and Shunk, D.L.**

'Enhancing Group Technology Modelling with Database Abstractions'. *Journal of Manufacturing Systems*, Volume 7, Number 2, 1988. pp.95-106.

74 **Nolen, J.**

'Group Technology and Computer Integrated Manufacturing'. An article in 'Capabilities of Group Technology', published by The Computer and Automated Systems Association of SME, 1987. Dearborn, Michigan. pp.13-20.

75 **Crowley, R.E.**

'Lets Discuss CAD/CAM Integration'. An article in 'Capabilities of Group Technology', published by The Computer and Automated Systems Association of SME, 1987. Dearborn, Michigan. pp.47-50.

76 **Guerrero, H.H.**

'Group Technology: I. The Essential Concepts'. *Production and Inventory Management*, First Quarter, 1987. pp.62-71.

77 **Gaither, N., Frazier, G.V. and Wei, J.C.**

'From Job Shops to Manufacturing Cells'. *Production and Inventory Management Journal*, Fourth Quarter, 1990. pp.33-36.

78 **Tersine, R.J. and Tersine, M.G.**

'Inventory Reduction: Preventive and Corrective Strategies'. *The International Journal of Logistics Management*, Volume 1, Number 2, 1990. pp.17-24.

79 **Hyer, N.L.**

'MRP/GT A Framework for Production Planning and Control of Cellular Manufacturing'. An article in 'Capabilities of Group Technology', published by The Computer and Automated Systems Association of SME, 1987. Dearborn, Michigan. pp.351-366.

80 **Burbidge, J.L.**

'The Principles of Production Control'. MacDonald & Evans Ltd. Third Edition, 1971.

81 **Propen, M. and Hoffman, A.S.**

'Computer Aided Methods for Advanced Engine Design'. An article in 'Capabilities of Group Technology', published by The Computer and Automated Systems Association of SME, 1987. Dearborn, Michigan. pp.141-145.

82 **Marucheck A.S. and Peterson, D.K.**

'Microcomputer Planning and Control for the Small Manufacturer: Part I. MRP and Planning'. *Production and Inventory Management*, First Quarter, 1988. pp.34-37.

83 **Orlicky, J.**

'Material Requirements Planning: The New Way of Life in Production and Inventory Management'. McGraw-Hill Inc, 1975.

84 **Belt, B.**

'MRP and Kanban - A Possible Synergy?'. *Production and Inventory Management*, First Quarter 1987. pp.71-80.

85 **Aggarwal, S.C.**

'MRP, JIT, OPT, FMS? Making Sense of Production Operations Systems'. *Harvard Business Review*, September-October, 1985. pp.8-16.

86 **Kanet J.J.**

'MRP 96: Time to Rethink Manufacturing Logistics'. *Production and Inventory Management*, Second Quarter, 1988. pp.57-61.

87 **Sheldon, D.**

'MRP II - What it Really is'. *Production and Inventory Management Journal*, Third Quarter, 1991. pp.12-15.

88 **Goldratt, E.M. and Fox, R.E.**

'The Race'. North River Press Inc, 1986.

89 **Bloch, E. and Conrad, K.P.**

'Manufacturing Systems: Meeting the Competitive Challenge'. An article in 'Design and Analysis of Integrated Manufacturing Systems'. National Academy Press, 1988.

90 **Karmarkar, U.**

'Getting Control of Just-in-Time'. *Harvard Business Review*, September-October, 1989. pp.122-131.

91 **Reimer, G.**

'Material Requirements Planning and Theory of Constraints: Can they Coexist? A Case Study'. *Production and Inventory Management Journal*, Fourth Quarter, 1991. pp.48-52.

92 **Kirkwood, R., Smith, S. and Tranfield, D.**

'The Implementation Cube for Advanced Manufacturing Systems'. *International Journal of Operations and Production Management*, Volume 9, Number 8, 1989. pp.5-19.

93 **Starr, M.K.**

'How "Fast Response Organisations" Achieve Global Competitiveness'. *IEEE Engineering Management Review*, Volume 18, Number 4, December 1990. pp.85-89.

94 **Schroeder, R.G.**

'Operations Management: Decision Making in the Operations Function'. Third Edition. McGraw-Hill, Inc, 1989.

95 **Leong, G.K., Snyder, D.L. and Ward, P.T.**

'Research in the Process and Content of Manufacturing Strategy'. *OMEGA International Journal of Management Science*, Volume 18, Number 2, 1990. pp.109-122.

96 **Wisner, J.D. and Fawcett, S.E.**

'Linking Firm Strategy to Operating Decisions Through Performance Measurement'. *Production and Inventory Management Journal*, Volume 32, Number 3, 1991. pp.5-11.

97 **Collins Dictionary of the English Language.**

William Collins Sons & Co. Ltd, 1984.

98 **Burrows, P.**

'This Unisys Plant is Full of Surprises'. *Electronic Business*, February 19, 1990. pp.22-27.

99 **Microsoft MS-DOS Operating System Version 5.0 User's Guide and Reference.**

Microsoft Corporation, 1991.

100 **Hughes, J.**

'It's Methodology, Not Technology, that Counts'. *The FMS Magazine*, Volume 5, Number 2, 1987. pp.81-85.

101 **Taylor, J.**

'Information Systems and Structured Techniques'. *Industrial Management and Data Systems*, Volume 90, Number 7, 1990. pp.9-15.

102 **Flatau, U.**

'Designing an Information System for Integrated Manufacturing Systems'. An article in 'Design and Analysis of Integrated Manufacturing Systems'. National Academy Press, 1988.

103 **Burbidge, J.L.**

Letter in *Production Planning and Control*, Volume 1, Number 2, 1990. p.127.