Multi-flow control of flexible machining cells

This item was submitted to Loughborough University's Institutional Repository by the/an author.

Additional Information:


Metadata Record: [https://dspace.lboro.ac.uk/2134/27140](https://dspace.lboro.ac.uk/2134/27140)

Publisher: © S. Rahimifard

Rights: This work is made available according to the conditions of the Creative Commons Attribution-NonCommercial-NoDerivatives 2.5 Generic (CC BY-NC-ND 2.5) licence. Full details of this licence are available at: [http://creativecommons.org/licenses/by-nc-nd/2.5/](http://creativecommons.org/licenses/by-nc-nd/2.5/)

Please cite the published version.
This item was submitted to Loughborough University as a PhD thesis by the author and is made available in the Institutional Repository (https://dspace.lboro.ac.uk/) under the following Creative Commons Licence conditions.

For the full text of this licence, please go to: http://creativecommons.org/licenses/by-nc-nd/2.5/
Loughborough University
Multi Flow Control of Flexible Machining Cells

by

Shahin Rahimifard

A Doctoral Thesis
Submitted in Partial Fulfilment of the Requirements for the Award of Doctor of Philosophy of Loughborough University

Department of Manufacturing Engineering
August 1996

© 1996 S. Rahimifard
"Man is a user of tools. Those who recognise the tools of tomorrow and learn to use them today, assure themselves of a place in tomorrow's prosperity."

Anonymous
DECLARATION

No part of the work described in this thesis has been submitted in support of an application for any other degree or qualification of this or any other University, or the C.N.A.A or other institute of learning.
ACKNOWLEDGEMENTS

I wish to express my sincere thanks to my supervisor, Dr. S.T. Newman, for his direction, support, patience and friendship, and to Professor R. Bell, for his unique style of encouragement and special interest in this research. I am also grateful to my Director of Research, Dr. R. Jones for his sound advise in the latter part of the research. My thanks is also made to my colleague Mr. P. Coleman for his collaboration and helpfulness throughout the research.

I would like to offer my gratitude to fellow researchers at Loughborough University, especially Mr. T. Ellis, Dr. A. Molina, Mr. A. Zarifi, Mr. V. Botja, Mr. K. Toh, Mr. R. Monfared and Dr. J. Harding for the inspiring and helpful discussions. I am also indebted to Professor D.J. Williams, and in particular to Dr. A. West for their encouragement and understanding during the final stage of the research.

I would also like to thank Dr. N. Shires of The CIMulation Centre for his help in the development of the simulation models of the multi-flow controller. My thanks also goes to the following industrialists for their valuable time in participation and collaboration with the research: Mr. A. Langridge of ISIS Informatics Ltd, Mr. M. Pickering of Camtek Ltd, Dr. P. Mason and Mr. A. Edwards of Cincinnati Milacron UK Ltd, together with Mr. M. Novels and Mr. G. Hackwell of The CIMulation Centre. I am also grateful to the Design, Control and Production Group of EPSRC for the funding of the research programme.

Last but not least, I like to thank my entire family for their constant support, motivation and reassurance over the duration of the research.
SYNOPSIS

This thesis reports on the research carried out into the design and implementation of an integrated planning and control system, where the issues involved in the short term planning and control of the interrelated flows of workpieces, fixtures and cutting tools are addressed simultaneously. Multi-Flow Control is the research terminology used in this thesis for such a planning and control system. The principal objective of the research is to generate knowledge and generic solutions to harmonise the interactions between these three fundamental material flows within machining cells and to reduce the overall manufacturing cost.

The research contribution is divided into four major parts. The first part reviews the most relevant publications, together with the categorisation of the contemporary approaches to production planning and control. The second part is concerned with the realisation of a suite of software modules to demonstrate the proposed novel planning and control structure, namely the multi-flow controller. In the third part, three planning strategies are established, namely workpiece dominated, tool dominated and fixture dominated, together with a number of underpinning job allocation policies. The final part, explores a systematic method for the design, implementation, and analysis of a large number of computer-based experiments, using the multi-flow controller to assess the effectiveness of these planning strategies.

The multi-flow controller is shown to be a powerful method for planning and control of the three principal material flows within flexible machining environments. This has been achieved by the application of simulation techniques to the novel concept of parallel generation of schedules. The advantages of this approach shows a reduction in time and effort required for the production of schedules and reduces operational errors by synchronising the planning of the related flows. In addition, the research identifies various scenarios where reductions in manufacturing costs can be achieved by utilisation of the most appropriate job allocation policies.
## ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CAE</td>
<td>Computer Aided Engineering</td>
</tr>
<tr>
<td>CAP</td>
<td>Computer Aided Fixture Planning</td>
</tr>
<tr>
<td>CAM</td>
<td>Computer Aided Manufacture</td>
</tr>
<tr>
<td>CAP</td>
<td>Computer Aided Process Planning</td>
</tr>
<tr>
<td>CIM</td>
<td>Computer Integrated Manufacturing</td>
</tr>
<tr>
<td>CLS</td>
<td>CLuSter based job allocation policy</td>
</tr>
<tr>
<td>CLS_f</td>
<td>Fixture CLuSter based job allocation policy</td>
</tr>
<tr>
<td>CLS_t</td>
<td>Tool CLuSter based job allocation policy</td>
</tr>
<tr>
<td>CML</td>
<td>Combined Machine Loading job allocation policy</td>
</tr>
<tr>
<td>CMM</td>
<td>Coordinate Measuring Machines</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer Numerical Control</td>
</tr>
<tr>
<td>CTMS</td>
<td>Computerised Tool Management System</td>
</tr>
<tr>
<td>EDD</td>
<td>Earliest Due Date</td>
</tr>
<tr>
<td>FMC</td>
<td>Flexible Machining Cells</td>
</tr>
<tr>
<td>FMS</td>
<td>Flexible Manufacturing Systems</td>
</tr>
<tr>
<td>JIT</td>
<td>Just In Time</td>
</tr>
<tr>
<td>JP</td>
<td>Joblist Profile</td>
</tr>
<tr>
<td>LPT</td>
<td>Longest Processing Time</td>
</tr>
<tr>
<td>MH</td>
<td>Manufacturing Horizon</td>
</tr>
<tr>
<td>MML</td>
<td>Multi Machine Loading job allocation policy</td>
</tr>
<tr>
<td>MPS</td>
<td>Master Production Scheduling</td>
</tr>
<tr>
<td>MRP</td>
<td>Material Requirements Planning</td>
</tr>
<tr>
<td>MRP II</td>
<td>Manufacturing Resource Planning</td>
</tr>
<tr>
<td>NC</td>
<td>Numerical Control</td>
</tr>
<tr>
<td>No. TEA</td>
<td>Number of Toolkit Exchange Activities required</td>
</tr>
<tr>
<td>No. TJ</td>
<td>Number of Tardy Jobs</td>
</tr>
<tr>
<td>OPT</td>
<td>Optimised Production Technology</td>
</tr>
<tr>
<td>OR</td>
<td>Operations Research</td>
</tr>
<tr>
<td>PFM</td>
<td>Part and Fixture Matrix</td>
</tr>
<tr>
<td>PPC</td>
<td>Production Planning and Control</td>
</tr>
<tr>
<td>PTM</td>
<td>Part and Tool Matrix</td>
</tr>
<tr>
<td>SML</td>
<td>Single Machine Loading job allocation policy</td>
</tr>
<tr>
<td>SPT</td>
<td>Shortest Processing Time</td>
</tr>
<tr>
<td>TQF</td>
<td>Total Quantity of Fixtures of various types required</td>
</tr>
<tr>
<td>TRP</td>
<td>Tool Requirements Planning</td>
</tr>
<tr>
<td>WLB</td>
<td>WorkLoad Balancing</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS

Declaration
Acknowledgements
Synopsis
Abbreviations

1. Chapter 1: Introduction 1

2. Chapter 2: Literature Survey on Planning and Control of Machining Cells 6
2.1. Introduction 6
2.2. Workpiece Management 6
   2.2.1. Aggregate Planning or Master Production Scheduling 7
   2.2.2. Production Scheduling 8
   2.2.3. Production Activity Control 9
   2.2.4. Real Time Scheduling and Control 11
   2.2.5. Computer Graphical-Based Scheduling Support Systems 12
   2.2.6. Planning and Control of Flexible Manufacturing Systems 14
2.3. Tool Management 16
   2.3.1. Computerised Tool Management Systems 17
   2.3.2. Tooling Data 19
   2.3.3. Tool Rationalisation 21
   2.3.4. Tooling Strategies 21
   2.3.5. Tool Requirements Planning 23
   2.3.6. Tool Constrained Based Scheduling 24
   2.3.7. Tool Management within FMS 26
2.4. Fixture Management 27
   2.4.1. Traditional Fixture Design 28
   2.4.2. Flexible Fixturing 28
   2.4.3. Modular / Reconfigurable Fixtures 29
   2.4.4. Automated Design of Flexible Fixtures 30
   2.4.5. Computer-Aided Fixture Planning 31
   2.4.6. Integration of Computer-Aided Fixture Planning in CIM 33
3. Chapter 3: Review of Approaches for the Generation of Production Schedules

3.1. Introduction

3.2. Classification of Approaches for the Generation of Production Schedules
   3.2.1. Operations Research
   3.2.2. Artificial Intelligence
   3.2.3. Simulation Based
   3.2.4. Hybrid Approaches

3.3. An Assessment of Production Planning and Scheduling Approaches

4. Chapter 4: Contemporary Practices in Planning and Control of Flexible Machining Cells

4.1. Introduction

4.2. The Concept of Flexible Machining

4.3. A Typical Configuration for Flexible Machining Cells

4.4. The Major Issues Related to Workpiece Flow within FMC
   4.4.1. Production Planning and Control
   4.4.2. Tasks Involved in Generation and Implementation of Production Plans
   4.4.3. Push and Pull Type Control Strategies
   4.4.4. Scheduling Rules

4.5. The Major Issues Related to Tool Flow within FMC
   4.5.1. Tool Exchange Policies
   4.5.2. Tooling Activities
   4.5.3. Planning for Tool Flow within FMC

4.6. The Major Issues Related to Fixture Flow within FMC
   4.6.1. Fixture Design
   4.6.2. Palletising and Fixturing Policies
   4.6.3. Fixturing Activities
   4.6.4. Planning for the Fixture Flow within FMC

5. Chapter 5: The Context of the Multi Flow Control Research

5.1. Introduction

5.2. Evaluation of Related Research Publications
   5.2.1. Planning and Control of FMS
   5.2.2. The Modelling Technique
   5.2.3. Planning and Control Rules and Policies
5.2.4. Decision Making Tasks in Planning and Control
5.2.5. Workpiece Flow Related Research
5.2.6. Tool Flow Related Research
5.2.7. Fixture Flow Related Research
5.3. The Context of the Multi-Flow Control Research
5.4. Loughborough University Research Programme
   5.4.1. Information Generation and Support
   5.4.2. Hierarchical Modelling of Tool Flow
   5.4.3. Multi-Flow Control of Flexible Machining Cells

6. Chapter 6: The Scope of the Research
   6.1. Introduction
   6.2. Research Aims and Objectives
   6.3. The Scope of the Research
      6.3.1. Realisation of an Interactive Multi-Flow Control Structure
      6.3.2. Parallel Generation of Schedules for Workpieces, Fixtures and Cutting Tools
      6.3.3. Decision Support for the Planner/Cell Manager
      6.3.4. An Information Model to Support the Multi Flow Controller
      6.3.5. Planning Strategies for Economic Manufacture
      6.3.6. Design of Computer-Based Experiments
      6.3.7. Analysis of the Experimental Results

7. Chapter 7: An Integrated Structure For Planning and Control of Flexible
   Machining Cells: 'The Multi-Flow Controller'
   7.1 Introduction
   7.2. Research Objectives
   7.3. Common Planning and Control Environment for Workpiece, Fixture and
      Cutting Tool Flows
   7.4. Interactive Planning and Control Structure
   7.5. Utilisation of the Off-line and On-line Planning and Control Techniques
   7.6. The Multi-Flow Controller: A Computational Viewpoint
      7.6.1. Multi-Flow Scheduler
      7.6.2. Multi-Flow Simulator
      7.6.3. Manufacturing Database
   7.7. The Role of the Cell Manager
Chapter 11: Multi-Flow Planning Strategies for Economic Manufacture

11.1. Introduction

11.2. Economic Manufacture within Flexible Batch Machining Applications

11.3. Workpiece Dominated Planning Strategies
   - 11.3.1. Multi Machine Loading Job Allocation Policy

11.4. Tool Dominated Planning Strategies
   - 11.4.1. Tool Cluster Based Job Allocation Policy
   - 11.4.2. Single Machine Loading Job Allocation Policy
   - 11.4.3. Combined Machine Loading Job Allocation Policy

11.5. Fixture Dominated Planning Strategies
   - 11.5.1. Finite and Infinite Fixture Capacity Planning
   - 11.5.2. Fixture Cluster Based Job Allocation Policy
   - 11.5.3. Fixture Availability Based Job Allocation Policy

12. Chapter 12: Design of the Computer Based Experiments

12.1. Introduction

12.2. Multi-Flow Control Experiments

12.3. Manufacturing Criteria Influencing the Design of the Multi-Flow Control Experiments
   - 12.3.1. Business Configurations
   - 12.3.2. Part and Tool Matrix
   - 12.3.3. Part and Fixture Matrix
   - 12.3.4. Cell Configuration
   - 12.3.5. Rough Cut Plan

12.4. Generation of a Number of Data Sets for the Multi-Flow Control Experiments
   - 12.4.1. Data Values Relating to Business Configurations
   - 12.4.2. Data Values Relating to Part and Tool Matrix
   - 12.4.3. Data Values Relating to Part and Fixture Matrix
   - 12.4.4. Data Values Relating to Cell Configuration
   - 12.4.5. Data Values Relating to Rough Cut Plans

12.5. The Implementation of the Experiments

13. Chapter 13: The Programme of Experiments and Analysis of the Results

13.1. Introduction

13.2. Manufacturing Performance Measures
   - 13.2.1. The Number of Toolkit Exchange Activities in the Cell
References

Appendices

A2. The Role of Simulation in Operational Planning and Control of Flexible Machining Cells 244
A3. Planning and Control of Fixture Flow within Flexible Machining Systems 255
A4. A Methodology to Develop EXPRESS Data Models 266
A5. An EXPRESS Data Model for the Multi-Flow Controller 288
Chapter 1

INTRODUCTION

In recent years, among the various manufacturing activities production planning and control has been the area with the largest proportion of research and development. This is due to the significant financial incentives for manufacturing companies to constantly improve their planning and control practices within an increasingly competitive world market. In the area of discrete part manufacture, the need for generating efficient planning and control systems has further increased with the pressures of flexible manufacturing. Flexible machining which was first introduced in the 1960's, is now common place within many manufacturing companies, offering numerous advantages such as the production of a wide range of part types with short lead times, low work in-progress, economical production of small batches and high resource utilisation. To achieve these potential benefits, there is a need to develop very complex, detailed and highly tuned operational plans and production schedules for the daily operation of such cells.

Flexible machining cells present planning and control systems with several operating problems that were not previously encountered in the traditional jobshop, because of the tightly controlled and integrated environment in which they operate. The timely provision of cutting tools and fixtures to the appropriate machines are among the most influential difficulties which play a vital role in the overall performance of such cells. The study of planning and control procedures of flexible machining cells indicates that tooling and fixturing requirements are often planned independently from the work(master) scheduler and cell controller, and usually at a much later period. As a result, inadequate warning is given to the tool room/store and fixturing stations for the cutting tool and fixture requirements, with little or no time to prepare. This lack of preparation time leads to delays in machine down time and bottlenecks in tool build, tool pre-setting, tool procurement, fixturing and defixturing operations.
The latest advancement in the areas of information management and simulation based planning and control of manufacturing systems, has made it possible to research the design and realisation of an integrated planning and control system where issues involved in the short term planning and control of the flows of workpieces, fixtures and cutting tools can be addressed simultaneously. The 'multi-flow controller' is the research terminology used in this thesis for such a planning and control system. This research aims to generate knowledge and generic solutions to harmonise the interactions between these three principal material flows within machining cells and to reduce the overall manufacturing cost. The multi-flow control research does not aim to automate the decision making procedure involved in planning and control, but to act as an 'advisory system' to the person responsible for decision making, usually referred to as the 'cell manager'. This thesis addresses two major research issues:

i) the design and realisation of a multi-flow controller for the planning and control of workpieces, fixtures and cutting tools.

ii) the generation of a number of competitive and novel planning strategies to reduce the cost of tooling and fixturing requirements within flexible machining cells without affecting part throughput.

The structure of the thesis is divided into four sections of background/review, theoretical research, experimental research and research conclusions, as illustrated in figure 1.1. The background/review section consists of four chapters, and provides a review of related research publications and background knowledge to the research. Chapter 1 is the main introduction to the research work and the layout of the thesis. A survey of relevant literature in the area of planning and control of flexible machining cells is presented in chapter 2. Chapter 3 provides a categorisation of approaches for the generation of manufacturing plans, and outlines a structure against which planning and scheduling systems may be described. The final chapter in the background/review section briefly overviews the various configurations of flexible machining facilities and describes the contemporary practices within such systems for the management of workpieces, fixtures and cutting tools.
The theoretical research section, comprises eight chapters which identify the context, objectives and the scope of the research and also describes the adopted procedures to explore the research issues and achieve the research objectives. This section commences with chapter 5 which outlines the context of the research by evaluating the competitive published work to position and assess the author's contributions, and also the domain boundaries of the author's multi-flow control research within the production planning and control literature. The research objectives are outlined in chapter 6, together with a description of the scope of research which is explained in more detail within the remaining chapters of this section. The research issues involved in the design and implementation of the novel common planning and control environment for workpieces, fixtures and cutting tools flows, namely the multi-flow controller, are discussed in chapters 7, 8, 9 and 10. Chapter 11 describes the development of a number of novel planning strategies using the multi-flow controller for economic manufacture.

The experimental research section, chapters 12 and 13, describes a series of computer based experiments which highlights the capabilities of the multi-flow controller and illustrates the benefits of the utilisation of the novel planning strategies developed throughout the research. The design of these experiments is described in chapter 12 which also outlines a systematic method for the implementation of the experiments. Chapter 13 analyses the results of these experiments and outlines the new knowledge obtained through the research.

The final section of the thesis, namely research conclusions consists of three chapters. The analysis of the wide range of research issues reported in the thesis from initial requirements and design of the multi-flow controller to a broad comparison of the novel planning strategies is presented in chapter 14 as the concluding discussions. The summary of the conclusions drawn from the research are offered in chapter 15. The final chapter of the thesis chapter 16, provides a list of suggested research ideas for the possible continuation of this research.

The appendices include a range of supporting reports on the structure of the commercial simulation and scheduling software used as the basis to develop the prototype multi-flow controller, namely ARENA and PREACTOR, together with documents on the information modelling, and a number of related published papers by the author on various aspects of the research.
The research work reported in this thesis has been carried out as a part of a British Government funded research programme which is briefly summarised in Chapter 5 as a part of the research context. This programme also includes further research on the hierarchical modelling of tool flow, which is the subject of a complementary thesis by Mr. P. Coleman (1996). The close collaboration with this research work is described in Chapter 4 and cross referenced where appropriate.
Figure 1.1: The Structure of Chapters of the Thesis
Chapter 2

LITERATURE SURVEY ON PLANNING AND CONTROL OF MACHINING CELLS

2.1. Introduction

The planning and control of manufacturing systems has been the most popular research subject among many industrialists and academics over the past forty years, resulting in an enormous body of publications. This chapter presents a survey of the most related published work in the area of planning and control for machining cells. The literature survey has been divided into three major sections, covering publications on the issues of workpiece management, tool management and fixture management.

2.2. Workpiece Management

In the field of production planning and scheduling, the major aim is to allocate the available resources to the production orders to be processed, referred to as jobs. Often not only the mere establishment of a valid schedule is aimed at, but the creation of a schedule which is optimal for the given problem. In metal cutting applications, the majority of planning, scheduling and control research has always been concerned with the flow of workpieces through manufacturing systems. All the other manufacturing elements involved in production such as machines, transporters and manual operators have been dealt with as resources, the availability or shortage of which influences the workpiece flow(Gupta et al. 1989, Aanen et al. 1993, Chan and Tang 1995). Traditionally, production planning and control(PPC) activities based on this workpiece dominated approach can be viewed in a hierarchy of three levels, as illustrated in figure 2.1 :-

i) aggregate planning to set the long term production levels in the form of a master production schedule(MPS).
ii) **production scheduling** as medium term production activity planning, which takes the MPS as an input and generates production schedules for execution.

iii) **production activity control** which monitors the progress of production schedules, making the short term modification required by changes in shop floor status.

A summary of recent research work within each of these three levels of PPC, together with the most related research issues to the scope of this thesis, namely the real-time planning and control, computer graphics-based scheduling support systems and the planning and control of flexible manufacturing systems is provided below.

### 2.2.1. Aggregate Planning or Master Production Scheduling

Aggregate planning, better known as master production scheduling (MPS) is the task of identifying plans to produce products, expressed in specific quantities and dates, to fulfil a series of anticipated product demands (Bauer *et al.* 1991). Gessner (1982) states that the two most important pieces of information presented in a master scheduler are the production quantities and the completion dates. The problem of lot sizing and due date determination has been addressed by a large number of researchers, resulting in a wide range of algorithms, methods and techniques used in different manufacturing applications (Browne *et al.* 1988, Stadtler 1988, Smith 1989, Cheng 1986, Co *et al.* 1990, Sule and Saxena 1992, Gallego 1993).

![Figure 2.1: A Simplified Hierarchical Structure for Production Planning and Control](image)
The formulation of the MPS must seek to reconcile the many requirements of the company functions which are involved in the results of the formulation. These requirements are defined by Arosio and Sianesi (1993) as:

- **marketing and sales requirements** as the need to have a wide range of the company's products constantly available or be able to produce them in short time, in order to deal with a high level of customer demand changes;
- **financial requirements** to limit lead-time between production and sales in order to reduce the financial resources tied in stocks and finished goods;
- **production requirements** to maintain a constant rhythm of production, manufacturing large lots in order to contain production costs and limit the number of manufacturing system set ups; and
- **resources and labour requirements** whereby the MPS has a smooth resources and manpower utilisation profile.

Sridharan and Berry (1990) state that the frequent adjustments to the MPS, influenced by changes in customer requirements and sales forecasts as well as changes brought about by factors inherent in the design of lot-sizing methods, are the most important sources of schedule instability in MRP systems. Higgins and Browne (1992) describe the MPS functions as the main link between the marketing/sales, engineering and manufacturing departments. This link is typically managed by a team of personnel from the different departments, referred to as a planning board. They argue that as manufacturing is moving away from making products for inventory purposes (make-to-stock), and is becoming more customer-driven in its approach (make-to-order), a different and more responsive MPS framework is required. They introduce a novel concept of concurrent planning tools, to aid in the decision processes to integrate the marketing/sales, engineering and manufacturing activities.

2.2.2. Production Scheduling

The need for production scheduling arises whenever a common set of resources in the manufacturing system must be shared to make a variety of different products during the same time period. The objective of manufacturing scheduling is the efficient allocation of machines and other resources to jobs, or operations within jobs, and the subsequent
time-phasing of these jobs on individual machines. This task of assigning a set of resources to batches of parts is usually carried out under the influences of a number of constraints (Wild 1979). The presence of a large number of conflicting constraints within discrete part manufacturing applications, such as to meet delivery dates, to minimise the job lead times, to reduce the overall length of the required production period, to balance the workload of various resources and to ensure a uniform rate of productivity transforms the production scheduling into a very complex task (Bellman et al. 1982, Grant and Clapp 1988, Elsayed and Kao 1990, Chryssolouris et al. 1991, Dauzere-Peres and Lasserre 1993, Baptiste and Le Pape 1995). Over the past four decades, a wide range of techniques, methods, tools and approaches have been adopted by a large number of researchers to solve a series of complicated scheduling problems. A review of these production scheduling approaches is provided in chapter 3.

The output from the MPS function is usually in the form of a list of jobs, often with associated due dates, and is used as an input to initiate the production scheduling function. The production scheduling function is a combination of routing, dispatch/loading, sequencing and schedule generation tasks. Therefore, the research publications in this area can be viewed in terms of various constraints associated with these tasks. A sample of more recent research publications in this area are:

- routing decisions (Chen and Chung 1991, Fanti et al. 1993, Mamalis et al. 1995);
- sequencing based on set up times (Zhou and Egbelu 1989, Hitomi et al. 1989, Rajgopal and Bidanda 1991, Cao and Bedworth 1992, Arosio and Sianesi 1993, Suh and Esat 1993); and

2.2.3. Production Activity Control

Production activity control is the task of executing work plans, generated in the production scheduling stage, monitoring the progress and making any corrective modifications to ensure that the scheduled jobs are processed as planned. A number of reference
Hierarchical models have been developed for the overall control of a modern manufacturing system. The most well known of these models are the NBS/NIST and CAM-I models (O'Grady and Lee 1988). The NBS/NIST model was developed by the National Institute of Standards and Technology (NIST) - USA, and consists of five levels, namely facility, shop, cell, workstation and equipment. The CAM-I model developed by Computer Aided Manufacturing International at the Massachusetts Institute of Technology, contains four levels of factory, jobshop, work centre and unit resource. O'Grady and Seshadri (1991) combine these two models and propose a hierarchy which consists of four levels of factory, shop, cell and equipment. In flexible machining applications whichever model is adopted, the control at cell level is of critical importance since it provides the links between the off-line control level (say at factory, shop level) to on-line control at the machine / equipment level (Xiang and O'Brien 1995). Stecke (1988) defined the cell level control problems of flexible manufacturing systems to be those associated with the continuous monitoring of the system, i.e. keeping track of production to be certain that the production requirements and due dates are being met as scheduled, and listed the following as the minimum required functionality:

- procedures for process and tool life monitoring and data collection on production progress;
- policies for handling the breakdowns of machines and other resources;
- schedules for periodic, preventive maintenance; and
- policies for inspection of in-process and finished parts.

Hadavi et al. (1990) state that the required functions of a cell controller can vary and depend on the cell size and the degree of decision making capabilities given to it. They argue that these functions, in addition to what is suggested by Stecke, can also include sequencing and routing of jobs, short term scheduling of jobs and supervising the support services such as material handling, tool transport and tool exchange and fixturing operations. Bauer et al. (1991) and Kohler (1993) describe the design and implementation issues of a typical shop level control system. The recent publications in the area of production activity control address a wide range of issues such as:

- supervising the tool flow (Kendall and Bayoum 1988, Hammer 1989, Han et al. 1989, Veerarmani 1994, Hedin et al. 1994);
• resource failure (Tabe and Salvendy 1988, Li et al. 1993, Olumolade and Norrie 1996);
• real time scheduling and control (see section 2.2.4);
• computer graphical based scheduling and control (see section 2.2.5); and
• planning and control of flexible manufacturing facilities (see section 2.2.6).

2.2.4. Real Time Scheduling and Control

One of the primary reasons for the complexity of planning and control functions is the dynamic nature of manufacturing systems. The most common complaint by industrialist with regard to scheduling and control research work is that often the rules, strategies and systems developed by academic researchers cannot deal with the dynamic nature of production systems. As a result, since the early 1980s a number of researchers have focused on the utilisation of the latest advancements in the field of information technology to suggest dynamic structures and frameworks for planning and control functions (Hadavi et al. 1990, Herman and Safka 1982, Galgut 1982, Kinoshita et al. 1983).

The terms 'real time' and 'on-line' are usually used to refer to planning and control systems with capabilities of incorporating dynamic rules and strategies. Askin and Stanbridge (1993) classify scheduling rules as static and dynamic. Static rules such as earliest due dates and minimum number of operations have performance indices that are independent of enclosed time. Dynamic rules such as slack time remaining or the machine with the shortest queue are time dependent, and must be therefore used in conjunction with real time data. Recent examples of scheduling approaches based on the use of dynamic rules are provided by Davis and Jones (1988), Shaw (1989), Chang and Sullivan (1990), Mahmoodi et al. (1990), Mori et al. (1991), Mottet and Widmer (1991), Yih (1992), Sabuncuoğlu and Hommertzheim (1992), Mamalis et al. (1995), and Chiu and Yih (1995).

Within a real-time planning and control structure, there is often a need for a detailed model of the manufacturing system which has been integrated via a computer network to the physical resources on the shop floor (Harmonosky and Robohn 1991). This model continuously receives information on the progress of previous production instructions and the system status through shop floor data collection facilities. This updated information is then used to generate further production instructions and to make appropriate corrective modifications to overcome any possible problems caused by manufacturing disturbances (Smith et al. 1994). Real-time planning and control systems are often set up
using a knowledge based model (Brown 1988, Sarin and Salgame 1990, Farhoodi 1990, Shaw et al. 1992), or a simulation model (Wu and Wysk 1989, Rogers et al. 1991, Bengu 1994, Flower and Cheselka 1994, Roy and Meikle 1995). The success of such systems relies very much on the design of the information structure and the quality of information being exchanged between the control system and the shop floor (Chang and Sullivan 1990, Walters and Warwick 1990, Szelke and Markus 1994). As a result, real-time planning and control systems are often used in applications with expensive and modern manufacturing systems with certain levels of automation which can support a fast and responsive information structure.

2.2.5. Computer Graphical-Based Scheduling Support Systems

In recent years, there has been a rapid development of computer graphics-based scheduling support systems, known as ‘leitstand’, in Germany (Sridharan and Kanet 1995). Leitstand makes extensive use of recent advances in computer graphics to support human decision makers in manufacturing settings and fits perfectly into the CIM concept by connecting the planning module with the shop floor (Adelsberger and Kanet 1991). The word ‘leitstand’ is German for ‘command centre’ or ‘directing stand’. A leitstand is a computer aided decision support system for interactive production planning and control, and comprises of the following five components, as shown in figure 1.1 (Sridharan and Kanet 1995):

i) a database manager for managing the database and for communication and interaction with other computer-based systems and databases.

ii) a schedule generator for automatically generating schedules (or partial schedules) and for performing complex schedule edits.

iii) a schedule editor for assisting a human scheduler to manipulate and edit a schedule.

iv) an evaluation component for helping to measure and analyse the performance characteristics of a given schedule.

v) a graphic interface for providing visual representation of schedules (e.g. Gantt Charts for production resources).
It is clear from figure 2.2 that a leitstand uses information from external sources such as:-

- a production planning system, where it receives information concerning customer demand (such as due dates, order quantities, and order priorities);
- an engineering database, where it receives information concerning process plans (such as process times, set up times, and routing alternatives); and
- a shop floor data collection system which provides information regarding the status of resources and orders within a production system (such as machine capacity, current queues, tooling status).

A leitstand helps users in getting to the details quickly by providing the capability to focus on a specific job and its schedule throughout the shop or an individual operation. While making available detailed information on machine utilisation, machine loading patterns, and job lead times, it provides the option to selectively access, view, present or
skip information concerning a portion or the entire schedule, thus avoiding information overload. A leitstand system typically has a built-in constraint checking capability, so that on editing a schedule one need not be concerned with violating any hard technical constraints such as machine-operation matching, or an operation precedence relationship. Most importantly a leitstand system provides the flexibility of interacting with a human operator to allow the intelligent fine tuning of schedules based on latest system status and localised information (Kanet and Sridharan 1990).

2.2.6. Planning and Control of Flexible Manufacturing Systems

In the last two decades there has been a shift in manufacturing requirements from productivity towards flexibility. The flexibility is expected to prolong the service life of a manufacturing facility and enable it to respond quickly and economically to dynamic market changes (Chen and Chung 1991). The main advantages associated with a flexible manufacturing facility are economical production of small batches, because of the relatively short set up times, possibility to produce a wide range of part types, short lead times, low in-process inventories, high machine utilisation and high quality (Stecke 1988, Fertin 1991, Chen et al. 1995).

One of the main characteristics of FMS which distinguishes such systems from the traditional job shop environment is the automatic work handling devices. These automatic work handling devices are commonly in the form of automated guided vehicles (AGV) or industrial robots used for part transfer, but are also used in a few installations for both part and tool transfer. Therefore, a section of the planning and control research publications is concerned with constraints related to the operation of such devices within an FMS (Egbelu and Tanchoco 1984, King and Wilson 1991, Sabuncuoglu and Hommertzheim 1992, Ulusoy and Bilge 1993).

Comprehensive reviews of planning approaches and scheduling rules for FMS can be found in Gupta et al. (1989, 1991) and Rachamadugu and Stecke (1993). These reviews have indicated that the early investigation relating to planning and control of FMS focused on applying known static rules (Okamura et al. 1982, Stecke 1985, Shaw and Whinston 1986, Raynolds and McMahon 1987, Gupta et al. 1989, Wilson 1989, Archetti et al. 1989). Aanen (1989) state that the operational planning problems of an FMS are too complex to solve in one step. They have decomposed this problem into a planning phase
and a scheduling phase. In the planning phase, the orders to be processed within a planning horizon (average of 10 days) are sequenced and divided into daily tasks. In the scheduling phase, the orders within these daily tasks are allocated to machines and other resources. Aanen et al. (1993) describe a very similar two phase approach for planning and scheduling of FMS, to minimise the sequence-dependent changeover time and the transfer time using the branch and bound method.

More recently, a large number of researchers have argued that the planning and control of FMS are dynamic problems and the best solution is achieved using dynamic scheduling rules with real time planning and control systems (Slomp and Gaalman 1988, Chan and Bedworth 1990, Garetti et al. 1990, Hatono et al. 1991, Mori et al. 1993, Fanti et al. 1993). The idea beyond the concept of dynamic scheduling is to postpone the loading decisions, and thereby preserve the routing options, for as long as possible in order to be able to use the system’s routing flexibility in an opportunistic way. Therefore, dynamic scheduling implies making routing decisions for a part incrementally as the part completes its operations one after another. In other words, the next machine for a part at any stage is decided only when its current operation is nearing completion.

An alternative dynamic scheduling approach is suggested by Chandar and Talavage (1991). They develop a decision rule set for real-time dispatching of parts with alternative processing possibilities. A part, upon completion of an operation, is not routed to a specific machine but is sent to a general queue and thus a machine is given a global option for choosing parts to be processed from this queue. However, for effective use of the system’s routing flexibility under these circumstances, the machines need an intelligent part selection strategy that takes into account the current state and trends of the system.

There are advantages and disadvantages associated with both static (off-line) and dynamic (on-line or real time) approaches. Scheduling can be a very tedious task with off-line methods due to both the difficulty in generating the schedules, and updating it frequently in a dynamic environment. On the other hand, scheduling decisions made by on-line methods may not provide best results due to the lack of a broad systems view. A better way may be to use a hybrid approach (both off-line and on-line) to achieve improved overall system performance (Wu and Wysk 1989, Harmonosky and Robohn 1991, Yih 1992, Mori et al. 1993, Mamalis et al. 1995).
2.3. Tool Management

Some of the most complicated and difficult issues in operating machining facilities are managing, coordinating and controlling the wide variety of cutting tools. This includes not only having and maintaining the required number of cutting tools to process parts in a machining system, but also managing and coordinating other elements, such as redundant or replacement tools, tool assembly component requirements, tool storage, reconditioning and preset considerations, tool life monitoring, broken tool detection and managing information flow relating to cutting tools. The tooling system affects a wide range of manufacturing issues such as product design options, machine loading, job batching, capacity scheduling and real-time routing.

The term tool management is defined as ‘getting the right tool to the right place at the right time’ and refers to a range of decision making tasks from selecting the appropriate tool with optimal machining parameters and the most economic processing rate for a particular operation(Kendall and Bayoum 1988, Noto et al. 1993, Maropoulos 1995a), to the loading of tools and jobs on machines and the determination of the optimal tool inventories required for a particular production schedule( Brad 1988, Carrie and Bititci 1989, Ram et al. 1990, Mottet and Widmer 1991, Lin and Wang 1993, Leung and Khator 1994). Gray et al. (1993) suggest a hierarchical approach to decompose this complex decision making problem by classifying tool management into the following three decision levels:

i) **tool-level decisions** on the economic determination of tool type, feed rate, and machining speed for any given part operation, tool standardisation, real-time monitoring and adaptive process planning.

ii) **machine level decisions** on sequencing of parts and tools on a specific machine, the allocation of tools to magazine slots, and tool replacement strategies.

iii) **system level decisions** on system set up, economic production rates, part routing and scheduling, tool requirements planning, tool sharing among machines and tool inventory management.

The various aspects of this decision making process has been the focus on many research programmes over the last two decades. A review of this tool management research is provided by Eversheim and Kals(1991), Gray et al.(1993) and by Maropoulos(1995a, 1995b). However, it is still the general belief among both the
academic and industrial communities that the importance of effective tool management within machining systems has not been universally recognised (Martin 1989, Gruver and Senninger 1990, Gray et al. 1993, O'Brien et al. 1993, Maropoulos 1995a). As a result at present, quite often in manufacturing systems, the machining has to be stopped for tooling problems which could be due to such factors as; damaged cutting edges (i.e. worn tools), quality of refurbishment/regrinding and presetting was poor as they were rushed through the tool room, or even the incorrect tool type was supplied (Acaccia et al. 1989). Petuelli and Muller (1995) state that on average 53% of all interruptions of metal cutting processes are caused by poor tooling, resulting in a reduction of machine uptime by about 18%. A full description of all TMS related research work is beyond the scope of this literature survey. The author guides readers to the reviews of Ozbayrak (1993) and Coleman (1996). However, the following tool management issues relating to the multi-flow control research, are described in this literature survey:

- computerised tool management systems;
- tooling data;
- tool rationalisation;
- tool strategies;
- tool requirements planning;
- tool constrained based scheduling; and
- tool management within FMS.

2.3.1. Computerised Tool Management Systems

In the last two decades, a large number of researchers have concentrated on the design and implementation of computerised tool management systems (CTMS), to be used in particular within FMS (Carrie and Bittici 1988, El Maraghy 1989, Zhou and Wyak 1989, Averyanov and Margul 1989, Zuin 1990, Eversheim and Kals 1991, Chan 1992, Gray et al. 1993, Telzlaff 1995). A clear definition of the functional requirements of a typical CTMS is provided by Gray et al. (1993). These general functions, illustrated in figure 2.3, are:

- a design function to coordinate tooling inventory, tool tracking, tool handling, and tool loading and unloading;
- a planning function to ensure that the appropriate tools are available when needed and are provided in the right quantities;
Figure 2.3: An Integrated Overview of Tool Management Functionality
(Adapted from Gray et al. 1993)
• a scheduling function to account for tool availability and tool changes;
• a control function to coordinate either manual or automatic tool transfers between machines and tool stores; and
• a monitoring function to identify and react to unexpected tool wear and breakage.

With increasing automation in manufacturing systems, there is a growing interest in the integration of CTMS with system design, planning and control. This is reflected by the research work of Carrie and Bititci (1988), Zoh and Wyak (1989), Lee and Chua (1991), Hannam (1992), Hedin et al. (1994), Veeramani (1994). These publications have paid considerable attention to the benefits of improving the integration of CTMS with other sub-systems of the CIM framework. The benefits reported include:-

• better tracking and cost accountability of tooling (see section 2.3.2 on tooling data);
• reduction in production costs due to minimising the number and type of required tools (see section 2.3.3 on tool rationalisation);
• increases in productivity due to reduction in set up and tools' stockout (see sections 2.3.4 and 2.3.5 on tool strategies and tool requirements planning); and
• improvement in part and routing flexibility (see section 2.3.6 on tool scheduling).

2.3.2. Tooling Data

Most of the efforts to increase the productivity in metal cutting applications have concentrated on the improvement of the machining technology, the automation of processes, the optimisation of the production schedule as well as the sequence of the workpieces to be machined. As a result, there is a highly developed and well defined information structure with regard to the flow of workpieces within manufacturing systems. In comparison, even in the most modern machining facilities, little information about the status of cutting tools, tool life, their present locations and when and where they will be next used, is collected and stored in manufacturing databases. This lack of attention to structured tooling data management has resulted in the poor performance of many manufacturing systems (Carrie and Bititci 1988, Kehoe et al. 1991, Hannam 1992, O'Brien et al. 1993).

Hannam et al. (1990) developed a relational database for tooling data, using a Relational Information Management (RIM) software package developed by Boeing Computer Services, to provide manufacturing planners with an effective and user friendly
facility for the selection and control of tooling. Kehoe et al. (1991) outline a structured methodology for the specification of the information system requirements for tool management. The proposed methodology is based upon formalised SSADM, and identifies the data structures, data flow and data dynamics for a typical tool management system. O'Brien et al. (1993) have highlighted the importance of effective tooling information management, with the aid of a case study based on Dunlop Cox Ltd, which is a major supplier of mechanisms for automotive seating equipment. Veeramani (1994) states that at the foundation of every effective computerised TMS is an information system that encompasses all facets of tool-related information. It is important, to recognise that such information systems have a direct effect on a variety of tool-related activities from the rationalisation of cutting tool requirements at the product design phase to orchestration of tool flow on the shop floor. Finally, Shayan and Liu (1995) describe a systematic way to design a generic data relation model which can be adopted as the central core for all other tool management related activities, as shown in figure 2.4.

![Figure 2.4: A Centralised Tool Database for Tool Planning and Control](Adapted from Shayan and Liu 1995)
2.3.3. Tool Rationalisation

In many cases, the number of tools required to machine a range of part types has proliferated because of a lack of basic tool control in the part design process (Veeramani 1992). Hannam et al. (1990) state that tooling variety arises both in the design office by designers specifying new features and non-standard dimensions for commonly used features and in the process planning office by process planners specifying new tools because they have inadequate knowledge or sources of information on existing tools within the tool store. Smith (1993) states that through careful and astute manufacturing analysis of each workpiece, minimal design engineering changes and/or optimised part programming routines, it is possible to reduce or eliminate unnecessary tools. Analysis of this type can have a considerable effect on reducing overall cutting tool requirements. He argues that such rationalisation and consolidation are the key issue in a successful tool management system.

The cost of cutting tools is a significant component both in the initial capital investment and operational costs of machining facilities. Various figures have been reported with regards to the tooling cost and the cost of lost production for tooling problems. Gray et al. (1993) state that industrial data suggests tooling accounts for 25% to 30% of both the fixed costs and variable costs of production in an automated machining environment. Khator and Leung (1994) state that tool costs represent 25% of the operating cost of a typical machining facility. Petuelli and Muller (1995) state that about 40% of the total cost of an operational machining centre is due to its tooling cost. Therefore, any small saving achieved by the tool rationalisation process can amount to a significant reduction in the overall annual production cost of machining facilities (Veeramani 1992).

2.3.4. Tooling Strategies

Tooling strategies are a set of rules used to allocate tools to parts, batches of parts, groups of part types or machines. Several researchers have suggested and developed a number of tooling strategies under different names. As an example set, strategies defined by Tomek (1986), Acaccia et al. (1989) and Luggen (1991) are described below. Tomek (1986) defines three basic tooling strategies which are :-
i) *batch of parts-group of tools*: a set of tools are delivered to a machine for a batch of parts (possibly mounted on a single fixture) and tool sharing between succeeding batches is ignored.

ii) *several part batches - one group of tools*: based on group technology and sharing identical tools among several batches.

iii) *common tool inventory shared by a group of machines*: identical sets of tools are pre-loaded on each machine to minimise the migration of tools. The majority of required tools reside in the tool magazine, and individual tools are added as and when required.

Acaccia *et al.* (1989) refer to tooling strategies as tool-delivery tactics and outlines the following as the most common tool-delivery tactics:

- **all-migrant tactic**: the tools are bonded to the individual parts and handled simultaneously;
- **product-batch tactic**: the tools are referred to as a part batch so they are partially assigned to the parts;
- **fabrication-window tactic**: the tools are selected according to a production span and cover a manufacturing period;
- **machining-list tactic**: the tools are referred to as the tasks and the parts gathered according to a group technology technique; and
- **all-resident tactic**: the tools are bounded to the workstation and the parts have predefined routings.

Luggen (1991) describes four tooling strategies, namely:

i) **mass-exchange strategy** for removing all the tools in each machine tool matrix at the completion of specified production requirements and replacing them with the new parts required tooling.

ii) **tool sharing strategy** permits the logical sharing of tools within the framework of a fixed production requirement. Common tooling among the fixed production requirements is recognised, identified and shared among the various parts to be manufactured in the fixed production period.

iii) **tool migration strategy** removes all the tools which have completed their manufacturing services from the magazines, while needed new tools are inserted in available tool pockets.
iv) **assigned tools strategy** identifies the most-used tools for the production requirements and assigns permanent residence to these tools in each machine for the full production run.

It is clear that the underlying principal of these three sets of tooling strategies and many others outlined by other researchers (de Souza and Bell 1991, Amoako-Gyampah *et al.* 1992, Hedin *et al.* 1994, Khator and Leung 1994) are very similar. A complete study of the effects of these tooling strategies on the issues such as design of tool management, tool requirement planning and tool flow control have been carried out by a number of researchers at Loughborough University (de Souza 1988, Ozbayrak 1993, Coleman 1996).

### 2.3.5. Tool Requirements Planning

Tool requirements planning (TRP) is the task of calculating the net tool requirements over a manufacturing period as a function of the number of each part type to be produced, the tool types required, the machining times for each tool operation, the tooling strategy adopted and the expected tool lives, including some probability for premature breakage of tools.

Chung (1991) suggested that tool planning should be achieved in two stages. The first stage involving a rough-cut tool planning (RTP), where a rough estimate of the tool requirements is calculated. He draws a comparison between RTP and the rough-cut capacity planning for work throughput. He describes three methods for calculating rough-cut planning of tool requirements. These methods are the :-

i) **overall factors method** which calculates rough-cut tool requirements for each tool type based upon the ratio of tool usage during the previous year.

ii) **tool bills method**, analogous to a bill of material, indicating the amount of tool hours of each tool type required by each item and each component.

iii) **tool profiles method** which incorporates a time-phase projection of tool requirements based on tool usage over the manufacturing lead time of the scheduled workpieces.

Koulamas (1991) presents methods for computing the tool requirements at any level of a multi-level machining system by utilising the bill of material and a tool data matrix. He also describes an algorithm for reducing the tool requirements without affecting the
end product’s completion time. Zavanella and Bugini(1992) describe an analytical approach to planning tool requirements based on ‘kit management’ and ‘tool sharing management’ strategies.

Ozbayrak(1993) developed a TRP model using the LOTUS 123 spreadsheet based on the four most common tooling strategies. Furthermore, he studied the TRP-based performance of these tooling strategies based on different scheduling rules and manufacturing requirements. Khator and Leung(1994) have also developed a TRP model based on the ‘migration of tools at the completion of a part type’ tooling strategy, formulated as a linear program.

2.3.6. Tool Constrained Based Scheduling

The total number of tools required to process a set of parts on a number of machines is usually larger than the available magazine storage capacity. Therefore often, decisions should be first made on how the jobs should be sequenced and second on which tools should be changed at the machine prior to the processing of each job. The majority of the general purpose scheduling research does not consider tooling costs, tool change technologies, magazine size, tool set up, tool lives and tool commonalities as constraining factors in their approaches(Carrie and Perera 1986, Melnyk et al. 1989, Alberti et al. 1991, Ghosh et al. 1992, Modi and Shanker 1995).

A number of researchers have used simulation techniques for the tool constrained based planning and scheduling. Melnyk et al.(1989) used a simple simulation model to prove that the level of tool availability has a significant impact on shop floor performance as measured in terms of mean flow time, mean tardiness, number of tardy jobs and number of tool changes. Acaccia et al.(1989) developed an expert-simulation model as a tool-dispatcher from the tool room/store. Alberti et al.(1991) have used a part and tool flow simulation model for optimal FMS management, where the coordination task between part and tool flow is modelled considering issues such as tool life, capacity of tool storage devices, performance of the automated tool handling system, and loading strategies of tools. Amoako-Gyampah et al.(1992) compared four tool allocation and scheduling strategies in the presence of three part selection rules through a simulation study of a five machine FMS with an automated tool handling system. The performance measures used in this study were; mean flow time, mean tardiness, percentage of tardy jobs and average machine utilisation. Ghosh et al.(1992) in a similar simulation study to Amoako-Gyampah
et al. (1992) evaluated the same four tool assignment rules but with two different part dispatching procedures. Kayshap and Khator (1994) used simulation to investigate the impact of control rules for tool selection and initial work release on the performance of a manufacturing system in a tool shared environment. Various rules for tool sharing were studied with makespan and tool transporter utilisation as performance measures. Grieco et al. (1995) carried out a similar study to Albreti et al. (1991), with some very restricting assumptions such as tools can be carried one at time, tools can be exchanged among machines and part programmes can start without having to wait for all the tools.

Other researchers have used mathematical and analytical techniques in this area. Brad (1988) uses heuristics for minimising the number of tool switches on a flexible machine. Co et al. (1990) formulated mixed-integer programming to address the batching, loading and tool configuration problems. Leung et al. (1993) used a linear integer model for concurrent part assignment and tool allocation with material handling consideration. Lin and Wang (1993) used the enumeration methods and dynamic programming formulation to minimise the tool changeovers at machine level. Modi and Shanker (1995) developed a two stage heuristic to minimise the part movement, balancing the workload with machine, tool and process plan flexibilities.

Some researchers have explored the possibility of dynamic scheduling and on-line tool management systems. Han et al. (1989) analysed the effect of various tool loading policies and job dispatching rules and their combination, with the aim of minimising the processing time, using a real-time tool control and job dispatching framework. Mottet and Widmer (1991) explored the dynamic scheduling approach to minimise the number of tools in circulation in the manufacturing system. Among other modelling techniques used for tool constrained based scheduling are; object-oriented modelling (Rogers et al. 1990), Knowledge based systems (Giardini et al. 1991, Shivathaya and Fang 1995), Petri net based approach (Reddy et al. 1992), and neural networks (Arizono et al. 1995).

In the research publications, there are two clear approaches to the problem of tool scheduling and tool flow control, namely:

i) part oriented where tool flow is a consequence of part flow and the configuration of the tool magazine is dynamic.

ii) tool oriented where the flow of the parts is constrained by the availability of the tools on the machine and the tool magazine configuration is static.
The research work considered up to now in this section is from the part dominant category. In the tool dominant category often applications of group technology and clustering techniques are used to form a group of cutting tools that can be hosted on a machine to process a range of part types. Ventura et al. (1990) used a 0-1 linear integer program and a Lagrangian dual formulation for grouping parts and tools in FMS. de Souza and Bell (1991) applied the ‘rank order clustering’ algorithm, developed by King (1980), to a part and tool matrix to form a number of tool cluster sets. These tool cluster sets are scheduled on a workstation, based on parts as the primary priority and tool clusters as the second priority management rules. Ozbayrak (1993) extended this work and showed that the effective utilisation of this tool dominant approach can significantly reduce the tool requirements with little or no effects on the part throughput times.

2.3.7. Tool Management within FMS

FMS are acclaimed for their flexibility to manufacture a large variety of parts with high efficiency and for the ability to respond quickly to part-mix changes. This flexibility is due to reasons that identical parts can have alternate routes within the system and that each machine is equipped with an efficient tool changer which increases system capability, in terms of the range of possible manufacturing operations. FMS are a very expensive investment for manufacturing companies that want to reach a high level of flexibility in automating their production facilities. In FMS, where a high degree of production flexibility and unmanned manufacture are expected, cutting tools present great technical difficulties, caused by large tool magazines, automatic tool transport devices and sophisticated software based on new FMS management strategies. As a result, the design of tool management systems within FMS, involves a vast amount of analysis and system development work. A large number of researchers have addressed the variety of tool management design, planning and implementation problems within FMS (Kusiak 1986, Tomek 1986, Carrie and Bititci 1988, Ranky 1988, Han et al. 1989, Ventura et al. 1990, Gruver and Senninger 1990, de Souza and Bell 1991, Giardini et al. 1991, Amoako-Gyampah et al. 1992, Zavanella and Bugini 1992, Cantamessa and Lombardi 1993, Ozbayrak 1993, Chan 1992, Reddy et al. 1992, Hedin et al. 1994, Kashyap and Khator 1994, Telzlaff 1995, Modi and Shanker 1995, Shayan and Liu 1995).

Kiran and Karson (1988) noted that following the financial disasters of a number of FMS installations, manufacturing companies and machine tool builders have begun to
realise that tooling can have a significant impact on the effective performance of FMS. Hannam et al. (1990) state that one of the main limits on FMS flexibility is the tooling system. It is the organisation of this tooling system which is the key element in planning the effective use of a true flexible FMS. Leung and Khator(1994) stated that to enable FMS to operate in unmanned technology mode, it is necessary to develop automated tool management systems(TMS). This automated TMS should comprise of an automatic tool changer, a device for automatic tool replacement, devices for automated transportation of tools, devices for tool monitoring and a tool control system. Such automated TMS enable an effective tool sharing scheme, resulting in a significant reduction of the tooling cost in the system.

Telzlaff(1995) describes an algorithm which allows performance evaluation of an FMS with its tool management system. The procedure applies queuing network theory, in order to estimate important performance parameters for a specific tool management configuration. The tool blocking times(i.e. the times a machine is idle because it is waiting for the required tooling) and their relationship to important tool management design parameters are modelled. The design parameters considered include the number of transportation vehicles, the transportation times to machines, tool magazine sizes and the number of tools to be transported to a machine per order.

2.4. Fixture Management

In metal cutting applications, for any machining operation to be successful, parts must be located and held to remain in position and orientation on a fixture when subject to external forces during the manufacturing operations. Hoffman(1987) defines fixtures as the workholding devices which provide positive location and support while restricting the movement of a part subjected to the forces associated with the manufacturing process. During any fixturing task, the essential ingredients which govern accurate and efficient workholding are location, support and clamping. Positive location and support provided by the 3-2-1 locating principle sufficiently constrain the part and the remaining degree of freedom may be eliminated by clamping(Markus et al. 1990, Ranky 1990). To relate the published work to this thesis, the author considers issues involved in fixture management under the following headings:-

- traditional fixture design;
• flexible fixturing;
• modular/reconfigurable fixtures;
• automated design of flexible fixturing;
• computer aided fixturing planning (CAFP); and
• integration of CAFP in CIM.

2.4.1. Traditional Fixture Design

The traditional approach to fixturing involved the design and manufacture of special purpose fixtures. These fixtures are generally dedicated devices designed and manufactured for specific parts and machining operations (see section 4.6.1). The lead time and effort associated with the manual design and manufacture of special purpose fixtures can be as long as one to three months which is unacceptable in modern manufacturing applications (Lewis 1983). Earlier research work has attempted to reduce both the design time and the design cost, by integration of part and fixture design processes using computer aided design (CAD) systems (Berry 1982). However, the typical cost of such dedicated fixtures are reported to amount to 10-20% of initial cost of the overall flexible machining facilities (Grippo et al. 1998).

2.4.2. Flexible Fixturing

As products become more and more customer-oriented, smaller batch production volumes are required, and thus faster changes of part design are an important feature of discrete part manufacture. Thus, the use of FMS technologies have steadily increased to take advantage of this underlying small batch philosophy (Luggen 1991). A major bottleneck in FMS is the inability of hard-dedicated fixtures to be set-up and changed quickly and automatically (Ranky 1990). Ranky states that considerable progress has been made in the development of the various sub-systems of FMS, such as CNC machining centres, automated part and tool transport systems, coordinate measuring machines (CMM) and computer network communication and control systems for overall coordination of the manufacturing system. He further argues that the flexibility of an automated manufacturing system clearly depends on the flexibility of its sub-systems. Therefore, the overall flexibility of an FMS cannot be fully exploited without flexible fixturing systems which are, of course, essential ingredients of all machining operations, since they interface
with material handling systems, the machine tool and other equipment. Flexible fixturing technology involves employing a single fixturing system to hold workpieces of various shapes and sizes for a range of manufacturing operations. Grippo et al. (1988) identify the various degrees of flexibility that a true flexible fixturing system should possess:

- **mix flexibility** which relates to the processing of a mix of different part types loosely related to one another;
- **part flexibility** which relates to the addition of parts or removal from the part set;
- **routing flexibility** which relates to the assignment of parts to any machine within the system, in order to maintain workload balance;
- **design change flexibility** which relates to the potential for the faster implementation of design changes in a part or parts;
- **volume flexibility** which relates to the ability to accommodate changes in production volume for various parts; and
- **failure flexibility** which relates to capability to re-route when a machine or line segment is out of service.

Almost all the recent research efforts have been directed towards developing alternative approaches to traditional fixturing methods, by replacing dedicated fixtures with flexible fixture systems and to reduce the requirements for fixtures within modern manufacturing systems (Trappey and Liu 1990, Fuh et al. 1993, Dia and Yuen 1995, Shirinzadeh et al. 1995). These alternative fixture designs and techniques include: sensory-based fixturing techniques, modular and reconfigurable fixtures, programmable configurable clamps, phase-change fixtures and adaptable fixtures (Grippo et al. 1988, Shirinzadeh et al. 1995). Among the modern fixture designs for machining operations, the modular fixtures have become hugely popular (Lewis 1983, Gandhi and Thompson 1986, Hoffman 1987, Lim et al. 1992), as they offer significant advantages in terms of flexibility, reusability and cost over the special purpose fixtures (see section 4.6.1).

2.4.3. Modular / Reconfigurable Fixtures

Modular fixturing systems are based on an extension of the classical machinists’ approach to developing a variety of fixtures from a combination of elements such as base elements, supporting elements, locating elements, and clamping elements. These elements are not only interchangeable and reusable but can be assembled in a variety of ways for
constructing a fixture (Anon 1986). Modular fixtures reduce fixture design and fabrication time, make fixture alteration easier and allow various components to be shared among multiple fixtures. They can be built without a formal design and can be modified quickly to accommodate engineering or customer changes, as well as manufacturing process improvements. Lim et al. (1992) summarise the main factors which have created a need for modular systems which include:

- faster changes of customer demand;
- trends to move from large volume to small scale customised production;
- rapid design obsolescence, changes and modifications;
- requirements for shorter lead time for manufacture; and
- increases in the costs of skilled designers, engineers and tool makers.

Current research efforts in the area of modular fixtures focus on the development of strategies to allow automatic assembly of fixture layout using robots (Shirinzadeh 1994). Research is also being conducted to develop software systems for automatic design of fixture layouts for modular fixtures (Markus et al. 1990).

2.4.4. Automated Design of Flexible Fixtures

Fixture design is a complex activity, requiring a large amount of information and extensive knowledge covering design, manufacture, assembly and inspection processes. Using the computer to aid in the design of flexible fixtures has attracted wide international research (Grippo et al. 1988). Automation in fixture design ranges from a kinematics approach to CAD/CAM technology to using expert systems. Asada and By (1985) developed a kinematics modelling approach where the characteristics of workpiece fixturing such as a deterministic position and accessibility are formulated as geometric constraints. These constraints are structured in terms of a boundary Jacobian matrix and fixture displacement vector. Murali and Wilson (1988) use a line of restraint to determine the kinematic freedom of motion for workpieces with fixture elements, so as to determine sets of contacts that would eliminate the translation and rotation motion of the workpiece.

The degree of expertise required in the optimal design of flexible fixtures has motivated researchers to explore the possibilities of employing artificial intelligence techniques for automating the fixture design process (Markus et al. 1990, Lim et al. 1992, Ngoi and Leow 1994). Markus et al. (1984) used the PROLOG language to develop an
expert system that aids modular fixture assembly. Nee et al. (1987) applied AI and CAD concepts to develop computer aided fixture design with a human interface. Bartholomew et al. (1988) outlined the steps required to build an expert system which aids in the automatic layout of modular fixture components on a CAD/CAM system. Darvishi and Gill (1990) actually developed an example of such an expert system for fixture design. Trappey and Liu (1990) carried out a comprehensive review of fixture design research. This review concluded that most of the automatic fixture design techniques employ a solid modelling system, and expert system shell and some form of feature extractor or feature-based design to select and position the fixturing elements from a database.

A typical methodology for the automated design of modular fixtures using a knowledge based system (an expert system) is defined by Grippo et al. (1988), and shown in figure 2.5. The inference engine searches through the knowledge base featuring a domain of fixture design knowledge, and also other databases containing workpiece characteristics, tooling data and process planning information. Once a viable fixture configuration has been established, a CAD system driven by the inference engine selects modules represented as solid models from a database. A post process phase then determines whether the fixturing constraints have been violated (Grippo et al. 1988, Nee and Kumar 1991). Dai and Yuen (1995) state that most researchers neglect the importance of efficient information and knowledge representation and manipulation in automated fixture design systems. They use a feature-based approach to develop a product model with a comprehensive hierarchical semantic structure to encompass information and knowledge needed for fixture design, manufacture, assembly and inspection. An object-oriented programming facility is utilised to ensure that information on higher levels can be inherited to lower level feature classes. Furthermore, fuzzy logic theory and fuzzy reasoning are used as a decision support tool in determining the most appropriate locating and clamping points of a fixturing system.

2.4.5. Computer-Aided Fixture Planning

The development of a flexible fixturing system is characterised by two areas. The first is the software development which allows the design, analysis, verification and automatic generation of fixture programs to be used by automated systems (Shirinzadeh 1994).
Figure 2.5: The Methodology for the Automated Design of Modular Fixtures Using Knowledge Based Systems (Adapted from Grippo et al. 1988)
The other is the development of the hardware for various types of manufacturing processes, as mentioned in section 2.4.2. The software modules may be referred to as computer-aided fixture planning (CAFP) systems.

The typical functions of a CAFP are summarised by Nee et al. (1992) and Shirinzadeh et al. (1995) as:

- **pre-processing** to retrieve part's geometry from the CAD databases;
- **fixture layout design** using knowledge based rules and information pertaining to manufacturing processes (see section 2.4.4);
- **design analysis** to perform kinematics and force analysis for the designed fixture layout;
- **fixture verification** to verify the validity of the designed fixture layout in view of the planned manufacturing process;
- **interference detection** to provide a graphical simulation of the fixture set up and to determine the cycle time; and
- **post-processing** to create fixture set up programs and to generate data files required by resources such as a cell controller.

Pendey and Ngamvinijaksakul (1995) argue that the majority of the research on fixtures deals with design and related problems with little or no work being done on the allocation and stock policy for fixtures. They have stated that any fixture planning system should comprise of two main sections. The first section deals with data storage and manipulation and the second section deals with mathematical computation required for fixture allocation, as shown in figure 2.6. Based on this structure, they have developed a fixture planning system for modular fixtures in FMS. This fixture planning system utilises the Fox-Pro database management system and a turbo C program as the fixture allocator section. They conclude that their system has limited flexibility in its functionality, as relational databases and a simple programming language have been used, and that there is a further need for research and development in this area.

2.4.6. *Integration of Computer-Aided Fixturing Planning in CIM*

Fixture planning and programming is an important sub function within computer-aided process planning (CAPP), which is the link between CAD and CAM systems in a CIM environment (Fuh et al. 1993). A CAFP system requires information with respect to part
design and geometry, i.e. CAD data, in addition to the process planning information for designing a valid fixture layout.

Shirinzadeh et al. (1995) state that the development of a fully flexible fixturing system is strongly dependent upon the integration with CAD/CAE/CAM/CAPP and robotics/factory automation, which are essential ingredients of modern manufacturing and assembly. They also argue that for an automated fixture design and planning system to be successfully implemented in the factory of the future, it has to be integrated with other sub-systems of a computer integrated manufacturing (CIM) framework.

Figure 2.6: Procedures for Optimal Fixture Planning
(Pendey and Ngamvinijsakul 1995)
Chapter 3

REVIEW OF APPROACHES FOR THE GENERATION OF PRODUCTION SCHEDULES

3.1. Introduction

This chapter reviews the design and implementation of production planning and scheduling systems. The chapter describes the various approaches undertaken by researchers, and provides a brief assessment of these approaches.

3.2. Classification of Approaches for the Generation of Production Schedules

Among the various manufacturing activities, production planning and scheduling has been the area with the largest proportion of research and development projects in recent years (Gupta et al. 1989, Cheng and Gupta 1989). This is due to the significant financial incentives for manufacturing companies to constantly improve their production practices (Grant and Clapp 1988). Planning and scheduling constraints, requirements and policies vary significantly between different manufacturing applications. As a result, the majority of production planning and scheduling systems developed, are designed to suit a particular application, for example, discrete part manufacture, the process industry and assembly of printed circuit boards. However, the approaches and techniques used to develop these systems can be classified under the following headings:

i) operations research.

ii) artificial intelligence.

iii) simulation based.

iv) hybrid approaches.
3.2.1. Operations Research (OR)

In the context of production management, OR is the science of planning and executing an operation to make the most efficient and economical use of resources available (Ravindran et al. 1987). OR techniques attempt to model the real world, often with the aid of mathematical relationships and equations, so that their performance can be optimised with respect to an appropriate set of criteria or constraints (Cohen 1985). The scheduling problem can be defined as a constraint satisfaction problem which can be solved by means of an optimisation process that relaxes the constraints and assigns a penalty to their violation (Hutchison and Chang 1990, Branddimarte 1992, MacCarthy and Liu 1993). The OR heuristics offer the advantage of focusing on the performance variability, objective functions and providing optimal solutions under a series of structured situations. As a result, most of the research on production scheduling has come from the operational research community. The published research work in this area, has reported a number of successful solutions using OR techniques to solve the common problem of allocating $n$ jobs to $m$ resources (Archetti et al. 1989). Some of these solutions are:-

- **single machine solutions**: single machine scheduling problems arise in practice more often than one might expect, as suggested by the large number of publications in recent years (Lawrence 1991, Kyparisis and Douligeris 1993, Sung and Park 1993, Vickson et al. 1993, Zheng et al. 1993, Uzsoy 1994).

- **algorithmic solutions**: algorithms are step-by-step procedures which follow a simple set of rules to achieve an optimum solution. One of the most famous of these algorithmic solutions was developed by Johnson (Johnson 1963) which aims to minimise the maximum flow time of the parts within manufacturing systems. More recently a number of researchers have developed further algorithms for various manufacturing applications (King 1980, Branddimarte 1992, Sabuncuoglu and Hommertzheim 1992, Shargul et al. 1995).

- **enumeration methods**: these techniques are used in applications where a large number of scheduling solutions are possible. Dynamic programming (French 1982, Bellman et al. 1982) and Branch and Bound (Winston 1977, Bellman et al. 1982) are two of such enumeration methods in which all possible scheduling solutions are
listed and the non-optimal ones are eliminated. The main drawback of enumeration methods is the long computing time required to generate the schedules.

- **scheduling heuristics**: are the non-optimising approaches to scheduling problems. Barr (1981) describes a heuristic as 'a rule of thumb, strategy, trick, simplification or any other kind of technique which drastically limits the search for a solution in large problem space'. All that can be said for a useful heuristic is that it offers solutions which are good enough most of the time'. Single stage heuristics are known as dispatching rules, scheduling rules or priority rules. Blackstone et al. (1982) compared several such rules based on the results of published studies. The use of schedule heuristics is not as popular as it was in 1970s. However one can still find published studies based on the use of this approach to find scheduling solutions (Mosier et al. 1984, Stecke and Talbot 1985, Mahmoodi et al. 1990, Mukhopadhyay et al. 1991, Lahiri et al. 1993).

3.2.2. *Artificial Intelligence (AI)*

An alternative approach has been advocated by the artificial intelligence community (Fox and Smith 1984). Knowledge based systems have been utilised to develop intelligent planning and control environments, some of which have learning capabilities. This approach has been popular in applications where scheduling decisions for short intervals are taken by an operator or the shop floor manager. The knowledge required to make such decisions is extracted through a knowledge acquisition process and coded in the form of 'production rules' (Kusiak 1990), to generate knowledge based software (expert system) that operates as the scheduler (Clark and Farhoodi 1987). The architecture of a typical knowledge-based scheduling system is illustrated in figure 3.1. This architecture consists of five major modules:

- **knowledge acquisition** which extracts the knowledge from an expert scheduler and encodes it in the form of production rules;
- **knowledge base** where production rules are stored;
- **working memory** used to store the data related to a current application instance;
- **inference engine** which uses the production rules in making decisions; and
- **user interface** which presents these decisions to the system's users.
One of the most useful characteristics of a knowledge based scheduling system is that a production rule used in a specific circumstance can be automatically explained to the system’s user. In addition, new knowledge can be added to the system simply by adding new production rules, whereas in comparison, the updating of scheduling systems based on other approaches and techniques is a more complicated procedure.

Learning has been referred by many researchers (Shaw et al. 1992, Yih 1992, Chiu and Yih 1995) as an essential element of any intelligent knowledge based system. Learning is defined as a process by which a system (e.g. scheduler) can acquire new knowledge and improve its performance in decision making, from experiences in a given domain. This process may result in either the enlargement of the knowledge base or the reduction in number of production rules which are found to be invalid.

3.2.3. Simulation Based

Simulation has been used to support many different manufacturing activities including product design, process design, facility design and more recently in production planning and scheduling. Carrie (1988) describes the role of simulation in the twofold context of system development and system operation. In the context of system operation, the original method of using simulation was to test the quality of a plan or a schedule, before it is released to the manufacturing system. Simulation models, by introducing variability, have had the capability to predict bottlenecks, queuing problems and over utilisation of resources. However since the 1980s, some of the well established simulation languages have been utilised to develop simulation models that can act as a scheduler and produce the work list sequences for a finite number of resources (Kachitvichyanukul 1991, Pritsker and Yancey 1991, Dar-el and Feuer 1992, Bengu 1994).

Simulation based finite capacity scheduling systems are usually designed to be used in conjunction with an infinite capacity planning system such as an MRP II system (Cheng 1988, Bengu 1994, Chan and Tang 1995, Roy and Meikle 1995), to convert the delivery schedules (i.e. the rough cut plans) into a detailed timing plan of necessary production activities required to fulfil customer demands. These finite schedules are generated by initialising the simulation model to the current state of the facility and then simulating the flow of actual jobs through the system based on a planned dispatching sequence of jobs. By changing the job selection rules (see section 4.4.4. for a comprehensive list of such rules) different alternative short term schedules can be generated. These alternative schedules can be compared based on the overall manufacturing goals (e.g. resource utilisation, number of tardy jobs) and the best schedule can then be selected for implementation (Roy and Meikle 1995).

The use of on-line simulation to model planning and scheduling has been investigated by many researchers (Halevi and Weill 1984, Jain and Osterfeld 1989, Wu and Wysk 1989, Rogers and Flanagan 1991, Harmonosky and Robohn 1991, Fanti et al. 1993). If a manufacturing environment involved little or no uncertainty, production plans generated off-line would be adhered to perfectly, giving performance that matches predictions exactly. However, in most applications some uncertainty such as resources breakdowns, material and tool shortages and changes in job priorities are always present, requiring the modification of plans generated on-line in the light of current events and system status. This necessitates the making of some intervention in the form of scheduling.
decisions on-line, effectively rescheduling those areas of the manufacturing system by disturbances. With an on-line simulation based planning approach, there is a need for a detailed model of the manufacturing system which has been integrated via a computer network to the physical resources on the shop floor. This model receives information on system status through shop floor data collection facilities and issues appropriate corrective instructions to overcome any possible problems (Smith et al. 1994). The success of such an approach relies very much on the design of the information structure and the quality of information being exchanged between the control system and the shop floor.

3.2.4. Hybrid Approaches

Recently a combination of two or more of the previously stated approaches has been used to design and develop scheduling systems with the purpose of utilisation of the advantages offered by each approach. For example the combination of a knowledge-based system and operations research methods is a promising approach to build computer-based shop floor scheduling system (Kusiak and Ahn 1992). Kusiak suggested a generalised architecture in which there are basically two components: a knowledge based system, and a collection of models with related optimisation algorithms. If a scheduling problem fits the stored model, an optimisation algorithm is used to solve this problem. Otherwise additional constraints are generated and passed on to the expert system for evaluation. This process of modification, generation and evaluation of solutions is continued until a satisfactory solution is obtained. Alternatively, a combination of knowledge based systems and simulation models are used to develop knowledge based simulation models for the planning and control of production systems, some with real time capabilities (Jain and Osterfeld 1989, Manivannan 1991).

Finally, it should be noted that object-oriented programming (Rogers et al. 1990, Tolio and Semeraro 1991, Adiga and Lin 1993, Cha 1995, Gausemeier et al. 1995), petri-net (Mori et al. 1991, Hatono et al. 1991, Reddy et al. 1992) and neural networks (Suh and Esat 1993, Chiang and Moon 1991, Arizono et al. 1995) are some of the other techniques used to develop manufacturing schedulers. The use of these techniques with comparison to other approaches has not been popular among researchers and as a result, these techniques have not been classified in the same level as the other well established approaches.
3.3. An Assessment of Production Planning and Scheduling Approaches

The OR optimisation techniques, mathematical or enumeration, all suffer from one fundamental problem; the difficulty of expressing the business requirements and scheduling constraints in the form of a simple mathematical function. As a result, all of this OR related research, in order to be able to systematically formulate a particular manufacturing application(situation/scenario), has made a large number of assumptions to simplify the variables and the constraints involved. But, in the majority of modern manufacturing applications, greater flexibility is required from the scheduling systems due to the constant changes in demands. Therefore, the simplification of the scheduling task by inclusion of such a large number of assumptions cannot be justified. Furthermore, in modern manufacturing applications a number of goals and constraints need to be satisfied simultaneously. This, in turn, adds further complexities to the procedure of formulating applications.

Although the option of using reasoning similar to human schedulers appears attractive, a review of the published work in this field suggests that there are very few operational knowledge based scheduling systems(Adiga and Lin 1993). This is not surprising as most of this research has not addressed the basic issues, such as the dynamic and stochastic nature of the system(Sarin and Salgame 1990) and dependence of scheduling solutions on domain characteristics specific to organisations, that make scheduling a complex problem.

Traditionally, two major drawbacks have been associated with the use of simulation models. Firstly, to develop complex models, an extensive modelling expertise is required and in general the process of development of simulation models was seen as both expensive and time consuming. Secondly, simulation models often required a significant computing power to keep their execution time within reasonable time limits. However, the recent development of PC-based simulation tools has been a significant breakthrough in simplifying the modelling effort and to reduce the time required for the design and implementation of simulation models(Chang and Tang 1995). In addition, the latest technology in personal computer(PC) hardware, has increased the computing power of such devices and reduced execution time of the simulation based tools. On the other hand, it is very difficult to develop a generic simulation model that can suit a range of applications, and so the majority of simulation based scheduling systems, like any other manufacturing software, require customisation. One of the biggest advantages of the
simulation based approach for generation of the production plans and schedules over the other techniques is that it can provide an accurate representation of the capacity of the manufacturing facility. This representation can be very detailed, including the material handling devices to provide an accurate estimation of the time required to process a job through a manufacturing system. Therefore, using the flexibility of simulation models, it is now also possible to develop schedulers for very complex applications (Dar-el and Feuer 1992) where, for example, part operation routing is particularly complicated in a multi-cell environment or applications in the process industry where time constraints are very restricted (Dines 1993).

Solberg (1989) presents a novel perspective to categorise these various approaches, and uses the concept of a paradigm. The notion of paradigm may be described as 'the world view taken at some period of history by a significant number of scientists within a certain domain of research'. Solberg identified three distinct paradigms, of the scheduling research community, namely the optimisation paradigm, the data processing paradigm and the control paradigm. The optimisation paradigm takes the view that the production planning and scheduling problems are problems which require an optimum solution and many of the techniques described so far in this chapter fit within this paradigm.

The data processing paradigm reflects the view of an entirely different community of researchers who see manufacturing scheduling problems fundamentally in terms of data management issues and therefore, planning and scheduling are performed through calculation of the net effects of customer orders upon the manufacturing system. An obvious example of this approach is MRP / MRP II. Finally, the control paradigm reflects the view of those researchers who see production planning and scheduling problems as control issues, and have focused on hierarchical control where commands are issued downwards and status information is sent upwards through layers of responsibilities. Solberg points out that the three separate research communities have adopted different approaches to what is essentially the same problem and therefore, each research community deals only with some aspects of the real scheduling problem.
Chapter 4

CONTEMPORARY PRACTICES IN PLANNING AND CONTROL OF FLEXIBLE MACHINING CELLS

4.1. Introduction

This chapter describes the current practices relating to the planning and control of flexible machining cells. The initial part of the chapter briefly summarises the evolution of flexible machining from its introduction to current day installations. The major part of the chapter is concerned with reviewing the issues relating to the three principal flows, based on a typical configuration for a modern flexible machining cell.

4.2. The Concept of Flexible Machining

The concept of flexible machining was first introduced by Williamson in London in the 1960s (Luggen 1991). The system based on this concept was called ‘System 24’ because it was scheduled to operate for 24 hours a day under the control of a computer, with 16 hours of unmanned production. Williamson planned to use Numerical Controlled (NC) machines to carry out a series of machining operations on a wide range of detailed parts. Workpieces would be mounted manually on a pallet, which would then be delivered to the machines and loaded automatically. Each machine would be equipped with a magazine from which tools could be selected systematically to perform a variety of different operations. This system aimed to combine the versatility of computer-controlled machines with very low manning levels.

In the 1970s and 1980s with the introduction of robots, automatic guided vehicles, automatic inspection devices and other types of computer controlled workstations into machining facilities, the term ‘flexible manufacturing systems’ (FMS) replaced the earlier labels for such systems. Today, global competition is forcing manufacturing companies to
design and implement production systems which are more flexible with respect to product variety, and with greater productivity. FMS can provide the flexibility required for small batch manufacturing, at levels of productivity normally achieved with larger volume manufacturing. FMS are primarily intended for the manufacturing of mid-volume, mid-variety products, as illustrated in figure 4.1.

Although, the basic concept and principles of flexible manufacturing has more or less remained unchanged since the 1960s, there has been an explosion in the design of machine tools and system controllers. The introduction of programmable controllers in the 1970s has resulted in development of Computer Numerical Control (CNC) machine tools which are capable of performing a much wider variety of machining operations. These advancements in machine tool design and the ever increasing requirements for more flexibility to produce smaller batches have gained a significant popularity for 'flexible manufacturing cells'. As a result, the configuration of flexible machining facilities has dramatically evolved from the original systems with a number of NC milling, grinding, drilling and turning machines into cells with a number of identical multi axis CNC machining centres. These flexible manufacturing cells are now common place within many manufacturing companies, offering numerous advantages such as the production of a wide range of part types with short lead times, low work in-progress, economical production of small batches and high resource utilisation (Mertines and Wieneke-Toutaoui 1991).

![Figure 4.1: General Range of Application Solutions Based on Workpiece Volume and Variety Requirements (Luggen 1991)](image)
4.3. A Typical Configuration for Flexible Machining Cells

In this thesis the author considers typical configurations of flexible machining cells (FMC) and their supporting facilities, as illustrated in figure 4.2, including :-

i) a number of machining centres (often identical) which contain a tool magazine where cutting tools required for the next job(s) are stored, a part buffer where raw materials are delivered and machined parts are removed, and a machining area where metal cutting operations are carried out.

ii) a cell tool store where a number of fresh tools are delivered to/from the central tool store/room and stored temporarily, before being sent to the machines. Spent/used tools are collected in the cell tool store and then returned to the central tool store/room.

iii) a part warehouse where raw materials are delivered to and stored temporarily, and the machined parts are returned.

iv) a fixturing area which contains a fixture store and a fixturing station where workpieces are mounted onto fixtures.

![Diagram of a typical configuration for a flexible machining cell]

**Figure 4.2 : A Typical Configuration for a Flexible Machining Cell**
v) a loading station from which workpieces are loaded/unloaded to/from a transporter.
vi) a number of temporary buffers where workpieces are stored temporally if a machining centre or loading station is not available to receive them.
vii) a workpiece transporter which is often an automated guided vehicle (AGV) or a rail guided vehicle (RGV).
viii) a tool transporter which can be a manual operator with a tool trolley, an automatic device such as an overhead gantry or simply the same transport used for carrying both the workpieces and cutting tools.

Based on this flexible machining configuration, the daily operation of such a cell involves the processing of production plans and schedules, by converting a list of jobs to a number of machined parts. FMC present planning and control systems with several operating problems that were not encountered earlier in the traditional jobshop because of the tightly controlled environment in which they operate (Stecke 1988, Gupta et al. 1993). Some of the common policies, strategies and practices related to the planning and control of the flows of workpieces, fixtures and cutting tools within FMC are outlined in the remaining sections of this chapter.

4.4. The Major Issues Related to Workpiece Flow within FMC

Workpieces represent a number of part types (a part being a component or a sub assembly of a product), varying in shape, size and list of required machining operations. These are often delivered to the machining cell, having been through a preparation stage, such as forging, casting or simply a cutting operation. Workpieces have to be mounted on a workholding device (a fixture), before being sent to the machining centres. They are dispatched in a specific sequence (see section 4.4.4) from the loading station and are taken by a transporter to a machining centre (or a temporary buffer if a machine is not available) which carries out a list of predefined machining operations. Once machined, the parts are returned to the loading station and fixturing area where they are removed from the fixture and stored in a part warehouse. Some of the strategies and rules used for the planning and control of workpiece flow are discussed in the next four sections of this chapter.
4.4.1. Production Planning and Control

In the context of manufacturing, the term ‘planning’ refers to the activities of determining what is to be produced, in what quantities, when it is to be produced, and what resources are to be used. Similarly, the term ‘control’ is used to refer to the activities of determining whether the production is carried out in accordance with the plan, and where this is not the case, take corrective actions (Bauer et al. 1991). Based on these definitions, production planning and control processes can be defined as the techniques and strategies used to direct and regulate the movement of goods/workpieces through the entire manufacturing cycle from the requisitioning of raw materials to the delivery of finished products. The main objectives of the production planning and control process are to minimise the inventory investments (in terms of raw material, work in progress, components and sub-assemblies, finished products), and maximise the efficiency in the utilisation of manufacturing resources (e.g. workstations, equipment, tools and labour) over a specific time horizon. The most common techniques and strategies adopted for production planning and control (Lawrence 1987) are briefly described below:

i) **Material Requirements Planning (MRP) and Manufacturing Resource Planning (MRP II):** In MRP / MRP II systems (Painter 1987, Reyner 1987), the requirements of products are calculated based on the forecast and open customer orders. These requirements are then explored in the bill of material (BOM) files which break down a product into its constituent components. The net requirements for these components are then calculated by deducting available inventory from the gross requirement, taking into account the specific values for the minimum stock levels (Bauer et al. 1991). A schedule for the production of this net requirements is generated. The system then, issues work orders to the relevant work centres. MRP / MRP II is the most widely used technique for production planning and control (Burgoine 1988). However, in recent years the pressures of the competitive world market has made it virtually impossible for manufacturing companies to make accurate forecasts of their order demands, resulting in a diversion from the traditional use of MRP/MRP II systems (Lawrence 1987).

ii) **Just in Time (JIT):** JIT is a technique in which production of any product is solely based on the customer orders (Ohno and Mito 1986). This production strategy aims
to improve overall productivity through elimination of wastage and reduction of work in progress (Sarker 1989, Hay 1990). JIT utilises a pull scheduling technique (see section 4.4.3) normally referred to as ‘kanban’ in which a system of cards is used to signal the need to delivery and produce more parts. The JIT strategy heavily relies on established relationships with suppliers to achieve just in time deliveries of raw materials, purchased components and tools (Lubben 1988, Egbelu and Wang 1989). This technique was first implemented by Japanese companies (Ohno and Mito 1988) and can provide significant savings in production costs if it is effectively planned and implemented within an appropriate manufacturing application (Voss and Clutterbuck 1989).

iii) Optimised Production Technology (OPT): OPT is based on a number of rules (Bauer et al. 1991) which, when followed, are claimed to help increase manufacturing profitability. OPT identifies three important criteria that are useful in the evaluation of the production progress namely, throughput, inventory and operating expenses. The goal of the OPT technique is to increase throughput while simultaneously decreasing inventory and operation expense through realistic and optimised schedules (McManus 1987). The majority of OPT rules relate to the development of correct schedules and often an analytical method based on these OPT rules is used to generate these schedules. OPT was seen as an extension to the MRP / MRP II approach to manufacturing. Lundri gan (1986) suggested that OPT brings together the best of JIT and MRP II into a ‘Westernised Just In Time’.

4.4.2. Tasks Involved in Generation and Implementation of Production Plans

The generation and implementation of production plans is a complex task and involves a number of specific functions. These individual functions are outlined by Browne et al. (1988) and are briefly described below:

- **aggregate production planning** determines the quantities and types of products to be produced during a specific time period. These product quantities are further divided into manageable partitions (Stadtler 1988), referred to as batches or lot sizes.
• **production process planning** identifies the production processes that transform the raw materials into the finished products and generates a process route for individual products through the overall manufacturing system.

• **production scheduling** generates time phased execution plans for the jobs to be processed (Gessner 1982). This is achieved by sequencing the operations within jobs, allocating machines and other resources to jobs, or operations within jobs, and the subsequent time-phasing of these jobs on individual machines, and producing a series of work-to-lists for individual resources and dispatching lists for stores and the loading stations.

• **production control** determines whether the operations are executed according to the schedules and takes corrective steps to modify the plans whenever the actual production progress is deviated from the schedules set at the planning stage (Smith 1989).

4.4.3. **Push and Pull Type Control Strategies**

Planning and control systems are classified into push type, pull type and hybrid systems (Hirakawa et al. 1990). The strategies within push type systems are based on forecasting demands for a particular time period in the future, whereas a pull type systems function is based on the actual demand calculated from existing customer orders. Hence the terminology of 'make to stock' for push type systems (Sriharan and Berry 1990), and 'make to order' for pull type systems (Yang and Jacobs 1992). A more technical terminology used to refer to these systems is 'forward planning' and 'backward sequencing' for push and pull type systems respectively.

In planning terms, a push type system starts by assigning the first operation of a job onto the first possible time slot on a resource and sequences subsequent operations accordingly, whereas a pull type system starts by assigning the last operation of a job so that it meets its final due date and then allocating the previous operations accordingly, as shown in figure 4.3.
The performance of pull and push type systems will vary significantly between applications for different production system configurations, manufacturing goals and business requirements. As a result, it is difficult to generalise about the advantages and disadvantages associated with each system. However, some of the advantages generally reported for push types systems are; higher average resource utilisation, shorter lead times and immediate delivery from stock. The benefits of pull type systems are; lower work in progress, smaller buffers/queues and more flexibility towards changes in demand (Hirakawa et al. 1990, Lee et al. 1994, Siha 1994).

4.4.4. Scheduling Rules

A scheduling rule (referred to as sequencing, allocation, dispatching or loading rule in some research publications) is used to select the next job (a batch of one or more workpieces) to be processed from a set of jobs awaiting service. These rules can be also used to introduce work into the system (dispatching), to route work in the system and to assign parts to resources. Scheduling rules can be static i.e. they can be applied at the beginning of a scheduling period, resulting in a fixed schedule for the period, or dynamic i.e. changing over production time. A comprehensive list of manufacturing scheduling rules are identified by Gupta et al. (1989). These are broadly classified in two following groups, and are summarised in table 4.1 and 4.2:-

i) simple priority rules

ii) combination of simple priority rules
<table>
<thead>
<tr>
<th>Group Number</th>
<th>Group Identification</th>
<th>Priority Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Due Date (DD)</td>
<td>Select the job with the:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i) EDD: Earliest Due Date</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii) OPNDD: earliest Operation Due Date</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iii) MDD: earliest Modified Due Date</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iv) MOD: earliest Modified Operation Due date</td>
</tr>
<tr>
<td>2</td>
<td>Processing Times (PT)</td>
<td>Select the job with the:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i) SI: Shortest Imminent operation time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii) LI: Largest Imminent operation time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iii) SR: Shortest Remaining process time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iv) LR: Largest Remaining process time</td>
</tr>
<tr>
<td>3</td>
<td>Setup Time Rules (STR)</td>
<td>Assign the Job with the:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i) HGST: Highest priority to highest Setup Time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii) SGST: Slightest priority to highest Setup Time</td>
</tr>
<tr>
<td>4</td>
<td>Number of Operations (NOP)</td>
<td>Select the job with the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i) FOPNR: Fewest Operations Remaining</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii) MOPNR: Most Operations Remaining</td>
</tr>
<tr>
<td>5</td>
<td>SLacK (SLK)</td>
<td>Select the job with the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i) S1: Least amount of slack</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii) S2: least static slack (period between due date and arrival time)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iii) RSTP1: least ratio of the job slack time to the remaining processing time</td>
</tr>
<tr>
<td>6</td>
<td>Random Arrival Times (RAT)</td>
<td>Select the job with</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i) FIFO: First In First Out</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii) LIFO: Last In First Out</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iii) RDM: Random order</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iv) BAT: assign the highest priority to the job with Earliest Available Time</td>
</tr>
<tr>
<td>7</td>
<td>Machines</td>
<td>Select the job with the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i) WINQ: that will go on to a machine that has the least work load</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii) SMCPT: that has Shortest Machining Centre Process Time at the next machine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iii) NINQ: whose direct successor machine has the shortest queue</td>
</tr>
<tr>
<td>8</td>
<td>Tools</td>
<td>Select the job which includes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i) MTM: least number of tool movement</td>
</tr>
<tr>
<td>9</td>
<td>Cost Rules (CR)</td>
<td>Select the job</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i) Cost: with minimum tardiness and processing cost</td>
</tr>
</tbody>
</table>

Table 4.1: Simple Priority Rules (Gupta et al. 1989)
4.5. The Major Issues Related to Tool Flow within FMC

Cutting tools are the metal removing objects of various shape and size, used to carried out a number of machining operations on the workpieces within the machining stations. They often consist of an assembly of 3-4 components such as tool holders, chucks, shanks, collets, tool extensions, cutting tips or edges. As a result, a cutting tool has to be assembled(built up) and carefully measured(preset), before being used at a machining station. There are an enormous number of tool types varying in their design, material, and their cutting capabilities. Tool types are often categorised based on various types of machining operation such as milling, drilling, turning, grinding, boring, tapping, and chamfer tools. Cutting tools gradually lose their accuracy in cutting capabilities over a period, in which case they are referred to as worn or spent. The period in which a tool can
be used for the machining operation with certain accuracy is referred to as its tool life. The tool life can be defined in terms of a number of minutes or hours of cutting time (e.g. 90 minutes) or in terms of the number of parts (e.g. 75 parts).

A collection of cutting tools representing the range of tool types required for the machining operations of a particular part type is defined as the 'basic toolkit' for that part type. Similarly, a batch of two or more workpieces (of the same or various part types) representing a job would require an unique 'toolkit'. A duplicated tool within a toolkit is referred to as a 'sister tool'. Some of the common policies, strategies and practices related to the planning and control of the tool flow within FMC cells are outlined below.

4.5.1. Tool Exchange Policies

The strategies/rules used to manage the procedure of the provision of tools required by a job (a workpiece or a batch of workpieces) from stores to the machining centres is referred to as 'tool exchange policies'. The selection of a suitable tool exchange policy for an application depends very much on the range of part types and the commonality of their tooling requirements. This subject has been investigated by a number of researchers (see section 2.3.4), both internationally (Tomak 1986, Luggen 1991, Lin and Wang 1993, Sule 1993) and at Loughborough University (de Souza 1988, Ozbayrak 1993, Coleman 1996). The influences of tooling strategy related research work on the multi-flow control research, are explained in detail in chapter 5. Although the underlying principals of the strategies suggested by various researchers are very similar, the terminology used to name these strategies are different in each case. In this thesis, the author has adopted the terminology used by the researchers at Loughborough University. Based on this terminology, a brief description of the most commonly used tool exchange policies are provided below:

i) **Full Tool Kitting**: where all the tools required by a job are delivered and loaded into the machine tool magazine before the start of the machining operations, and on completion of the job are removed from the magazine. This policy is used when a set of new tools is used for every job to ensure the precision and accuracy of machining operations or in applications with little tool requirement commonality between part types.
ii) **Differential Tool Kitting**: in this tool exchange policy the objective is to share common cutting tools required by various jobs on a machining centre, providing the tool is not worn out (i.e., the tool life has not been exceeded). This is achieved by identifying the overlap in tool requirements of the two sequential jobs on a machine, leaving the tools required by the second job in the tool magazine of the machine. The extra set of tools required by the new job, is then delivered and exchanged with those cutting tools not required any more. This policy will provide a more effective tool life utilisation in comparison with the full tool kitting exchange policy but requires a more sophisticated tool requirements planning procedure.

iii) **Consolidated Tool Kitting**: This policy is similar to differential tool kitting exchange, in that only a subset of the full toolkit required by a job which does not reside in the machine, is delivered and exchanged at the machine. However, unlike the differential tool kitting exchange policy, the tools which will not be required by the second job, are not removed from the tool magazine, with the assumption that they will be used by the subsequent jobs on the machine, until the tool magazine is filled with partially used tools (a condition referred to as a saturated tool magazine). At this stage if a new tool is required by a job, a decision has to be made to take off a tool from the tool magazine based on the life left or the tool not being required for future jobs. Thus, the consolidated tool kitting exchange policy enables a very high tool life utilisation, particularly in applications with a great degree of tool requirement commonality within a range of part types.

iv) **Residential Tool Kitting**: this policy can only used if a complete range of tool types used by all the part types can be accommodated within the tool magazine of machines. As a result, every tool type is assigned to a predefined position within the tool magazine and all the machines are loaded with an identical range of cutting tools. Cutting tools are then delivered to and exchanged on the machine, only if the existing tools within the magazine are worn. Tools are always loaded into the same position within the tool magazine and their usage and remaining life is continuously monitored. It is clear, that the residential tool kitting policy will provide the opportunity to utilise the maximum expected tool life. However, this policy requires the duplication of a tool type on every machine and often a large tool magazine size for machining centres.
v) Common Tool Kitting: this is similar to the residential tool kitting policy in that a section of the tool magazine of each machine is preloaded with the tools required by the majority of the part types (referred to as a common toolset). However, the second section of the tool magazine, referred to as an overflow buffer, is assigned to the tools required by a subset of part types. The common tool kitting policy provides the majority of advantages offered by the residential tool kitting policy, and additionally, can be used in applications where a full range of tool types cannot be accommodated in all of the tool magazines of the machines.

4.5.2. Tooling Activities

Tooling activities are the operations carried out (often manually) in tool store/room, and can be classified as follows:

i) **tool assembly**: the process of combining the various elements of a cutting tool such as tool holders, chucks, collets, shanks and cutting tips to produce a tool assembly.

ii) **tool disassembly**: the process of disassembling a worn tool into its basic elements.

iii) **tool preset**: the measurement of predefined positions of the cutting edges of a tool assembly so that it complies with required preset measurements.

iv) **tool rework**: the process of refurbishment/regrinding the cutting edge/tip of a tool to regain its original accuracy and precision in cutting capabilities.

v) **tool delivery**: the task of transporting tools to a cell tool store from a central tool store and returning the worn tools back to the tool room.

vi) **tool exchange**: the process of replacing worn/unwanted tools with new tools in the tool magazine of the machines.

4.5.3. Planning for Tool Flow within FMC

The planning for tool flow can be considered, using a hierarchical division of tool stores and tool buffers. There are three common storage areas for cutting tools within flexible machining cells and its supporting facilities, as illustrated in figure 4.4. There are:-
Figure 4.4: A Typical Tool Flow Configuration Using a Hierarchic Division of Tool Stores

- **central tool store/room** where all the components of cutting tool assemblies are stored. The activities of tool assembly, disassembly, rework and presetting take place with the central tool store/room.
- **cell tool store** is a buffer between the central tool store/room and magazines of machine tools. The assembled, preset and new tools, required in the short term (e.g. a shift, a day) within the machining cell are temporarily stored in the cell tool store. Similarly, the worn tools which are recently taken off the machines are temporarily held in the cell tool store, before being transported back.
- **machine tool store** which often is in the form of a tool magazine (e.g. tool chain, drums or cylindrical magazine) where a varied set of cutting tools are held, corresponding to operation sequences of the assigned parts.
Based on this hierarchical division of tool stores, there are two areas of tool flow planning required: -

i) planning for the tool flow between the central tool store and cell tool store i.e. planning for the tool delivery activities. This involves planning for tooling activities within the central tool store/room (e.g. tool rework, assembly, presetting activities), so that the right tool, in the right quantities, with preset measurements, at the right time can be delivered to the cell tool store.

ii) planning for the tool flow between cell tool store and machine tool store i.e. planning for the tool replacement activities (see section 4.5.2 for the list of tooling activities). This requires the planning for the implementation of the adopted tool exchange policies (see section 4.5.1).

The short term planning of tool flow is often based on tool requirements planning (TRP). TRP is the task of calculating the net tooling requirements over a time period (e.g. a shift, a day, a week) as a function of the number each part type to be produced, tool types required, machining times for each operation using each tool, expected tool lives and the probability of premature breakdowns (Gray et al. 1993).

4.6. The Major Issues Related to Fixture Flow within FMC

Fixtures are workholding devices upon which workpieces are mounted before being sent to machining centres for their machining operations, and are usually loaded onto a pallet before being transported, as illustrated in figure 4.5. There are an enormous number of fixture designs, varying in shape, size, capacity (i.e. the number of parts that can be mounted on the fixture at any time) and number of working faces. These fixture designs are based on the shape, size and machining requirements of parts, together with the size and configuration of machining centres (e.g. horizontal or vertical machines). Based on the size of pallets, fixtures, workpieces and machines, there could be one or more fixtures been loaded onto a pallet. These fixtures can be temporary loaded or permanently fixed on the pallet depending on the number of available pallets and the variety of fixture types. As a result, the nature and number of fixturing activities required within a machining cell can vary significantly based on the pallet, fixture and part configuration. These fixturing activities are explained in more detail in section 4.6.3.
Fixtures have a greater role in the daily operation of flexible machining cells than their traditional use in the jobshop environment. The utilisation of unmanned machines in such cells, requires fixture design to be carefully considered to allow workpieces to be even more rigidly and accurately secured on work holding devices. Furthermore, specially designed fixtures have been developed to maximise the possible machining time per machine set up(with multi-parts per fixture). These specially designed fixtures can be used with a limited number of part types, or even with one part type.

The planning for fixturing(mounting a part onto a fixture) and defixturing operations is nearly always carried out manually by the operators based on the schedule of jobs presented every day at the start of the shift. This lack of preparation time can potentially lead to delays and machine down times. In addition, in applications where specially designed fixtures are used for specific part types, it is the availability of these fixtures that determines the sequence with which jobs are sent to the machines. Therefore, effective management of fixtures within the FMC plays a vital role in the overall performance of such systems.
4.6.1. Fixture Design

Fixture designs which are more commonly used within FMC are:-

i) *Specially Designed Fixtures* : these fixtures are designed to be used with one or more specific part types and could have a capacity of one or more parts. They have a fixed configuration (i.e., shape and size) and are often used in flexible batch machining cells where a limited range of part types are machined in medium to large batches over a long period. This type of fixture offers high accuracy in positioning the workpieces, reliability over a long period, a shorter time period for fixturing and defixturing operations and the possibility of maximising the machining time per machine set up with multiple parts per fixture. However specially designed fixtures have the following disadvantages; a complex, time consuming and expensive design procedure, high initial cost per fixture and can be made obsolete through changes in part design.

ii) *Modular Fixtures* : these fixtures consist of a mounting plate or a mounting block together with various clamps, nuts, screws, pins and supporting arms which are used in different combinations to produce a number of fixture configurations that can securely hold a range of part types(see section 2.4.3). The fixture configurations are initially designed and photographed. These pictures of fixture configurations, together with the list of required components and instructions for reassembling are used to generate a series of assembly cards which will be used to reassemble the fixture configurations. These types of fixtures are used in machining applications with small to medium batches but a large variety of part types and offer a reduction in the initial design cost, reduction in initial cost per fixture, reusability for new part designs(i.e. they do not become obsolete). The disadvantages associated with the use of modular fixtures are as follows : they require the fixturing activities of fixture assembly and disassembly which can be very time consuming, they require a more frequent recalibration activity, and cannot be effectively used to maximise the cutting time per machine set up with multiple parts per fixture.
4.6.2. Palletising and Fixturing Policies

There are four common practices for mounting parts on a fixture with flexible machining applications, as shown in figure 4.6. These are :-

i) a single and unique part type is mounted on a unique fixture type.

ii) a single and unique part type is mounted on a number of alternative fixture types. In such cases, a preferred fixture type is defined for the part type. However, an alternative fixture type can be used, if the preferred fixture type is not available.

iii) a number of parts of a unique type is mounted on a single, unique fixture type.

iv) a number of parts of different types are mounted on a single fixture type.

4.6.3. Fixturing Activities

Fixturing activities are the operations that are carried out (often manually) within the fixture store and fixturing stations, and can be classified as follows :-

i) fixturing operation: mounting (securing) one or more workpieces onto a fixture.

ii) defixturing operation: removing one or more machined parts from a fixture.

![Figure 4.6](image-url): The Various Configuration for Mounting Parts on Fixtures
iii) fixture assembly: assembling a combination of mounting plates or mounting blocks together with clamps, supporting arms, pins, nuts and screws to build a particular fixture configuration.

iv) fixture disassembly: disassembling a fixture configuration into its basic elements.

v) fixture calibration: measurement of distances, set ups and positions on a fixture.

vi) fixture load: loading/clamping a fixture onto a pallet.

4.6.4. Planning for Fixture Flow within FMC

In the application with modular fixtures a fixture configuration has to be assembled for a particular part type, before workpieces can be mounted and sent to the machines. The activities of fixture assembly and fixture disassembly usually require a much longer period to be carried out. Typical configurations for the flows of fixtures and workpieces while using modular fixtures are illustrated in figure 4.7.

Figure 4.7: Typical Fixture Flow Configuration for Modular Fixtures
In the applications with specially designed fixtures a quantity of every fixture type is stored in the fixture store. These fixtures are withdrawn from the store as and when required and are returned to the store, following a defixturing operation. Clearly, the main difference between the two configurations is that of activities related to fixture assembly and disassembly which will be not required with specially designed fixtures. Therefore, a different set of strategies for planning and management of fixturing activities should be adopted with modular fixtures. In some machining applications using modular fixtures, the various fixture configurations are often constructed in some quantities and are stored. These fixture configurations are then withdrawn from the store similar to the specially designed fixtures and are used as and when required, without the need for fixture assembly or disassembly operations. Clearly, this would eliminate the need for fixture assembly and disassembly activities associated with modular fixturing and unlike specially designed fixtures these fixture configurations can be eventually broken down and reused for new part designs. However, this method of using modular fixtures introduces the need for extra fixture inventory and requires a greater space to store the assembled fixtures.
Chapter 5

THE CONTEXT OF THE MULTI-FLOW CONTROL RESEARCH

5.1. Introduction

This chapter presents an evaluation of the related research publications for all the themes of this thesis, and aims to position and assess the author's contribution to the research area. It also identifies the context of the multi-flow control concept within the overall production planning and control process. Finally, a brief description of a government funded research programme is provided, on which the research work reported in this thesis has been carried out.

5.2. Evaluation of Related Research Publications

In order to evaluate the related research publications for the general theme of the thesis and to position and assess the author's contribution to this research area a number of categories of research work have been considered and are outlined below.

5.2.1. Planning and Control of FMS

The planning and control of FMS has been among the most popular research subject in the last two decades (see sections 2.2.6, 2.3.7, 2.4.6 in chapter 2). As a result, there are an enormous number of research publications covering a wide range of issues such as work loading and routing decisions, delivery dates, set up times, queue and buffer sizes, automatic work handling devices, and real-time scheduling and control of FMS. However, almost all of this research is based on the more traditional configurations of FMS with a number of different types of CNC milling machines, turning machines, and auxiliary equipment.
The latest technological breakthroughs in design of CNC machining centres, together with new manufacturing requirements for smaller batches have resulted in a shift towards flexible manufacturing cell configurations where a number of identical machine types are used. This has been reflected by an increasing number of research publications on the planning and control of flexible manufacturing cells in recent years (Grant and Nof 1989, Hitomi et al. 1989, Chan and Bedworth 1990, Elsayed and Kao 1990, Rogers et al. 1990, Williams and Rogers 1991, Chang and Tang 1995, Soon and de Souza 1995). Chan and Bedworth (1990) state that:

"From a review of the literature, it is apparent that there is a trend in industry away from grandiose schemes such as FMS to much more focused, smaller, manageable levels of factory automation. At present, the most feasible approach to automation, computerising and integrating the job shop process seems to be through flexible manufacturing cells."

The multi-flow control research is specifically directed towards FMC with a configuration similar to that outlined in section 4.3. Therefore, this research work is concerned with planning, control conditions and constraints different to those used in research publications based on FMS.

5.2.2. The Modelling Technique

A summary of the techniques and approaches adopted in the planning and control of manufacturing systems, with a brief assessment is provided in chapter 3. The case for the use of simulation based scheduling is highlighted by Soon and de Souza (1995) who state that:

"Most manufacturing systems are too complex to allow realistic models to be evaluated analytically. As an alternative, simulation based scheduling can provide an effective tool for shop floor scheduling while requiring few assumptions. The schedules generated are based on an accurate, realistic model of the production facility. It can allow various dispatch rules, or decisions regarding the system to be tried out and selected based on performance results."
The multi-flow control research is concerned with the operations and activities related to the three principal flows of workpieces, fixtures and cutting tools. As a result, in comparison with models reported in many related research publications, a much more detailed model of the machining facilities is required. Therefore, a simulation-based approach has been adopted to allow such complex and larger models to be constructed.

5.2.3. Planning and Control Rules and Policies

The largest section of manufacturing planning and control related research publications are based on assessment, evaluation and implementation of well known planning and control rules and policies in a wide range of applications with different sets of conditions and assumptions (Blackstone et al. 1982, Gupta et al. 1989, Stecke 1992). However, in the application of modern FMC with a number of identical CNC machining centres, the majority of these traditional rules and policies are not relevant, as they are related to loading non-identical machines, routing decisions, reduction of set up time and part movements. Chandra and Talavage (1991) state that:

"The conventional dispatching rules which are based on shallow heuristics, do not provide any well-founded assurance of long-term good performance. Moreover, these rules are particularly less relevant in flexible cells where a machine has a global choice of parts, as opposed to choice restricted to the subset of parts that are already dedicated to the machine. In order to make better use of the system's routing flexibility, we need a more intelligent decision process for job dispatching."

As a result, a section of research reported in this thesis is concerned with the generation of more intelligent job allocation rules to take advantage of this routing flexibility within FMC to minimise the cost of cutting tools and fixturing requirements.

5.2.4 Decision Making Tasks in Planning and Control

Planning and control of FMC is a very demanding task involving significant decision making, based on a number of manufacturing parameters and variables. A large number
of conflicting constraints and manufacturing goals such as meeting due dates, minimising inventory and operation costs, maximising the utilisation of resources and achieving a balanced work load across the resources make the planning task a very complex decision problem. A number of researchers have outlined frameworks for the automation of the decision making processes involved in the planning and control of manufacturing systems, often through the utilisation of a knowledge based system (Steffen and Greene 1986, Grant and Nof 1989, Dobson et al. 1992, Talavage and Shodhan 1992).

In flexible machining applications with a large number of jobs, a wide variety of part types, cutting tools and fixture types, a large number of CNC machines and very tight due dates; the effects of some of these decisions are vital, but not easily realised. Due to these complexities and the unpredictable nature of manufacturing systems, it has been virtually impossible to develop fully automated planning, scheduling and control systems. This has been highlighted by the very notable rapid development of computer graphic-based scheduling and control support systems (Sridharan and Kanet 1995). This technology, known as ‘Leitstand’ (the German word for a common centre or directing stand) in Europe, makes extensive use of recent advances in computer graphics to support the human decision maker (see section 2.2.5). Sridharan and Kanet (1995) state that;

“A leitstand is a computer-aided decision support system for interactive production planning and control and fits perfectly into the CIM concept by connecting the planning module with the shop floor. ....a leitstand provides the ability to quickly obtain information on machine utilisation, machine loading pattern, work run-out times and job lead times, so that any required corrective measures can be initiated by the decision maker.”.

The multi-flow control research does not aim to automate the decision making procedure involved in planning and control of machining cells, but to act as an ‘advisory system’ to the person responsible for decision making, referred to as the ‘cell manager’. As a result, within the structure of the software modules generated through the research work, namely the ‘multi-flow controller’, graphical interfaces have been designed and implemented for decision support and the frequent interactions with the cell manager.
5.2.5. Workpiece Flow Related Research

Traditionally, manufacturing planning and control systems have always been concerned with the flow of workpieces through production systems. All the other manufacturing elements involved in production, such as machines, transporters, and manual operators have been dealt with as resources with their availability or shortage influencing the workpiece flow. This view has also been repeated in the research work on planning and scheduling of flexible manufacturing systems (Gupta et al. 1989, Aanen et al. 1993). Researchers using this workpiece dominated approach have focused on a number of issues that are specifically related to the flow of workpieces, as described in section 2.2. However, more recently researchers have realised this workpiece flow is severely influenced by other material flows within the machining facilities. Veeramani (1992) states that:

"....there has been a growing realisation of the necessity to control not only workpiece flow but also tool flow in the manufacturing system. Since CNC machines have limited tool magazine capacities, the shop floor controller has to address job allocation in conjunction with tool allocation...."

Similarly, Leung et al. (1993) state that:

"Within the FMS environment, batches of parts are selected for production within a given time horizon, often referred to as the manufacturing cycle. Once the batch production requirement is known, two of most important planning tasks are the determination of part assignment and tool allocation. There is a reciprocal relationship between these two tasks as part assignment is dependent on tool allocation and vice versa. .....this paper addresses part assignment and tool allocation concurrently with explicit considerations given to material handling issues."

In addition Alberti et al. (1991) state that:

"In order to carry out a manufacturing process the simultaneous availability of the resources required(machine, tools, fixtures, work material, part
programs) must be provided. Due to limited availability both in space and time domains, a demanding synchronisation task must be accomplished. ....a simulator able to model the flow of parts and tools within an FMS is presented. The coordination task between part flow and tool flow is carefully modelled considering issues such as tool life management, capacity of tool storage devices, performance of the automated tool handling system, loading strategies of tools..”

Grieco et al.(1995) describe a part and tool simulator, similar to Alberti et al.(1991) and Ulusoy and Bilge(1993) provide a similar approach for simultaneous scheduling of machine and automated guided vehicles. In terms of research methodology, these research works are similar to the multi-flow control research in that they all consider a number of material flows within the manufacturing systems concurrently. However, the research objectives and the material flows considered, are quite different in each case.

5.2.6. Tool Flow Related Research

A number of researchers have addressed the general tool management problem within advanced machining facilities, as described in section 2.3, and as a result a number of tool management systems(TMS) structures have been suggested to carry out a number of functions such as the rationalisation of the purchasing, storage, inventory and procurement requirements, managing and supporting the tooling database for various design, planning and control processes. The majority of TMS operate independently from work scheduling systems and from the short term demand of job throughput. The importance of the integration of TMS with other planning systems has been recognised(Lee and Chua 1991, Veeramani 1994). However, none of this research work has identified a structure to provide an adequate basis for short term scheduling and control of tool flow at the machining cell level. Recently, Maropoulos(1995b) has carried out a comprehensive review of tooling technology, process modelling and process planning. In his paper he states that:

"The functionality of current, proprietary tool management systems is limited to aspects of procurement, logistics and information management. A review
of the state-of-art revealed that tool management systems had no facility available for tool scheduling, tool capacity planning, tool flow simulation and lacked standardised data interfaces. "...the supply of tools can be improved by linking tool management to scheduling and production control."

Additionally, Gray *et al.* (1993) state that;

"Our study points out several promising research directions... to date, most research effort in tool management focus on single-level decisions. The current research incorporating tooling economics within production scheduling exemplifies the benefits of integrating decision levels."

A major theme of the multi-flow control research is the design and specification of a multi-flow scheduling system which by considering the interactions of a number of scheduling rules for cutting tools and fixtures together with workpiece scheduling strategies, simultaneously generates schedules not only for jobs to be processed in a machining cell but also for the cutting tools and fixtures required by those jobs (see chapter 8).

5.2.7. Fixture Flow Related Research

The published research on the use of fixtures has mostly focused on the design of fixtures, as described in section 2.4, with little emphasis given to the management of fixture flow within FMC. Pandey and Ngamvinijsakul (1995) state that;

*Majority of the research deals with design and related problems and little or no work has been done on the allocation and stocking policy for flexible fixtures. Inadequate allocation of fixturing elements may result into inefficient production, poor machine utilisation, job tardiness etc. Fixture element location plan should be based on product demand requirements, processing times, operation sequence and number of machines.*

The planning for fixturing (mounting a part onto a fixture) and defixturing operations are nearly always carried out manually by operators based on the schedule of jobs presented to
them every day at the start of the shift. This lack of preparation time can potentially lead to delays and machine down times. Tomak (1986) states that;

"Fixturing influences the quality of FMS production. Fixture setting represents the main occupation of ‘manned areas’, and may thus create a bottleneck in the flow of parts within FMS. Altogether fixturing may present a serious problem especially for FMS production which copes with a great variety of parts."

In addition, Shirinzadeh et al. (1995) state that;

"Fixture planning is an important function within computer-aided process planning (CAPP), which is the link between the design and manufacturing in a CIM environment. Fixture planning has several requirements which must be integrated with other activities such as CAPP and production planning and control (PPC) within CIM."

Planning for fixture flow within FMC has been considered in conjunction with part and tool flow in the multi-flow control research work. One of the main objectives is to synchronise and harmonise the three principal material flows. Additionally, a number of fixture dominated planning strategies based on different fixture design and fixturing applications have been developed, and are described in chapter 11.

5.3. The Context of the Multi-Flow Control Research

It is clear from the review of the research publications on planning and control procedures in section 5.2, that many researchers have indicated a need for an integrated environment where issues involved in the short term planning and control for workpieces, fixtures and cutting tools can be addressed simultaneously. The “multi-flow controller” has become the in-house research terminology given to such an environment at Loughborough University.

The planning and control of machining facilities within a manufacturing company is seen as a subsection of the overall production planning and control, which also includes functions such as material requirements planning, planning and control of assembly areas,
inventory control, as illustrated in figure 5.1. The need for an efficient planning and control system has been further increased with the introduction of flexible manufacturing facilities. More recently, the term flexible manufacturing is used to refer to 'flexible casting systems' and 'flexible assembly systems'. However, the multi-flow control research has concentrated on applications of flexible machining facilities. Furthermore, among the application of flexible machining facilities, the particular domain of flexible machining cells is used within this thesis to test and validate the research concept and research experimentation. A typical configuration of a FMC is provided in section 4.3, and is illustrated in figure 4.2. FMC present several job sequencing and routing flexibilities that were not encountered in more conventional flexible manufacturing systems. The utilisation of these extra degrees of flexibility to achieve further economy in manufacturing cost through the harmonisation of material flow for maximum cell utilisation and the reduction in the cost of cutting tools and fixtures requirements, forms the context of the multi-flow control research work.

![Diagram](image)

**Figure 5.1**: The Context of Multi-Flow Control Research Within the Overall Production Planning and Control Framework
5.4. Loughborough University Research Programme

The research programme which forms the backdrop for the research reported in this thesis, is entitled “multi-flow control to improve flexible batch manufacturing performance”. This was a nationally funded programme (GR/H49450), supported by the Engineering, Physical and Science Research Council (EPSRC), from August 1992 for three years duration in the Department of Manufacturing Engineering at Loughborough University. This research programme had industrial support from four project collaborators, namely:-

i) The CIMulation Centre: a software house, which is a supplier of the ARENA simulation software and is the developer and supplier of the PREACTOR scheduling software.

ii) ISIS Informatics Ltd: a software house which is a leading supplier of tool management software, namely ISIS TOOLWARE (ISIS Informatics 1995).

iii) CAMTEK Ltd: a software house and a supplier of NC part programming software PEPS (Camtek Ltd 1995), and direct numerical control (DNC) systems.

iv) Cincinnati Milacron UK Ltd: a major machine tool vendor and flexible machining cell supplier.

The primary aims of the research programme were to apply novel ideas of short term scheduling and control to flexible machining cells, strongly influenced by tool management concepts. This aim was achieved by:-

• delivering generic solutions for the short term control of part, fixture and cutting tool flow and their interactions in flexible machining facilities, and producing pre-prototype software.

• generating knowledge and techniques to allow industry to minimise the cost of tooling support for batch manufacture whilst maintaining high system performance.

There were three research work streams within the overall workplan of the research programme, namely information generation and support, hierarchical modelling of tool flow and multi-flow control of flexible machining cells. These work streams aimed to show the feasibility of generating a framework for planning and control of FMC, as illustrated in figure 5.2. These work streams are briefly described below.
5.4.1. Information Generation and Support

Flexible machining cells process a wide range of part types, some of which are new part designs. An NC part programming software product (i.e. PEPS) was utilised to provide accurate and detailed process, tooling and fixturing requirements information, through the generation of part programmes (Newman et al. 1996). The required information was extracted from the part programmes, and this included the list of machine operations, required tools and fixture types for the machining operations, the total processing times per part and the machine times of operations using particular tool types. Clearly the generation and support of this information is both vital for tool requirements planning (see section 5.3.2) and generation of schedules (see section 5.3.3).

5.4.2. Hierarchical Modelling of Tool Flow

This work stream was carried out in two stages. In the first stage a model of various tool storage areas was developed, using the hierarchical structure of a central tool store, a cell based tool store and machine tool store. In addition, the various activities, queues and recycling operations within the tool room were modelled.

![Diagram](Figure 5.2: A Framework for Planning and Control of FMC (GR/H49450 Research Proposal))
In the second stage, a series of experiments based on different data sets (e.g. part and tool varieties, storage capacities including tool magazine sizes, number of machines and manufacturing demands) were designed using these hierarchical models to investigate the effects of the various tool exchange policies (see section 4.5.1) on total tooling requirements and on the planning and control of tooling activities within the tool room. A key element in this research was the provision of a facility to advise the cell manager on the availability of tools and fixtures, with the aid of the ISIS TOOLWARE software for tool management and tracking systems. This work stream is the subject of a forthcoming complementary PhD thesis by Mr. P. Coleman (1996).

5.3.3. Multi-Flow Control of Flexible Machining Cells

This work stream is the research of the author and is reported in this thesis. This work has applied short term planning and control strategies to the application of FMC, using a novel multi-flow controller, depicted in figure 5.3. As a part of this novel controller, a ‘multi-flow scheduler’ for simultaneous generation of workpiece, fixture and cutting tool flow schedules and a multi-flow simulator as a decision support facility, has been developed. Furthermore, based on using the controller, a number of novel planning strategies were generated to minimise the manufacturing costs.

![Diagram of Multi-Flow Controller](image)

**Figure 5.3**: The Original Overview of Multi-Flow Controller
(Gr/H49450 Research Proposal)
Chapter 6

THE SCOPE OF THE RESEARCH

6.1. Introduction

This chapter outlines the principal aims and the objectives of the author's research and identifies the scope in which these aims and objectives have been achieved.

6.2. Research Aims and Objectives

In the last few years, there has been a shift away from the traditional configuration of FMS which consists of a number of different CNC milling and turning machines, with other supporting facilities, towards more modern FMC with a number of identical CNC machining centres. It is also stated that modern FMC offer extra degrees of flexibility in loading and routing decisions over the traditional FMS configurations. The overall aim of the multi-flow control research is to take advantage of these extra degrees of loading and routing flexibilities within FMC to achieve maximum economy in manufacturing cost through:

i) the harmonisation of the three principal material flows, namely the flow of workpieces, fixtures and cutting tools, to maximise cell utilisation.

ii) the reduction of the tooling and fixturing costs through a number of novel tool dominated and fixture dominated planning strategies.

In achieving these principal aims, the major objectives of the research reported in this thesis are defined as follows:

• to explore an integrated and interactive multi-flow control structure for the planning and control of FMC.
• to research a novel framework for the simultaneous generation of schedules for the workpieces, fixtures and cutting tools, by taking advantage of the latest advancement in scheduling techniques offered through simulation based scheduling systems.

• to provide an advisory system for the decision maker/planner referred to as the ‘cell manager’, using a multi-flow simulation model.

• to establish an information model as the basis for the design and implementation of a powerful data manager (i.e. a database) to support such an integrated and interactive planning and control system.

• to extend the functionality of existing schedulers for the machining cell, by considering scheduling rules concerning tools and fixtures to provide alternative solutions to common workpiece dominated planning strategies. In these new strategies emphasis in planning is on the most efficient use of cutting tools (tool dominated) and fixtures (fixture dominated).

• to demonstrate the validity of the multi-flow control concept and to test and analyse the efficiency of the tool dominated and fixture dominated planning strategies.

6.3. The Scope of the Research

The scope of multi-flow control research is in line with its aims and objectives defined above, and are listed below and described in the next seven sections of this chapter:-

i) realisation of an interactive multi-flow control structure.

ii) parallel generation of schedules for workpieces, fixtures and cutting tools.

iii) decision support for the planner/cell manager.

iv) an information model to support the multi-flow controller.

v) planning strategies for economic manufacture.

vi) design of computer-based experiments.

vii) analysis of the results of experiments
6.3.1. Realisation of an Interactive Multi-Flow Control Structure

The most common reasons for machine downtimes during the production period is identified to be the lack of availability of the right cutting tools, shortage of appropriate fixture types or bottlenecks on manual tooling and fixturing operations, as described in sections 2.3. and 2.4. One major factor contributing to these problems is seen to be the way that tool and fixture planning are carried out independently from workpiece scheduling (often using different software), in different locations (tool room and fixture store), at different times by different operators. As a result, a need has been identified to investigate an integrated control structure where the issues involved in planning and control of these three related material flows can be addressed simultaneously, under the supervision of a single decision maker. The realisation of a 'multi-flow controller' based on this novel control structure forms a major part of this research.

6.3.2. Parallel Generation of Schedules for Workpieces, Fixtures and Cutting Tools

One of the major objectives of the multi-flow control research is to identify solutions and techniques for evaluating the interactions of a number of scheduling rules related to the provision of cutting tools and fixtures together with workpiece planning strategies, and simultaneously generating schedules not only for jobs to be processed in a machining cell but also for the cutting tools and fixtures required by those jobs. Therefore, efforts are required to investigate the specification, design and implementation of a novel scheduling model which is capable of concurrently generating tool schedules and fixture schedules, in addition to the common workpiece schedules.

6.3.3. Decision Support for the Planner/Cell Manager

The multi-flow control research does not aim to automate the planning control decision making procedures but to act as an 'advisory system' to the person responsible for decision making, referred to in this thesis as the 'cell manager'. The multi-flow control structure is seen as an interactive cell control structure which supports the cell manager to make decisions and then refine these decisions as and when required. Consequently, the design
and implementation of a flexible decision support facility to aid the cell manager throughout the process of generation and execution of schedules, using simulation techniques, constitutes an important part of the research scope.

6.3.4. An Information Model to Support the Multi-Flow Controller

Identification of the initial data requirements and generation of an information model which contains all of the necessary information for the functionality of the multi-flow controller, forms a vital part of the research. The speed with which this planning information is accessed, directly influences the time taken to generate schedules. Generation of the information model and development of a database management system based on this data model is seen as an important and supporting part of the research to minimise the time taken to generate and execute schedules.

6.3.5. Planning Strategies for Economic Manufacture

This section of research work explores the enhancement of common work dominated scheduling algorithms by evaluating their interactions with a number of scheduling rules concerning the provision of cutting tools and fixtures to provide alternative tool dominated and fixture dominated planning strategies. These novel planning strategies are classified into two categories which are directly concerned with:-

i) work and tool flow : these strategies aim to minimise the cost of cutting tool requirements and assume that fixtures can be made available as and when required (i.e. no fixturing constraints).

ii) work and fixture flow : three distinct fixturing scenarios based on the use of specially designed fixtures and modular fixtures are investigated. In each scenario an appropriate planning strategy will be generated to maximise the possible cell utilisation and minimise the number of fixturing operations. These strategies assume that tools can be made available as and when required (i.e. no tooling constraints).
6.3.6. Design of Computer-Based Experiments

In order to assess the validity of multi-flow control research concepts and to highlight the efficiency of tool dominated and fixture dominated planning strategies a comprehensive series of computer-based experiments, based on the use of mathematical and simulation models must be designed and implemented. The major issue involved in the design of these experiments is the synthesis of a number of data sets to be used as input. The adopted data values in these data sets must relate closely to those in existing flexible batch machining applications and represent a wide range of manufacturing challenges required to examine the performance of the various planning strategies.

6.3.7. Analysis of the Experimental Results

There is an enormous number of possible permutations for the implementation of the experiments, based on different data sets and various planning strategies. Furthermore, it is the critical comparison of the results of various subsets of these experiments that provides a better understanding of the performance of the planning strategies, and therefore, a structured framework for the implementation of these experiments is required to efficiently highlight the new knowledge provided by the research. Furthermore, the results of the experiments can be interrogated based on a large number of manufacturing performance measures. In order to be able to effectively analyse these results, a limited set of critical measures must be adopted to highlight the performance of the multi-flow planning strategies in various flexible batch machining scenarios.
Chapter 7

AN INTEGRATED STRUCTURE FOR PLANNING AND CONTROL OF FLEXIBLE MACHINING CELLS:
'The Multi-Flow Controller'

7.1 Introduction

This chapter describes the research issues involved in the design and implementation of the multi-flow control structure for planning and control of FMC. The major part of the chapter identifies the research objectives, and portrays the view of a common planning and control environment for workpieces, fixtures and cutting tools. The final part of the chapter discusses the computational vehicle for the work, namely the multi-flow controller, and identifies the role of the cell manager in using this planning and control facility.

7.2 Research Objectives

Traditionally, manufacturing control systems have always been concerned with the flow of workpieces through production systems and the importance of the effective management of cutting tool and fixture flows has been neglected. The multi-flow control research aims to generate novel solutions and techniques to maximise the use of the latest computerised numerical control machining centres, through timely provision of cutting tools and effective management of fixturing operations. To achieve this goal, the following research objectives are defined:-

- to establish an integrated common planning and control structure for the three principal material flows.
- to use the latest graphical based decision support systems for the design and generation of an interactive planning and control structure, to aid the human decision maker in achieving the specified manufacturing goals.
to integrate the production scheduling and production activity control functions, using a hybrid approach to take advantage of benefits of both off-line and on-line planning and control techniques.

7.3 Common Planning and Control Environment for Workpiece, Fixture and Cutting Tool Flows

FMC present planning and control systems with several operating problems, because of the tightly controlled and integrated environments in which they operate. The timely provision of cutting tools and fixtures to the appropriate machines are among the most influential difficulties which play a vital role in the overall performance of such facilities. Within the existing planning and control structures, the tool and fixture planning functions are often carried out by a computerised tool management system (CTMS) and a computer aided fixture planning system (CAFP), based on a workpiece schedule generated by a computer aided production planning (CAPP) system. In addition to these planning functions, CTMS and CAFP are responsible for a wide range of other tooling and fixturing functions as shown in figure 7.1.

![Diagram of planning and control environment](image)

**Figure 7.1**: The Present FMC Planning and Control Structure Using CAPP, CTMS and CAFP
Therefore, the tooling and fixturing requirements are planned independently from the workpiece scheduler and the cell controller, often at a much later period, after the workpiece schedules are generated. This planning and control structure, based on the use of CAPP, CTMS and CAFP, has two major drawbacks:

i) additional effort and time are required (often by different human operators) to generate the plans for fixture and cutting tool flows. Consequently, any delays in the generation of tool and fixture plans result in an inadequate warning to be given to the tool room/store and fixturing stations for the cutting tool and fixture requirements, with little or no time to prepare. This lack of preparation time leads to machine downtimes and bottlenecks in tool building, tool pre-setting, tool procurement and fixturing/defixturing operations.

ii) addition of 'new jobs', or changes to the priorities of 'existing jobs' within the workpiece schedule, requires further interrupts and amendments to the tool and fixture plans which again requires more of the operator's effort and time. Additionally, if these amendments are not carried out in time, it would cause confusion and lack of synchronisation of the generated production plans.

To overcome these common problems, the latest advancements in the areas of information management and simulation based planning and control of manufacturing systems, have been utilised to design and realise an integrated planning and control system, where the issues involved in the short term planning and control of the flows of workpieces, fixtures and cutting tools can be addressed simultaneously. The 'multi-flow controller' is the research terminology used in this thesis for such a planning and control system, and is depicted in figure 7.2.

![Figure 7.2: Overview of Multi-Flow Control Structure](image-url)
7.4. Interactive Planning and Control Structure

Planning, scheduling and control of machining cells is a problem of well known complexity. In some manufacturing applications, a number of attempts have been made to automate a range of decision making tasks involved in planning and control, often with the aid of knowledge based systems (see section 3.3). However, the procedure of automating the planning and control tasks, has restricted the flexibility of such systems. In flexible machining applications with a large numbers of jobs, wide variety of part types, cutting tools and fixture types, 4-8 CNC machines and very tight due dates; the effect of some of the planning decisions are vital, but not easily realised. For these complexities and the unpredictable nature of production systems, it has been virtually impossible to develop a fully automated planning, scheduling and control system for FMC. As a result, there has been a rapid growth in development planning and control structures with decision support facilities such as the computer graphics-based scheduling support systems, known as ‘leitstand’ (see section 2.2.5).

In designing the multi-flow control structure, there has not been any attempt to automate the decision making procedure involved in planning and control of machining cells, but to act as an ‘advisory system’ to the person responsible for decision making, referred to as the ‘cell manager’, as shown in figure 7.3.
Figure 7.3 illustrates some of the many issues which a cell manager has to consider while generating schedules for a manufacturing horizon. Therefore, the implementation of the interactive characteristics of the multi-flow controller is seen as an important part of the research. To achieve this, a complete list of required decision making tasks within the multi-flow control framework has been generated. Then, appropriate decision support facilities are designed and implemented to aid the cell manager in making these decisions. This decision support process can be in the form of:-

i) providing the option to selectively access, view or skip information concerning manufacturing plans so that planning and control decisions can be made based on the most appropriate and updated information.

ii) simulating the selected planning strategies and control rules to provide manufacturing performance measures, so that the consequences of decisions made can be realised.

7.5. **Utilisation of Off-line and On-line Planning and Control Techniques**

There are two quite different techniques for the generation and execution of production plans, namely off-line and on-line, which are described in section 2.2.4. In designing the multi-flow control structure, it became apparent that there was a potential to explore the advantages offered by both of these techniques. This was due to :-

i) a major objective of the research being to minimise the manufacturing cost through reduction of cutting tools and fixturing requirements. This could only be achieved through utilisation of a number of novel planning strategies and algorithms, using off-line techniques.

ii) it was intended to design and implement the multi-flow controller to be versatile and flexible, to deal with the dynamic nature of FMC and to deal with scenarios such as random arrival times of a number of jobs, machine breakdown, material and tool shortages and tardy jobs. This required some aspects of on-line planning.
Therefore a hybrid approach has been adopted to design and implement the multi-flow controller, which utilises the advantages of both off-line and on-line planning and control techniques. This hybrid approach, combines the production scheduling and production activity control functions (see section 2.2) to enable the cell manager both to compile production schedules and to execute these plans by generating a number of work-to-lists for individual resources, as shown in figure 7.4. Furthermore, it provides the cell manager with the ability to dynamically make any short term changes to schedules such as re-routing an operation or an entire job to another resource, introducing new jobs to existing schedules, removing one or more of the resources for a certain period from the schedules through breakdowns and delaying the start of jobs because of shortage of materials, fixtures or cutting tools. As a result, the multi-flow controller generates two distinct types of manufacturing plans based on different planning horizons. These are:-

i) medium term plans : which are based on a longer planning horizon, namely a month, two weeks or a week. The length of this planning horizon is influenced by a number of factors such as the average manufacturing lead times of products, size of the manufacturing system, the business requirements and the length of time for which a reasonably accurate rough cut plan can be generated by the master production scheduling process. The objectives are to keep this planning period as
long as possible so that the rationalisation of tool and fixture usage can be achieved among a larger number of jobs, resulting in a greater reduction of manufacturing costs.

ii) *short term plans*: which are based on a shorter planning horizon, i.e. a day or a shift. The length of this planning horizon depends on a range of issues such as the reliability of the manufacturing system in terms of machine and transporter breakdowns, the frequency with which additional workloads in terms of new jobs are required to be added to existing schedules and other dynamic factors influencing the manufacturing system. The objective is to keep this planning horizon as long as possible without the need to frequently make changes in short term schedules.

7.6. The Multi-Flow Controller: A Computational Viewpoint

In order to realise the research objectives discussed in previous sections of this chapter, a novel set of software modules, termed the multi-flow controller has been designed and implemented. The multi-flow controller consists of three software modules, namely a multi-flow scheduler, a multi-flow simulation model and a manufacturing database. These modules are totally integrated with the aid of a specially designed user interface around the manufacturing database, as shown in figure 7.5, and are described below.

7.6.1 Multi-Flow Scheduler

This is an enhanced scheduling model which is capable of simultaneous generation of short term schedules for the flows of workpieces, fixtures and cutting tools within FMC. The primary input to the multi-flow scheduler is a rough cut plan generated by the master production scheduling process (via MRP or equivalent) in the form of an unsequenced list of jobs for a specified manufacturing horizon and the machining cell status at the start of this horizon. The primary outputs from the multi-flow scheduler are three synchronised schedules for the control of the three principal flows. The multi-flow scheduler is described in detail in chapter 8.
Figure 7.5: An Integrated System Structure for Planning and Control of Flexible Machining Cells
7.6.2. Multi-Flow Simulator

The multi-flow simulator models the flow of workpieces, fixtures and cutting tools within the flexible machining cell and acts as a decision support facility which provides a window through which consequences of the decisions made during the planning and scheduling stages can be realised. The multi-flow simulator provides the cell manager with the manufacturing performance measures, based on a set of selected planning, fixturing and tooling strategies, and allows him to approve certain schedules with some confidence to be downloaded for execution. These processes of simulation, analysis and selection of planning strategies are described in chapter 9.

7.6.3. Manufacturing Database

Through utilisation of the latest advancement in data modelling and information exchange (Rahimifard and Newman 1996), a novel manufacturing database has been designed and implemented, to support the information requirements the planning and control of these three principal flows. The structure of this database, together with its data elements stored is outlined in chapter 10.

7.7. The Role of the Cell Manager

The multi-flow controller assumes that a rough cut plan in the form of a job list is offered to the scheduler (via MRP or equivalent). This job list is initially handled by the cell manager prior to the start of the manufacturing horizon. The cell manager then, recommends strategies for the provision of parts, fixtures and cutting tools. The strategies are offered to a multi-flow scheduler which in turn generates the individual schedules for the three principal flows. The proposed schedules are then downloaded to the multi-flow simulation model which provides output to the cell manager. This gives the cell manager insight into the potential performance of the cell and allows him to make value judgements on whether the schedules should be downloaded for implementation, as illustrated in figure 7.6. Based on these medium term schedules, a number of work-to-lists for various resources are generated.
Figure 7.6: Basic Functional Structure Using the Multi-Flow Controller Including the Role of the Cell Manager
Furthermore, the cell manager at the start of specific short term time intervals (e.g. a day or a shift) reviews a range of issues such as the progress of the schedules during the previous interval, requirements for the introduction of new jobs and any other possible manufacturing disturbances (e.g. breakdowns and shortage of materials, fixtures and tools). Any required modification to the short term schedules is then carried out at this stage, by the cell manager. Additionally, appropriate user interface structures have been designed and implemented to allow the cell manager the possibility for further interactions with the multi-flow scheduler during the short term time interval, to intervene with the progress of short term schedules as and when required. In summary the role of the cell manager within the multi-flow control framework is defined as follows:

- **selection of scheduling rules and strategies**: for the flows of workpieces, cutting tools and fixtures. This is achieved by considering the rough cut plan (joblist) for the next manufacturing horizon, together with the short term production goals and requirements such as due dates, job sequences, tool provision and fixture availability. These scheduling strategies are then offered to the multi-flow scheduler to generate the individual schedules and work-to-lists.

- **approval of the generated schedules**: the multi-flow simulation model is used by the cell manager to analyse the schedules and to gain insight into the potential performance of the cell, based on the generated schedules and to allow the cell manager to make valued judgements on whether the schedules should be down loaded for implementation.

- **introduction of additional jobs to an existing schedule**: the multi-flow scheduling system provides the cell manager with an appropriate user interface for adding unplanned jobs into a sequenced joblist to achieve the short term production requirements.

- **intervention with the short term schedules**: in a form of minor changes to the jobs sequences, based on detailed scheduling requirements such as minimisation of setup times or number of tool exchanges.

- **dealing with manufacturing disturbances**: identification of the actions, to be taken in the case of manufacturing disturbances and scheduling interrupts such as machine breakdown or shortage of raw materials and tools.
Chapter 8

PARALLEL GENERATION OF SCHEDULES FOR WORKPIECES, FIXTURES AND CUTTING TOOLS:
'The Multi-Flow Scheduler'

8.1. Introduction

This chapter describes the issues involved in the design and implementation of the multi-flow scheduling system which constitutes one of the major modules of the multi-flow controller. The initial part of the chapter outlines the research objectives and a novel approach for the parallel generation of schedules for workpiece, fixture and cutting tool flows, using simulation techniques. As part of the operational structure of the multi-flow scheduler, a number of novel planning strategies, termed tool dominated and fixture dominated, are also described. The final part of the chapter provides a computational viewpoint of the multi-flow scheduling system and highlights the range of the schedules that can be generated.

8.2. Research Objectives

A large number of researchers have addressed the research issues related to production scheduling of flexible manufacturing systems as previously identified in section 2.2.6 and 2.3.7. However, almost all of the suggested solutions, frameworks and techniques have been concerned with the generation of a single schedule to control the flow of workpieces within the machining facilities.

The multi-flow control research explores the feasibility and the potential benefits of designing and implementing a novel scheduling system which in addition to the common workpiece schedules, generates tool schedules and fixture schedules for a manufacturing horizon. Additionally, this novel scheduler aims to extend the functionality of existing manufacturing schedulers, by considering scheduling rules concerning cutting tools and
fixture flows to provide alternative solutions to common workpiece dominated planning strategies. In these new approaches emphasis in planning is on the most efficient use of cutting tools (tool dominated) and fixtures (fixture dominated). To achieve these goals, the following research objectives are defined as:

- to utilise a simulation based technique to generate a detailed scheduling model which includes activities relating to cutting tool and fixture flows.
- to explore methods for parallel generation of workpiece, fixture and cutting tool schedules.
- to investigate a framework where schedules can be generated not only based on common workpiece dominated planning strategies, but also based on a number of novel tool dominated and fixture dominated planning strategies.

8.3. A Simulation Based Multi-Flow Scheduling Model

The multi-flow control research aims to harmonise the flow of workpieces, fixtures and cutting tools by evaluating the interactions of a number of scheduling rules related to the provision of cutting tools and fixtures together with workpiece planning strategies. Therefore, as one of the major software modules of the multi-flow controller, an enhanced scheduling system, termed the 'multi-flow scheduler' has been designed and implemented, in order to investigate the interactions of these scheduling rules. The novel functional characteristics required from such a scheduler in comparison to existing machining cell scheduling systems are:

- to model the machining activities in greater detail to include the tooling and fixturing activities.
- to process a greater amount of data relating to cutting tools and fixture requirements.
- to allow the cell manager to select various combinations of planning strategies for the generation of schedules, from one planning horizon to the next.
- to include a scheduling process which is relatively fast in terms of data collection and computing time, in order to evaluate the application of short term scheduling within FMC.
The three most commonly adopted approaches as described in section 3.3, namely operation research (OR), artificial intelligence (AI) and simulation based approaches were considered for the construction of the model of the multi-flow scheduler. The OR techniques, mathematical or enumeration, all suffer from one fundamental problem; the difficulty of expressing the business requirements and scheduling constraints in the form of a simple mathematical function. As a result, all of the OR related methods, in order to be able to systematically formulate a particular manufacturing application, have to make a large number of assumptions to simplify the variables and the constraints involved. This inability to deal with constraints related to a range of complex tooling and fixturing activities within FMC, makes OR methods and techniques unsuitable for this research.

The option of using AI methods, with reasoning similar to human planners and capable of processing a large amount of planning knowledge and scheduling rules quickly and efficiently, appeared attractive in the first instance. However, further reviews of the published work in this field indicated the following two most commonly reported shortcomings for the AI techniques:

i) the inability to model the dynamic and stochastic nature of the manufacturing systems.

ii) the extensively long computing time required for large knowledge based systems to process an extensive amount of manufacturing data.

Needless to say, both of these shortcomings are of paramount importance to the functionality of the multi-flow controller. On the other hand, simulation techniques are particular useful in the design and implementation of detailed and complex manufacturing models. In addition, with the aid of the latest PC-based simulation software packages, it was feasible to develop models based on different planning strategies, easily and quickly. Finally, the greatest advantage of simulation models is their sophisticated techniques and ability to deal with randomness and the dynamic nature of FMC. Therefore, the simulation based approach was identified to be the most flexible, powerful and suitable method to be utilised.

As a result, a simulation based multi-flow scheduler has been designed and implemented which is capable of generating schedules not only for the processing of jobs in a machining cell but also for the cutting tools and fixtures required by those jobs, as shown in figure 8.1.
Figure 8.1: An Overview of Multi-Flow Scheduling System

8.4. Parallel Generation of Schedules for Workpiece, Fixture and Cutting Tool Flows

At present, within existing planning and control procedures for FMC, the planning of tooling and fixturing activities are carried out independently from the workpiece scheduler via different software modules, namely a computerised tool management system (CTMS) and a computer aided fixture planning system (CAFP). Furthermore, the tool and fixture planning activities are often performed at a much later period, after workpiece schedules are generated. Although these three planning activities are very closely related, it is surprising to find that traditionally they have been carried out by different planners, in different locations, using different software modules, at different times. This is primarily due to:

i) data relating the tooling and fixturing requirements of jobs being held in a range of computer files within different software packages, because in addition to planning activities, such data is required by other tooling and fixturing activities, such as tool and fixture assembly, tool presetting and inventory control.
ii) traditional scheduling techniques and the available computing power could not deal with complexity of combining these planning activities and be able to generate schedules within reasonable time limits.

However, the recent advancements in computer hardware, information technology and simulation based scheduling techniques have made it feasible to consider a procedure whereby these three related scheduling activities can be carried out simultaneously. In this procedure, referred to as the parallel generation of schedules, jobs are incrementally allocated to the machines within a certain time span to form a workpiece schedule, and concurrently their tooling and fixturing requirements are recorded in different computer files as a tool schedule and fixture schedule. There are a number of potential benefits for the use of such a procedure for the parallel generation of schedules, namely:

- the operators/planners time can be saved as these planning activities are carried out simultaneously.
- as soon as the workpiece schedule is generated, the tool and fixture plans can be issued to the tool room/store and fixturing stations, allowing a longer period to prepare for the tooling and fixturing requirements.
- The addition of 'new jobs' or changes in 'job priorities' can be more easily accommodated, as the three schedules are updated simultaneously.
- Cohesion introduced by producing tool and fixture schedules in addition to a workpiece schedule improves the production control process and information on the progress of schedules retrieved by shop floor data collection can be utilised effectively to achieve a more efficient monitoring and control procedure.

8.5. The Multi-Flow Planning Strategies

The multi-flow controller provides the flexibility of being able to adopt a number of novel tool dominated and fixture dominated planning strategies in addition to the common workpiece dominated strategies, as illustrated in figure 8.2. This flexibility is particularly advantageous in applications where the job throughput requirements for a manufacturing horizon changes significantly on a regular basis.
Typical examples of such applications are small manufacturing companies that are used as subcontractors by larger businesses. With such manufacturing companies production objectives will vary frequently from meeting the delivery dates (regardless of manufacturing cost) to the most economical methods of production, depending on the subcontracting customer. In addition, such manufacturing systems are expected to produce a wide range of part types over a short period. As a result, the requirement for a large number of cutting tools and fixtures and the related tooling and fixturing activities in this short period, often results in operational bottlenecks in the tool room/store and the fixturing stations. Therefore, any reduction in tool and fixturing requirements not only has a direct effect on the manufacturing cost, but also could result in reductions in machine down time due to delays for tools and fixture availability. These multi-flow planning strategies are divided in three categories, namely workpiece dominated, tool dominated and fixture dominated strategies. These planning strategies are briefly described below, and are discussed in more detail in chapter 11.
8.5.1. Workpiece Dominated Planning Strategies

This is primarily concerned with the generation of schedules for the most effective flow of workpieces through the machining cell. Selection of this mode of operation can be due to specific requirements such as tight due dates for jobs with expensive consequences for job tardiness, transportation bottlenecks or operations set up times at machines. The workpiece dominated planning strategies are based on finite capacity scheduling and utilise a multi machine job allocation policy to achieve a number of manufacturing goals for the most effective flow of workpieces such as the minimum work in progress and mean flow times of jobs. A subset of the sequencing rules published by Gupta et al. (1989), representing the most commonly used rules, are also implemented. These sequencing rules include first in first out, earliest due dates, jobs' priorities, processing time of jobs and number of operations per job. Furthermore, these rules can be applied based on a forward sequencing(push type system) or backward sequencing(pull type system) policy.

8.5.2. Tool Dominated Planning Strategies

In tool dominated planning strategies the emphasis is placed on the most efficient use of cutting tools so that the manufacturing cost relating to these elements can be minimised. These strategies represent a number of planning algorithms and procedures which minimise the number of cutting tools, and consequently tooling activities, required to process a specific number of jobs within flexible batch machining applications. This is achieved by utilisation of the following job allocation policies:

i) **cluster based job allocation**: a clustering algorithm is applied to the part and tool matrix to form a cluster of jobs that have similar tool requirements (de Souza and Bell 1991). The jobs within these individual job clusters are sorted based on a sequencing rule such as earliest due dates before being allocated to a specific machine or a group of machines in the machining cell.

ii) **single machine job allocation**: a job may consists of several transfer batches(a number of parts mounted on a fixture). The size of these transfer batches depends on the part types, fixture configuration and transporter capacity(see section 4.6). A job allocation policy, termed 'single machine loading', is used to avoid the allocation of a job's transfer batches to different machines as is the case with the multi machine loading policy used with workpiece dominated planning strategies,
as shown in figure 8.2. The argument being that by processing all these transfer batches on a single machine, duplicated/identical tools are not required on different machines at the same time, resulting in a reduction of the number of required cutting tools and related tooling activities for a job.

iii) combined machine job allocation: this job allocation policy is adopted in the cases where single machine loading fails to meet the completion dates of jobs. In such a case, a limited subset of jobs is selected to be allocated across two or more machines, providing an alternative to the single machine or the multi machine loading policies.

8.5.3. Fixture Dominated Planning Strategies

These planning strategies are capable of minimising delays caused by a shortage of fixtures in scenarios where a limited number of fixtures of a particular type is available (e.g. in the case of specially designed fixtures), and minimising the number of fixture assembly and disassembly operations in scenarios with the modular fixtures. The fixture dominated planning strategies are divided into two categories of finite fixture capacity planning based on the use of specially designed fixtures and infinite fixture capacity planning based on the use of modular fixtures, as described in Rahimifard and Newman (1996b), which is included in appendix 3.

The single and combined machine loading job allocation policies adopted with tool dominated strategies, also result in a reduction of the number of fixtures of a particular type required at any time during the manufacturing horizon, because transfer batches of a job requiring similar fixtures are not simultaneously sent to different machines (see section 13.6 and figure 13.4). Additionally, the following two job allocation policies are also adopted in fixture dominated planning strategies:

i) cluster based job allocation: a clustering algorithm is applied to the part and fixture matrix to form a series of job clusters with similar fixture configuration requirements. The jobs within these job clusters are sorted based on sequencing rules such as earliest due dates before being allocated to a specific machine or a group of machines in the cell.

ii) fixture availability based job allocation: is used where the allocation of jobs to resources is restricted by the quantity of fixtures of a particular type. In such cases the order in which jobs are sent to the machines is constrained by the availability of
appropriate fixtures. In this job allocation policy, jobs are assigned to resources based on their fixture requirements and this ensures that the total fixture requirement during the manufacturing period does not exceed the quantity of fixtures available for each fixture type.

8.6. The Multi-Flow Scheduler: A Computational Viewpoint

A commercial simulation based planning and scheduling software system, named PREACTOR (The CIMulation Centre 1994) has been utilised as the basis for generating the multi-flow scheduling model. A brief overview of the functional structure of the PREACTOR scheduling software is outlined in appendix 1. The primary inputs to the multi-flow scheduler are an unsequenced list of jobs for a specified manufacturing horizon and the machining cell status at the start of this horizon. The primary outputs from the multi-flow scheduler are three synchronised schedules for the control of the principal material flows. Three modes of operation are implemented based on workpiece, fixture and tool dominated approaches, as illustrated in figure 8.3.

![Picture of the computational viewpoint of the multi-flow scheduler](image)

**Figure 8.3**: The Computational Viewpoint of The Multi-Flow Scheduler
One of these operational modes for generation of the triple flow schedules is selected by the user (i.e., the cell manager), based on the specific requirements of the manufacturing horizon. Alternatively where appropriate, schedules based on all three modes can be generated and analysed to select the one which produces the best manufacturing performance, using the multi-flow simulation model which is described in chapter 9. These modes of operation are described in more detail below.

8.6.1. Workpiece Dominated Mode

In this mode of operation, the sequencing of jobs and generation of schedules is achieved via a production sequencer module, as illustrated in figure 8.4. Within the user interface of the production sequencer, every manufacturing resource (e.g., machining centre) is represented via a window which is divided into time buckets (e.g., hours, days). Shaded time buckets indicate the times that the resource is not available (e.g., out of shift, broken down) and blank time buckets represent the period when the resource is available to carry out its processing function. The job list is represented by a window, labelled 'unallocated jobs' and jobs are depicted via icons appearing in this window. Finally, a sequence overview of jobs in progress is shown in a separate window in the form of a Gantt Chart. Scheduling rules can be selected via a pull down menu and applied to the jobs in an unallocated job queue, as shown in figure 8.4.

Figure 8.4: Production Sequencer of the Multi-Flow Scheduling System
8.6.2. Tool Dominated Mode

With the tool dominated operation mode, the emphasis is put on the minimisation of cutting tool requirements. This is achieved by utilisation of the two planning strategies discussed in section 8.5.2, as follows:

i) **clustering based job allocation**: The rank order clustering algorithm implemented in a LOTUS 123 spreadsheet model (Ozbayrak 1993) has been linked to the multi-flow scheduler (see figure 8.3). Lists of jobs together with their tool requirements are passed to this spreadsheet model which identifies and returns a number of job clusters to the scheduler. The jobs within these individual job clusters are sequenced based on their due dates before being allocated to a specific machine or a group of machines in the machining cell.

ii) **single and combined machine loading job allocation**: The PREACTOR software facilities are utilised to implement the 'single machine loading' and 'combined machine loading' job allocation policies (see figure 8.3) which are alternatives to a more common workpiece dominated planning strategy within batch machining applications, namely the 'multi machine loading' (see section 11.3.1).

8.6.3. Fixture Dominated Mode

This mode of operation is adopted to minimise the delays caused by fixture availability and the number of fixturing activities. The two categories of fixture dominated planning strategies based on the finite and infinite fixture capacity planning, are implemented using the following job allocation policies:

i) **cluster based job allocation**: lists of jobs together with their fixturing requirements are passed to a LOTUS 123 spreadsheet model which identifies a number job clusters with similar fixturing requirements, and returns them to the scheduler. The jobs within these job clusters are sequenced based on their due dates before being allocated to a specific machine or a group of machines in the machining cell.

ii) **fixture constrained job allocation**: a simulation model, generated using the ARENA simulation software (Systems Modeling 1994), assigns jobs to resources based on their fixture requirements and ensures that the total fixture requirement
during the manufacturing period does not exceed the quantity of fixtures available for each fixture type.

8.6.4. Summary of Outputs of the Multi-Flow Scheduler

The schedules generated by the multi-flow scheduler can be both in the format of Gantt charts or work-to-lists. Gantt charts are more popular where schedules are to be used by an operator, as they are easier to follow. However, in fully automated systems the scheduler is often linked to a cell controller which usually requires the schedules in the form of a series of work-to-lists for resources stored in an ASCII file. Currently, six interrelated forms of Gantt charts (or work-to-lists) are produced by the multi-flow scheduler as the schedules for workpieces, fixtures and cutting tools. These Gantt charts are derived from a unique manufacturing plan for a specific production period and provide the scheduling information in a particular format (view point) which can be useful (for an operator) to carry out a specific task in the overall machining cell process. These Gantt charts and their suggested usage are described below:

i) part types versus machines (workpiece flow) : this type of Gantt chart is the most commonly generated chart by existing scheduling systems and used at the load/unload station for dispatching the workpieces to machines.

ii) machines versus jobs (workpiece flow) : used in applications where workpieces have to visit a number of machines in sequence, before being completed and returned to the unload station, to identify the next destination for a workpiece.

iii) part types versus toolkits (tool flow) : a tool schedule that identifies exact times of when toolkits are required, as shown in figure 8.5a. This can be used in the tool store to prepare toolkits in advance of their requirements. Additional information about a particular toolkit within the schedule can be obtained by clicking on a section of the Gantt chart. This activates a query procedure to extract all the related information from the manufacturing database (which is described in chapter 10), as illustrated in figure 8.5b. Consequently, this type of schedule can be used as a basis to plan for the tooling activities within the tool store/room (e.g. tool assembly, refurbishment and regrinding).

iv) toolkits versus machines (tool flow) : this type of schedule is used to organise the flow of tools between the machines and the cell tool store within machining cells.
v) *part types versus fixtures (fixture flow)*: used at the fixturing /defixturing area as a set of instructions to mount the workpieces on the appropriate fixtures. It identifies the exact times of requirements for a fixture of a particular type and allows for the preparation of the fixturing activity prior to the starting times of jobs.

vi) *fixture versus machines (fixture flow)*: this fixture schedule, shown in figure 8.6a, is used to organise the flow of fixtures between machines and the load / unload station. As mentioned previously, additional information about a job can be extracted from the manufacturing database, as illustrated in figure 8.6b.
Figure 8.5: Part Types Versus Toolkits Gantt Chart (Tool Flow Schedule)
Figure 8.6: Fixture Types Versus Machine Gantt Chart (Fixture Flow Schedule)
Chapter 9

DECISION SUPPORT FOR THE CELL MANAGER: 'The Multi-Flow Simulator'

9.1. Introduction

This chapter describes the utilisation of a simulation model as a decision support tool to aid the production scheduling and control procedures of FMC. The first part of the chapter briefly outlines the research objectives for a novel concept of simulating the flows of workpieces, fixtures and cutting tools within FMC. The chapter also includes discussions on the major issues involved in the design and implementation of such a 'multi-flow simulation model'. The final part of the chapter describes the software module, generated based on these research concepts, namely the 'multi-flow simulator'.

9.2. Research Objectives

FMC present several operating problems that were not encountered in conventional manufacturing systems because of the tightly controlled environment in which they operate. In FMC applications with a large numbers of jobs, a wide variety of part types, cutting tools and fixture types, 4-8 CNC machines and very tight due dates; the effect of some of the planning decisions are vital, but not easily realised. This highlights the important role of planning decision makers and the effects of their decisions. The inclusion of tool and fixture scheduling policies within the control structure adds an extra dimension of complexity to the decision making. Therefore, a need has been identified to investigate the addition of an effective decision support facility as one of major modules of the multi-flow controller. To achieve this, the following research objectives are defined:-

- to explore a flexible method of modelling planning and control strategies.
• to establish a method of generating a specific set of manufacturing performance measures, based on which a planning and control strategy can be adopted for a manufacturing horizon.
• to examine the effects of additional constraints and manufacturing disturbances on a set of generated schedules.

9.3. Simulation Models as Decision Support Tools

A large number of conflicting constraints and manufacturing goals in FMC applications, such as meeting due dates, minimising inventory and operation costs, maximising the utilisation of resources and achieving a balanced work load across the resources make the planning task a very complex decision problem. In addition, there is an ever increasing number of production strategies which aim to minimise the throughput time and production costs, to maximise the use of resources, and to achieve higher efficiency and productivity. Therefore, the decision maker in charge of operational planning of FMC should have the facilities available to test and analyse alternative plans based on various strategies and decision scenarios.

The successful use of simulation as a design tool has encouraged researchers to investigate the possible ways and methods of using these models in planning, scheduling and control. The role of simulation models as solutions to the operational planning and control problems of FMC is discussed in Rahimifard and Newman(1995), which is included in appendix 2. The most common use of simulation techniques in production planning and control can be classified into the following categories:-

i) generation of simulation based scheduling systems.
ii) development of real time(on-line) planning and control systems.
iii) decision support facilities to evaluate planning strategies and control policies.

Simulation models, by introducing variability with the use of statistical distributions and random numbers, have the capability to predict bottlenecks, queuing problems, over utilisation of resources, etc. These models enable users to realise the effects of a set of decisions on the system under evaluation. Furthermore, they allow the assessment of the performance under a set of different operational strategies and the selection of the most appropriate ones for a particular application.
These capabilities are seen by the author as the essential requirements for the decision support facilities to be included in the multi-flow controller. As a result, a simulation model has been designed and implemented, to model the part, fixture and cutting tool flows around a machining cell, extending the concept of the research work carried out by Alberti et al. (1991) and Grieco et al. (1995) on the part and tool flow simulation. The logical structure of this multi-flow simulation model is described in section 9.6.

There is a wide range of workpiece, fixture and tool dominated planning strategies, supported by the multi-flow controller for the generation of schedules. These planning strategies are implemented within the multi-flow scheduler to achieve optimal solutions for a number of different manufacturing scenarios. These scenarios differ in terms of manufacturing goals and constraints associated with each one. The manufacturing goals and constraints are defined in terms of conditions such as business requirements (e.g. meeting completion dates or minimising operational costs), batch sizes, slack time per job, tool and fixture commonality between jobs, etc (see chapter 13).

In the multi-flow control framework, the cell manager is responsible for the selection of the most suitable planning strategy to be used for the generation of schedules for a manufacturing horizon, based on a specific set of manufacturing goals and constraints. The multi-flow simulator is designed and implemented to aid the cell manager in this selection process. This decision support is described in the following two sections and is achieved by:

i) the generation of a set of manufacturing performance measures as an indicator of the potential machining cell performance, based on a set of generated schedules.

ii) the measuring of the effects of inclusion of further constraints (e.g. transporters and buffer sizes) and a degree of randomness in terms of manufacturing disturbances (e.g. breakdowns), on a set of generated schedules.

9.4. Generation of Manufacturing Performance Measures

The multi-flow scheduler is capable of providing a limited set of manufacturing performance measures for each generated schedule, such as the number of tardy jobs and average machine utilisation. However, this limited set of manufacturing performance measures is not seen as sufficient information to be used by the cell manager for the
selection of the appropriate planning strategies. The following additional performance measures are identified to be essential to this decision making task:-

- performance measures for transportation devices.
- buffering/storage requirements such as temporary workpiece buffers and cell tool store.
- time dependent performance measures such as resource utilisation within a certain time interval (e.g. a day or a shift).
- frequency performance measures such as number of times a machine has been idle waiting for a transporter, tools or jobs.

The multi-flow simulator is designed to execute schedules generated by the multi-flow scheduler in a deterministic mode, to generate such manufacturing performance measures and act as a window through which the consequences of the decisions made during the planning and scheduling stages can be clearly realised. These manufacturing performance measures also enable the cell manager to obtain a certain degree of confidence in the generated schedules, before being downloaded for execution.

9.5. The Effects of Secondary Constraints and Manufacturing Disturbances on Generated Schedules

The multi-flow simulator is used to measure the effect of a range of the constraints such as transportation or temporary buffer storage capacities which are not considered in the first stage of planning, using the multi-flow controller. These secondary constraints are not seen as influential as the tooling and fixturing constraints within FMC applications. Nevertheless, they are considered important operational performance indicators and are included in the design of the logical structures of the multi-flow simulator, so that the effects of these secondary constraints on the progress of generated schedules can be realised.

The control function within FMC is the implementation of a specific production schedule, continuously monitoring the state of the system and the progress of the schedule. This function has to be able to take steps to overcome problems introduced by changes in the system status (e.g. machine breakdowns) or interrupts to the schedule (e.g. shortage of raw material and tools). The identification of the most suitable recovery procedures for
operational changes and interrupts requires a significant number of experiments with various sets of constraints and alternative decision scenarios. The multi-flow control planning procedures discussed previously are all based on a deterministic structure and do not take into account the effects of such manufacturing disturbances. However, the multi-flow simulator allows the cell manager to examine these effects by introducing a specific set of such manufacturing disturbances on the generated schedules. The introduction of manufacturing disturbances can be based on historical data, for example system reliability information. Alternatively, it can be based on an actual interrupt/disturbance, as it is happening during the manufacturing horizon, for which a recovery procedure should be identified.


The commercial simulation software ARENA (Systems Modeling 1994), has been utilised to construct this simulation model. ARENA is a simulation software tool which is based on the SIMAN simulation language(Pegden et al. 1990). Simulation models are constructed in ARENA using a set of Application Solution Templates(AST) which are a number of commonly used simulation routines that are used to model an application. A graphical animation of the simulation model can be generated, based on the structure and logic of the application specified by the model, as illustrated in figure 9.1. Furthermore, statistical graphs, charts and tables can be included in the working space of an ARENA simulation model. One of the main advantages of ARENA is that the simulation models can be developed in a fraction of the time required to generate a model, using a simulation language such as SIMAN. The functionality of the ARENA simulation software is briefly described in appendix 1.

The manufacturing resources included in the multi-flow simulation model are shown in figure 9.1 and are as follows:-

- **part storage area**: divided into an arrival section for raw material and a section for finished parts which are returned from the machining cell having been machined.
- **fixture / defixture area**: this is an area where fixtures are stored and workpieces are mounted or removed from the fixtures.
Figure 9.1: Manufacturing Resources Modelled By the Multi-Flow Simulator

- **load / unload station**: used to load or unload workpieces onto/from part transporter.
- **part transporter**: workpiece handling device used to transport workpiece to/from machining centres.
- **machining centres**: these are divided into part buffer, machining area and tool magazine so that the three activities of part load/unloading, machining operations and tool exchange can be modelled.
- **tool transporter**: used to transfer cutting tools to/from the machines.
- **cell tool store**: a tool store dedicated to the cell which receives fresh tools and returns the used tools to/from the central tool store.

9.6.1. Outputs from the Multi-Flow Simulator

The multi-flow simulation model has been integrated with a manufacturing database described in chapter 10, and the multi-flow scheduler. The initial input data is extracted from the database, and schedules in the form of a number of work-to-lists for individual resources within ASCII files, are entered from the multi-flow scheduler. The integration
of these software modules of the multi-flow controller are described in Rahimifard and Newman (1994). The multi-flow simulator is designed to interact with the 'cell manager' and to present the results (tables, graphs and charts) in the form most suitable for him/her to select/approve schedules to be used for the next manufacturing horizon. As stated previously, one of the major functions of the multi-flow simulation model is to produce manufacturing performance measures (see section 9.4). Typical examples of such measures for a 4 machine cell, are summarised in tables 9.1, 9.2 and 9.3. These tables indicate the resource utilisation, queue sizes and a breakdown of idle times of resources, for the schedule of \((P_x, T_y, F_z)\). In addition, an animation of the machining cell, illustrated in figure 9.1 for an 8 machine cell, is used as a visual aid that can very rapidly identify problems such as large queue sizes, low utilisation of resources and bottlenecks.

The multi-flow simulator is a discrete event model, and therefore it can be interrupted at any point during its execution to obtain a sample of manufacturing performance measures for a specific period of the overall manufacturing horizon (e.g. a shift). Alternatively, systematical interrupts based on a statistical distribution or according to a fixed plan can be introduced within the model to measure the effect of some the manufacturing disturbances. Finally, charts and histograms of various statistical results such as production rate per shift, number of jobs finished on time and the number of tardy jobs per shift can be also generated.

<table>
<thead>
<tr>
<th><strong>Resource</strong></th>
<th><strong>Average Utilisation</strong></th>
<th><strong>Variation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Machining Centre 1</td>
<td>88 %</td>
<td>10 %</td>
</tr>
<tr>
<td>Machining Centre 2</td>
<td>83 %</td>
<td>12 %</td>
</tr>
<tr>
<td>Machining Centre 3</td>
<td>78 %</td>
<td>5 %</td>
</tr>
<tr>
<td>Machining Centre 4</td>
<td>84 %</td>
<td>9 %</td>
</tr>
<tr>
<td>Part Transporter</td>
<td>54 %</td>
<td>6 %</td>
</tr>
<tr>
<td>Tool Transporter</td>
<td>67 %</td>
<td>12 %</td>
</tr>
<tr>
<td>Load / Unload Station</td>
<td>34 %</td>
<td>7 %</td>
</tr>
<tr>
<td>Fixturing / Defixturing Station</td>
<td>64 %</td>
<td>17 %</td>
</tr>
</tbody>
</table>

**Table 9.1**: Average Resource Utilisation for the Schedule \((P_x, T_y, F_z)\)
### Queue Names

<table>
<thead>
<tr>
<th>Queue Names</th>
<th>Average Queue Sizes</th>
<th>Max</th>
<th>Min</th>
<th>Final Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jobs in</td>
<td>12</td>
<td>18</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>Jobs out</td>
<td>8</td>
<td>12</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Temporary Buffer</td>
<td>5</td>
<td>8</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Cell Tool Store</td>
<td>11</td>
<td>18</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>Waiting for Fixture</td>
<td>4</td>
<td>7</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Waiting for Transporter</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 9.2: Queue Sizes After 3/4 of Shift \( n \), Based of the Schedule \((P_x, T_y, F_z)\)

### Resources

<table>
<thead>
<tr>
<th>Resources</th>
<th>Working (Min)</th>
<th>Idle (Mins)</th>
<th>Waiting for Jobs (Mins)</th>
<th>Waiting for Tools (Mins)</th>
<th>Waiting for Transporter (Mins)</th>
<th>Broken Down (Mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machining Centre 1</td>
<td>420</td>
<td>60</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Machining Centre 2</td>
<td>395</td>
<td>85</td>
<td>20</td>
<td>20</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>Machining Centre 3</td>
<td>375</td>
<td>105</td>
<td>10</td>
<td>30</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Machining Centre 4</td>
<td>405</td>
<td>75</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 9.3: Breakdown of Idle Times of Machines for the Schedule \((P_x, T_y, F_z)\)
Chapter 10

AN INFORMATION MODEL TO SUPPORT THE MULTI-FLOW CONTROLLER: ‘The Manufacturing Database’

10.1. Introduction

This chapter describes the specification of an information model based on the data requirements of the multi-flow controller. The research objectives are stated, together with a description of a manufacturing database, generated using the data structures defined in the information model.

10.2. Research Objectives

While designing an integrated system such as the multi-flow controller, one of the supporting but critical issues to be addressed, is the need for an efficient information management system. In recent years, the utilisation of database management systems (DBMS) has made a valuable contribution in areas of information management, and interfacing / integrating modules of software systems. However to maximise the benefits of such information systems, they have to be carefully designed and implemented. As a result, information/data models are constructed to understand the exact requirements, specification and the functionality of information systems.

The multi-flow controller, in addition to common workpiece planning and control information, requires significantly more data on fixturing and tooling requirements. Traditionally, such fixturing and tooling information is kept in various files within different software systems (e.g. computerised tool management systems and computer-aided fixturing planning). The speed with which such information can be accessed has a direct influence on the time required to generate the schedules. The
multi-flow control research aims to explore the applications of short term scheduling and control, and consequently, the schedule generation time must be very short. Therefore, a need was identified to design and implement a central data manager, specifically for the functionality of the multi-flow controller. To achieve this the following research objectives are defined:-

- to specify the data requirements and data structures needed for the functionality of the multi-flow controller.
- to construct an information model based on these data requirements and data structures.
- to generate a database management structure, using the data definition within the information model.

10.3. Data Requirements for the Multi-Flow Controller

The generation of the data requirements often starts with the production of a list of inputs and outputs (I/O) to and from the system. This list of I/O to/from the system might not provide an accurate explanation of the system behaviour, but it clarifies many aspects about system functionality. In figure 10.1 and 10.2, a simple and yet effective method is used to summarise I/O to/from the software modules of the multi-flow controller. These I/O diagrams are also useful when designing the cell manager interface as described in section 7.7. Typical data required by a scheduling system is as follows:-

- order information (number of jobs, batch quantities, job priorities, starting dates, due dates).
- part processing data (operations list, operation times, machines required, process routes).
- machine cell configurations (number of machines in the cell, machine types, machine set-up times).
- shift pattern data (number of shifts per day, shifts start and finishing times, shift pattern for week-ends).
Figure 10.1: Summary of Input/Output Data for the Multi-Flow Scheduler

Figure 10.2: Summary of Input/Output Data for the Multi-Flow Simulator
However, the multi-flow controller, in addition to the information stated above, requires the following data on tooling and fixturing to generate schedules for fixture and cutting tool flows within a machining cell:

- **tooling data** (list of tool types in the tool store, tool lives, tool assembly and tool inventory data).
- **Toolkit information** (list of tools required per part type, tool life used per part).
- **fixture data** (complete list of available fixture types, quantities, fixture assembly/disassembly and recalibration data).
- **fixturing information** (preferred fixture type for a part type, alternative fixture types used with a part type, fixturing and defixturing operation times).

### 10.4. The Information Model

Several tools and modelling methodologies have been developed to facilitate the generation of information models for complex manufacturing environments. However, none of these tools and methodologies provide a systematic structure that can be used for the development of information models from start to finish (Chadhá et al. 1991, Czernik and Quint 1992). Most of these techniques and methodologies have used various types of graphical representations of a system (e.g. IDEF0 and YOURDON) where data elements, data flows and to some extent the functionality of the system can be illustrated through a set of diagrams. Additionally, a number of attempts have been made to define standards for the construction of such data models and for the information exchange. In recent years the activity of the STEP (STandard for the Exchange of Product data model) committee has been predominant (Yang 1991). The STEP standard uses a formal data specification language, namely EXPRESS, to define information models.

The EXPRESS language was utilised to generate a common data model for the applications of scheduling and control within a European research programme, entitled 'Eureka-FORCAST' (Flexible Operational Real-Time Control and Scheduling Tools). As a result, a methodology has been developed to generate EXPRESS data models. This methodology is described in Rahimifard and Newman (1996a), which is included in appendix 4, and has been used to develop an EXPRESS data model for the multi-flow controller (see appendix 5), based on the data requirements described in section 10.3. A
simplified structure of this data model is depicted in figure 10.3, and a section of the data model defining the tool entity is outlined below:

\[
SCHEMA \text{ Multi-Flow Controller} ;
\]

Entity Tool

Tool_Id : ID_Type ; (* ID_Type is defined as STRING(24) *)
Tool_Description : STRING(30) ;
Tool_Life : Time ;
Max_Permissible_Life : Time ;
Tool_Used_In : Set [1:?] of Toolkit ;
(* Toolkit is another entity in the information model *)

End_Entity;

End_SCHEMA

Figure 10.3 : A Simplified Structure of Multi-flow Control Data Model
10.5. Database Management Requirements for Multi-Flow Control

Handling a large amount of data is an integral part of any planning and scheduling process. The dynamic nature of the scheduling problem produces an extensive body of data that is time dependent and must be stored. In the application of the multi-flow controller, it is vital to store the latest information available on the progress of the schedule and manufacturing system status, because :

- the planning and scheduling tasks are a continuous process and therefore the information on previous manufacturing periods is required as initial input data for the planning of the future manufacturing horizons.
- the nature of the recovery procedures (e.g. re-scheduling) carried out in the case of interrupts to present schedules (e.g. machine breakdowns, shortage of raw materials, cutting tools, etc.) requires the system to keep a log on the latest status of the schedule and the manufacturing system.
- the multi-flow controller has been designed and implemented to deal with the possibility of introducing new jobs (i.e. interleaving jobs) to an existing schedule, at short notice. There is a need to identify the most efficient method of accommodating these additional jobs without disturbing many activities within the manufacturing system, the most up-to-date information on the progress of the scheduled jobs.
- the multi-flow controller produces a wide range of reports on the issues such as; the progress of the previous schedules, overall utilisation of resources, interrupts, list of tardy jobs, etc.

All of these reasons are indications to illustrate the need for a powerful data manager. Database management systems have been utilised as the main data manager facility within integrated software systems for many years (Rahimifard et al. 1992). As a result, a database structure based on the definitions within the multi-flow control data model described in section 10.4, has designed and implemented as one of the software modules of the multi-flow controller. The computational viewpoint of this manufacturing database is described in the next section.
10.6. The Manufacturing Database: A Computational Viewpoint

The PREACTOR scheduling software (The CIMulation Centre 1994), provides the users with a data definition environment to develop customised database structures. The PREACTOR database definition environment has been utilised to generate a manufacturing database, as the main data manager within the multi-flow controller. This database has a relational structure in which data elements are stored in a number of tables. Each table is designed based on the definition of one of the data model entities. Similarly, the relationship between tables is defined using the data model structure, illustrated in figure 10.3. The tables appear as a set of computer screen windows, divided into rows and columns. Furthermore, each row is connected to a dialogue screen which includes a number of data fields. The manufacturing information is entered into the database, by typing the various data values in these data fields, as shown in figure 10.4. Examples of the information stored in the manufacturing database, in the form of orders, parts, operations, tools, toolkits, fixtures and machine tables are illustrated in figures 10.4-10.10. The manufacturing database is totally integrated with other modules of the multi-flow controller, so that the initial input data is automatically extracted and a range of outputs are stored in the database.

Figure 10.4: Order(Joblist) Table from the Manufacturing Database
Figure 10.5: Parts Table from the Manufacturing Database

Figure 10.6: Parts Table from the Manufacturing Database
Figure 10.7: Tools Table from the Manufacturing Database

Figure 10.8: Toolkits Table from the Manufacturing Database
Chapter 10

Figure 10.9: Fixtures Table from the Manufacturing Database

Figure 10.10: Machines Table from the Manufacturing Database
Chapter 11

MULTI-FLOW PLANNING STRATEGIES FOR ECONOMIC MANUFACTURE

11.1. Introduction

The multi-flow control research has investigated the generation of a number of novel planning strategies to economise on the manufacturing cost of flexible batch machining applications. These planning strategies are divided into three main categories of:

i) workpiece dominated strategies.

ii) tool dominated strategies.

iii) fixture dominated strategies.

A brief description of these planning strategies, together with their software implementation within the multi-flow scheduler has been provided in chapter 8. This chapter describes the algorithms and the functional structure related to the job allocation policies utilised within each of these planning strategies.

11.2. Economic Manufacture within Flexible Batch Machining Applications

Conventionally, the majority of existing planning strategies are concerned with the most effective flow of workpieces in machining facilities. This can be justified in many cases, where the cost of parts is very high in comparison with the cost of cutting tools and fixtures required to process these parts. In such cases, the most economical solutions are achieved by minimising the work-in-progress, mean flow times of jobs and meeting completion dates. However, in many flexible batch machining applications, the cost of cutting tools is a significant proportion of both the initial installation cost and the daily operational cost. Tool management publications have reported the tooling costs to be in
the region of 15% up to as much as 40% of manufacturing cost in some applications (see section 2.3). Therefore, by adopting appropriate planning strategies and economising on tooling cost, large reductions in the total manufacturing cost can be achieved.

Furthermore, the fixturing practices in FMC provide operational constraints that are not considered in the conventional workpiece dominated planning strategies. In the case of specially designed fixtures the emphasis is to maximise the possible machining time per machine setup with multi-parts per fixture configuration and, therefore, to reduce manufacturing cost by allowing for a longer unmanned production period and a higher machine utilisation. Alternatively, the use of modular fixtures reduces the initial costs of fixtures and allows the reusability of fixtures for different part types. However, the modular fixtures have to be re-assembled and setup before a different part type can be mounted on them. The fixture assembling and disassembling operations are time consuming and can result in higher manual operation costs. Therefore, the effective management of fixtures plays a vital role in the overall performance and manufacturing costs of FMC.

The multi-flow control research has aimed to generate a flexible and versatile structure of planning strategies in which the emphasis in planning can be based on the most effective flow of workpieces, cutting tools or fixtures to minimise the manufacturing cost, without affecting the production throughput requirements. The selection of one of these strategies (by the cell manager), is influenced by a range of factors such as business requirements, manufacturing goals and constraints, parts per tool and parts per fixture profiles, etc (see section 12.3). These planning decisions involve the selection of the following criteria, as shown in figure 11.1 :-

i) **a planning strategy** for generating production schedules which provides the most effective flow for one of the three principal flows within FMC, as discussed earlier.

ii) **a scheduling constraint** reflecting a finite or infinite capacity scheduling scenario. This only applies to the fixture dominated strategy within the multi-flow control framework (see figure 11.1).

iii) **a job allocation policy** represented by the procedures and algorithms used to assign jobs to machines.

iv) **a job sequencing rule** to be used for sorting a specific list of jobs into some order before work-to-lists are generated for the individual resources.
The Multi-Flow Planning Strategies

![Diagram showing the Multi-Flow Planning Strategies]

Keys:
- EDD Earliest Due Date
- LPT Longest Processing Time
- SPT Shortest Processing Time

Figure 11.1: The Structure of Planning Strategies Supported by the Multi-Flow Controller

11.3. Workpiece Dominated Planning Strategies

The workpiece dominated strategies are the most commonly adopted planning procedures in manufacturing companies and, consequently, a large number of researchers have investigated the various issues relating to the effective management of workpiece flow (see section 2.2). The research reported in this thesis, complements this research work (see section 5.2) and utilises a number of most suitable planning algorithms and scheduling rules to be implemented in the multi-flow controller. In line with the scope of the research, only the application of finite capacity planning is considered. The following manufacturing goals are targeted by the workpiece dominated strategies:

i) minimising the work-in-progress inventory.
ii) balancing the workload for resources.
iii) achieving rapid completion dates.
iv) reducing the mean flow times of jobs.
11.3.1. Multi Machine Loading Job Allocation Policy

In the flexible batch machining applications, a job is defined as an order for a number of parts, referred to as a ‘part batch’. The required number of parts often exceeds the fixture capacity, i.e. the number of parts that can be taken and transported to a machine and processed at a single machine visit. Therefore, jobs are usually divided into a number of transfer batches. The size of these transfer batches is directly related to the fixture capacity and the number of fixtures that can be mounted on a single pallet (see section 4.6).

The workpiece dominated planning strategies utilise a job allocation policy referred to in this thesis as ‘multi machine loading’ (MML), in which the transfer batches of a single job are allocated across different machines in the cell. An example of a schedule pattern generated using MML is illustrated in figure 11.2, and the procedures involved in the implementation of MML within the multi-flow control structure is depicted in figure 11.3. MML is identified to be the most suitable job allocation policy to achieve the manufacturing goals targeted by the workpiece dominated strategies, as outlined in section 11.3. Furthermore, a number of common job sequencing rules, are used in conjunction with MML to generate schedules, as illustrated in figure 11.1. These job sequencing rules are the earliest due date (EDD), and the rules related to operation times, namely the shortest processing time (SPT) and longest processing time (LPT).

![Figure 11.2: A Schedule Pattern Generated Using the Multi Machine Loading Policy](image-url)
Figure 11.3: Procedures Involved in Implementation of the Multi Machine Loading Job Allocation Policy within the Multi-Flow Controller
11.4. Tool Dominated Planning Strategies

The tool dominated strategies are adopted for the most effective flow of cutting tools within FMC, to reduce the tooling costs. This is achieved by targeting the following manufacturing goals:

i) minimising the total number of cutting tools required to process a specific number of jobs.

ii) minimising the number of manual tooling activities.

iii) achieving i) and ii) without compromising the workpiece throughput requirements.

The tooling costs for processing a specific number of jobs are influenced both by the selection of the tool exchange policies and job allocation policies. In line with the scope of the research, the issues relating to the tooling cost affected by the job allocation policies are discussed in this thesis. The selection of an appropriate tool exchange policy such as full kitting, differential kitting and consolidated kitting (see section 4.5.1) is a secondary decision, based on the adopted job allocation policies. The author refers readers to research work which is the subject of a complementary thesis by Mr. P. Coleman (1996), for further details on the selection of the most appropriate tool allocation policies. The tool dominated strategies are based on ‘infinite tool capacity planning’, as shown in figure 11.1, and therefore, it is assumed that an unlimited stock of cutting tools is always available in the tool store and can be assembled and delivered to the cell as and when required.

11.4.1. Tool Cluster Based Job Allocation Policy

A number of researchers have suggested the use of clustering techniques to solve the tool allocation problems (Ventura et al. 1990, de Souza and Bell 1991). In such approaches, a clustering algorithm is applied to the part and tool matrix to identify and group together the part batches (i.e. jobs) with similar tool requirements, before they are allocated to machines. The argument being that by processing a cluster of jobs with similar tool requirements on a machine (or a subset of machines), a reduction on the total tool requirements can be achieved.
At Loughborough University, three researchers have studied the various research issues related to the use of clustering techniques in tool management. de Souza (1988) explored the feasibility of utilising clustering algorithms in the tool management of a highly automated manufacturing system. Ozbayrak (1993) investigated the manufacturing system design issues related to the use of a cluster based tool exchange policy. Coleman (1996) examines the effects of a number of tool exchange policies (see section 4.5.1), including the clustering policy on various tooling activities, ranging from tool exchange activities required at a machine tool magazine to the transport, assembly, rework, recycle activities in the tool room/store, using a hierarchical tool flow model. The author refers the readers to these research works for further details on the mathematical modelling and computational implementation of clustering techniques and their influences on tooling requirements.

The research reported in this thesis, however, is concerned with the influences of clustering techniques as one of the tool related scheduling rules, on the other material flows within the machining cell to provide a holistic view of the potential capabilities of the multi-flow controller. As a result, a clustering model generated by de Souza and Ozbayrak, and further enhanced by Coleman is integrated within the multi-flow controller. This clustering model is based on a rank order clustering algorithm (King 1980), and is implemented in a spreadsheet environment (de Souza and Bell 1991). Consequently, the tool dominated planning strategies supported by the multi-flow controller utilises a ‘cluster based job allocation policy’. In this job allocation policy, a lists of jobs together with their tooling requirements are passed to this clustering model to form a part and tool matrix. The clustering model identifies and returns a number of job clusters to the multi-flow scheduler, as shown in figure 11.4. The jobs within these individual job clusters are sequenced based on a sequencing rule such as the earliest due date before being allocated to a specific machine or a subset of machines in the cell, depending on the number of jobs within each cluster.

In most applications, the use of the cluster based job allocation policy results in a significant reduction of the tool requirements and the related tooling activities required to process a specific number jobs (de Souza 1988, Ozbayrak 1993, Coleman 1996). However, the adoption of such a job allocation policy also influences a number of other manufacturing goals such as achieving a workload balance across the resources, and meeting the completion dates of the jobs. The interactions of these manufacturing goals are highlighted with the aid of examples in chapter 13.
Figure 11.4: The Procedures Involved in the Implementation of the Tool Cluster Based Job Allocation Policy within the Multi-Flow Controller
11.4.2. Single Machine Loading Job Allocation Policy

The implementation of the MML policy, used in workpiece dominated strategies often results in very high tooling costs because :-

i) identical sets of cutting tools have to be loaded on the different machines at the same time.

ii) the limited number of parts included in a transfer batch does not effectively utilise the tool lives, resulting in a large number of partially worn tools.

The multi-flow control research has explored the potential benefits of an alternative job allocation policy, referred to as 'single machine loading' (SML). With SML, all the transfer batches of a job are allocated to a single machine, thereby avoiding the duplication of identical toolkits on the different machines and the generation of a large number of partially used cutting tools. An example of a schedule pattern resulting from the utilisation of the SML policy, for the same joblist used in figure 11.2, is illustrated in figure 11.5. The procedures involved in the implementation of SML within the multi-flow control structure is depicted in figure 11.6. In addition, it should be also noted that with MML, identical fixture types are required to be present in different machines at the same period during the manufacturing horizon, whereas the use of SML relieves such pressures on fixture availability constraints. The utilisation of SML results in a reduction of tooling requirements, but also influences other manufacturing goals. The interactions of the manufacturing goals for SML are further discussed in chapter 13.

Figure 11.5 : A Schedule Pattern Generated Using the Single Machine Loading Policy
Figure 11.6: Procedures Involved in Implementation of the Single Machine Loading Job Allocation Policy within the Multi-Flow Controller
11.4.3. Combined Machine Loading Job Allocation Policy

In the modern applications of flexible batch machining, one of the most important manufacturing goals is the meeting of the completion dates for jobs. In 'make to order' applications, the due dates are assigned to jobs based on the delivery dates of the customer orders. In 'make to stock' applications, the due dates are identified through the aggregate planning process by a master production scheduler. To achieve this, a manufacturing horizon (a production period for which schedules are generated, e.g. a month or a week) is usually divided into a number of due date intervals (e.g. a shift or a day), as shown in figure 11.7. Then, these due date intervals are used to assign specific due dates to individual jobs, ensuring the workload allocated to a due date interval does not exceed the manufacturing capacities available within the interval.

In general, the MML policy by minimising the mean flow times of jobs, provides the best method of achieving the completion dates. However, as stated, MML often results in high manufacturing costs through the increase in tooling and fixturing requirements and their related activities. On the other hand, SML reduces these manufacturing costs but does not guarantee the meeting of job completion dates. As a result, the multi-flow control research has investigated the generation of a novel job allocation policy, termed the 'combined machine loading' (CML) policy. The CML policy incorporates the advantages offered by both MML and SML, by minimising tool and fixturing requirements and achieving the completion dates of jobs.

![Figure 11.7: The Due Date Intervals of a Manufacturing Horizon](image)

---

134
The job allocation process based on CML, depicted in figure 11.8, is carried out in two stages:

i) In the first stage the jobs are pre-allocated to the resources using SML and the due date intervals with tardy jobs are identified.

ii) In the second stage, a repetitive process considers the jobs pre-allocated to individual machines within the due date intervals with tardy jobs. Where completion dates have not been achieved on a machine, a job (referred to as 'problem job') is selected to be re-allocated to a minimum number of machines using MML, as shown in figure 11.8. The problem job, in the first instance, is divided between the machine which it was pre-allocated originally and the machine with the least workload for that specific due date interval. If the division of the problem job across two machines does not resolve the dilemma of the tardy jobs, the problem job would be further divided between three or more machines.

The problem jobs are selected based on one of the job characteristics. The following job characteristics are considered in the multi-flow control research:

- jobs with the longest processing time.
- jobs which require the minimum number of tools to be processed.
- jobs with the smallest number of transfer batches.
- jobs with the largest number of transfer batches.

The identification of the most appropriate job characteristics to be used for the selection of 'problem jobs' using CML depends on a number of other manufacturing constraints which are described in detail in chapter 12 and 13. Figure 11.8 illustrates the procedures involved in a CML policy based on the criteria of the jobs with longest processing time. Clearly, the CML job allocation policy incorporates a combination of both the SML and MML policies, and hence the name 'combined machine loading' policy. The schedule’s patterns generated using the CML job allocation policy for a joblist is illustrated in figure 11.9 and 11.10. As can be seen, jobs are pre-allocated using the SML policy which provides three tardy jobs (tardy jobs are shaded, with red boundaries in figure 11.9), and then these jobs are re-allocated using the MML to achieve the completion dates, as shown in figure 11.10.
Figure 11.8: Procedures Involved in Implementation of the Combined Machine Loading Job Allocation Policy within the Multi-Flow Controller
Figure 11.9: The First Stage of the Combined Machine Loading which Produces Three Tardy Jobs

Figure 11.10: The Second Stage of the Combined Machine Loading Policy with the Three Tardy Jobs being Divided between Two Machines
11.5. Fixture Dominated Planning Strategies

The fixture dominated strategies are adopted to achieve the most effective flow of fixtures by:

i) minimising the number of manual fixturing activities required to process a specific joblist.

ii) minimising the fixture inventory requirement of the machining cell.

iii) achieving i) and ii) without compromising the workpiece throughput requirements.

These manufacturing goals are similar to the ones used for tool dominated planning strategies. However, in flexible batch machining applications, the interactions of work and tool flows are quite different to those of work and fixture flows. The fixturing costs relating to the daily operational procedures of a machining cell are mainly due to the cost of manual fixturing activities, as fixtures, unlike cutting tools, do not have significant consumable/durable components. Therefore, the major emphasis in the fixture dominated strategies is the reduction of these fixturing activities. Furthermore, the number of fixturing activities depends on the use of specially designed fixtures or modular fixtures, as discussed in section 4.6.4. As a result, the fixture dominated strategies should consider the scheduling constraints based on finite fixture capacity planning for specially designed fixtures and infinite fixture capacity planning for modular fixtures, as illustrated in figure 11.1. These scheduling constraints are described in section 11.5.1.

It should be noted that, the number of fixturing and defixturing operations (mounting and removing parts on fixtures) required to process a specific number of jobs remains constant, regardless of the adopted job allocation policy. This is due to the fact that the number of transfer batches of jobs is totally dependent on a range of physical criteria such as the size of part types and fixtures, and transporter capacities. However, the adoption of a job allocation policy can influence :

i) the number of fixtures of each type required at any time during the manufacturing horizon, and

ii) the number of fixturing activities related to the assembly and disassembly operations of modular fixtures.
11.5.1. Finite and Infinite Fixture Capacity Planning

Finite fixture capacity planning is associated with the use of specially designed fixtures where a limited quantity of fixtures of each type is available, and consequently the fixture availability is a scheduling constraint. Although, the use of specially designed fixtures significantly reduces the number of manual fixturing activities (as they do not require fixture assembly and disassembly operations), in some applications the shortage of these fixtures can result in machine downtime and reduction in the production rate. In such cases, when the number of required fixtures of a particular type exceeds the quantity available, the start of the next job requiring the fixture type is often delayed until a fixture becomes available.

Infinite fixture capacity planning is associated with the use of modular fixtures where the quantity of fixtures available for a particular configuration is not limited to a constant number as a fixture set can be re-assembled to the various fixturing configurations, as and when required (see section 4.6.1). However, in the majority of applications, the use of modular fixtures increases the manual fixturing activities, and consequently, the fixturing costs. Three distinct and common fixturing practices within FMC applications, are identified and modelled within the multi-flow controller. These fixturing practices and their related rule sets are described below:

- **Fixturing practice 1**: this category of fixturing practice includes flexible machining applications where specially designed fixtures are used and a limited quantity of every fixture type is available. The rule set relating to this fixturing practice is as follows:
  
  i) let \( FT_1, FT_2, ..., FT_n \) represent the range of available fixture types, and
  
  ii) let \( Q_1, Q_2, ..., Q_n \) the quantities available for each fixture type.
  
  iii) if a job \( J \) requires \( FT_r \), then let \( Q_r = Q_r - 1 \).
  
  iv) start a fixturing operation and send the fixture and the workpiece(s) to a machine or a temporary buffer.
  
  v) on completion of the machining operations of the job \( J \), return the machined part(s) and the fixture to the fixturing station.
  
  vi) start the defixturing operation and send the machined part(s) to the part warehouse and the fixture to the fixture store.
  
  vii) let \( Q_r = Q_r + 1 \) and goto iii).
- **Fixturing practice 2**: This category of fixturing practice includes flexible machining applications where modular fixtures are used and the total number of available fixtures is very limited. Therefore, fixture assembly and fixture disassembly activities take place frequently to accommodate the requirements for various fixture configurations. The rule set related to this practice is as follows:

  i) Let \( FC_1, FC_2, \ldots, FC_n \) represent the range of available fixture configurations, and

  ii) Let \( Q \) the total quantity of available fixture sets.

  iii) If a job \( J \) requires \( FC_i \) then let \( Q = Q - 1 \).

  iv) If \( FC_i \) is not available in the store start a fixture assembly operation, else goto v)

  v) Start a fixturing operation and send the fixture and the workpiece(s) to a machine or a temporary buffer.

  vi) On completion of the machining operations of the job \( J \), return the machined part(s) and the fixture to the fixturing station.

  vii) Start the defixturing operation and send the machined part(s) to the part warehouse and the fixture to the fixture store.

  viii) If \( FC_i \) is required by next job or \( Q > 1 \) then goto iii) else,

  ix) Start a fixture disassembly operation and let \( Q = Q + 1 \) and goto iii).

- **Fixturing practice 3**: This category of fixturing practice includes flexible machining applications where modular fixtures are used and a number of fixture configurations are constructed and stored. The fixture assembly and fixture disassembly activities do not take place frequently, unless as a result of the introduction of a new part design or a new fixture configuration. The rule set related to this fixturing practice is as follows:

  i) Let \( FC_1, FC_2, \ldots, FC_n \) represent the range of pre-assembled fixture configurations, and

  ii) Let \( Q_1, Q_2, \ldots, Q_n \) the quantities available for each fixture configurations.

  iii) If a job \( J \) requires \( FC_i \) then let \( Q_i = Q_i - 1 \).
iv) start a fixturing operation and send the fixture and the workpiece(s) to a 
    machine or a temporary buffer.

v) on completion of the machining operations of the job J, return the machined 
    part(s) and the fixture to the fixturing station.

vi) start the defixturing operation and send the machined part(s) to the part 
    warehouse and the fixture to the fixture store.

vii) if \( Q_s = 0 \) and a job is waiting for FC, then start a fixture disassembly 
    operation to convert FC to FC; and let \( Q_s = Q_s + 1 \) and goto iii), else

viii) let \( Q_s = Q_s + 1 \) and goto iii).

11.5.2. Fixture Cluster Based Job Allocation Policy

The cluster based job allocation policy adopted by the fixture dominated planning 
strategies is similar to the cluster based policy used within the tool dominated strategy, 
except that the clustering algorithm is applied to a part and fixture matrix to identify jobs 
with common fixturing requirements. The jobs within a job cluster are then sequenced 
based on a sequencing rule such as the earliest due date, before being allocated to a 
machine or a subset of machines in the cell, depending on the number of jobs within each 
cluster (see figure 11.4).

The use of the cluster based job allocation policy can result in a significant 
reduction of the required number of fixtures at any time during the manufacturing horizon 
and fixturing activities, for any of the three fixturing practices, described in section 11.5.1. 
For example, in applications with specially designed fixtures (i.e. fixturing practice 1), 
grouping of jobs with common fixture requirements and allocating them to a machine or a 
subset of available machines will reduce the number of fixtures required at any time during 
the manufacturing requirements. Alternatively, in applications where fixture assembly and 
disassembly are carried out frequently because of the limited availability of fixture sets (i.e. 
fixturing practice 2), the use of cluster based job allocation policy reduces the frequency of 
fixture assembly and fixture disassembly requirements. However, the adoption of the 
cluster based job allocation policy can influence the other manufacturing goals such as 
balancing the workload of machines and achieving the completion dates of jobs. The 
interactions of these manufacturing goals are described in chapter 14.
11.5.3. Fixture Availability Based Job Allocation Policy

In the application of finite fixture capacity planning, the shortage of fixtures during the manufacturing horizon can result in delays and machine down times (see figure 11.11). The job allocation policies used in workpiece dominated strategies do not consider the fixture availability as a scheduling constraint. As a result, a fixture availability based (FAB) job allocation policy is generated as part of the fixture dominated planning strategy to assign a job to a machine if, and only if, the required fixtures are available to process the job. The procedures for the implementation of the FAB policy are depicted in figure 11.12. In this job allocation policy, the record of the total fixtures available and those already allocated to the jobs are updated every time a job is assigned to a machine. The allocation of a job which requires a fixture type that is not available at the time, is delayed until the fixture becomes available following a defixturing operation, as shown in figure 11.12. The comparison of the schedule patterns based on applying the SML and the FAB job allocation policies, is depicted in figure 11.11. As it can be seen, due to the limited number of fixtures, the processing of jobs may take longer than when an unlimited number of fixtures are assumed in the SML policy of the work dominated planning strategy. The interactions of the number of available fixtures with other manufacturing goals such as work-in-progress, mean flow times of jobs and completion dates of jobs are described in chapter 13.

![Figure 11.11: A Comparison of Schedules Generated Using the SML and FAB Job Allocation Policies](image-url)
sequence the jobs in the joblist based on a sequencing rule

update the quantities of fixtures in the fixture availability record

select the first job from the list of the sequenced jobs

is the fixture required by the selected job available?

allocate the Job to a machine

is this the last job in the joblist File

issue a request for the fixture

delay the start of the job till the fixture is available

End

Figure 11.12: The Procedures Involved in the Implementation of the Fixture Availability Based Job Allocation Policy within the Multi-Flow Controller
Chapter 12

DESIGN OF THE COMPUTER-BASED EXPERIMENTS

12.1. Introduction

This chapter describes the issues relating to the design and implementation of a series of computer-based multi-flow control experiments. The initial part of the chapter discusses a range of manufacturing criteria that influence the design of these experiments. The final part of the chapter describes the data set generated as initial input for the multi-flow control experiments.

12.2. Multi-Flow Control Experiments

The multi-flow control research has investigated a wide range of issues relating to an integrated structure for the generation and execution of manufacturing schedules, and a number of novel planning strategies to be used in conjunction with the multi-flow controller. Clearly, these research ideas have to be validated, and the performance of the multi-flow planning strategies examined and measured against various manufacturing scenarios representing different flexible batch machining applications.

In the experimentation stage of the research, it was identified that the variety of challenges required both in terms of business configurations and manufacturing data relating to part, tool and fixture types, machining operations and cell configurations cannot be provided through a limited number of industrial case studies. As a result, a comprehensive programme for a series of computer-based experiments has been designed and implemented to highlight the new knowledge provided by the research. The design and implementation of these experiments has involved the following three stages:-

i) identification of the manufacturing criteria that influence the design of these experiments.
generation of data sets representing a range of manufacturing scenarios to be used as input to the experiments.

iii) identification of a systematic approach to implement an experiment based on a data set.

12.3. Manufacturing Criteria Influencing the Design of the Multi-Flow Control Experiments

The multi-flow control experiments identify a number of flexible batch machining applications, representing a range of manufacturing criteria that are uniquely related to each application. These manufacturing criteria are depicted in figure 12.1, and are described below.

12.3.1 Business Configurations

Business configurations is the terminology used to define the nature of manufacturing companies in terms of their business practices influenced by factors such as:-

- 'make-to-stock' and make-to-order’ modes of operation;
- the work patterns in terms of number of shifts per day and per week, manually supported and unmanned shifts, shift patterns during weekends, etc;

![Figure 12.1: The Manufacturing Criteria Influencing the Design of the Multi-Flow Control Experiments](image-url)
12.3.2. Part and Tool Matrix

The part and tool matrix (PTM) represents the variety of part types and the range of cutting tools used to process these parts in each application. The PTM matrix has been viewed in terms of a parts per tools profile, as illustrated in figure 12.2, which identifies the number of part types requiring a particular tool type in their list of machining operations. The variety of part and tool types in an application depends on issues such as the business practices (e.g. an OEM producing a small family of products or a subcontractor processing a large number of part types for various customers), and the efficiency of the product design and process planning functions within the manufacturing company. In modern FMC applications with the aid of a tool rationalisation policy, it is intended to minimise the range of required tool types and encourage designers, process planners and part programmers to utilise only this limited set of cutting tools. However, in the wide range of flexible batch machining applications, there are three distinct tooling scenarios.

![No. of Part Types Using Each Tool Types](image)

*Figure 12.2: An Example of Parts Per Tools Profile*
A typical depiction of the parts per tool profiles for these tooling scenarios is shown in figure 12.3. These scenarios are:

i) a small range of tool types is required by a small range of part types, representing applications where a family of products is machined in large batches, as depicted in figure 12.3 - case (i).

ii) a medium range of tool types is required by a large range of part types, representing the most general case in batch machining applications, as shown in figure 12.3 - case (ii).

iii) a large range of tool types is required by a small range of part types, representing the applications typified by subcontractors, where a wide variety of unrelated part types is processed for different customers, as illustrated in figure 12.3 - case (iii).

12.3.3. Part and Fixture Matrix

The part and fixture matrix (PFM) represents the variety of fixture types (or fixture configurations in the case of modular fixtures) required by the range of part types in each application. In a similar manner to the PTM, the range of part and fixture types depends on the issues of business practices, part design and process planning functions. The PFM can be viewed in terms of a parts per fixture profile which identifies the number of part types that require a particular fixture type for their machining operations. A similar classification to the tooling scenarios as outlined in section 12.3.2, can be envisaged for parts per fixture profile. These classifications of parts per tool and parts per fixture have been used to develop a number of different data sets for multi-flow control experiments.

12.3.4. Cell Configuration

Cell configuration is the terminology used to define the issues relating to cell design, such as the number of machines, fixturing stations and loading stations in the cell, the number of transporters, average transporting times, average time for load and unload operations and average time for fixturing and defixturing operations. A typical FMC cell configuration, as described in section 4.3 and depicted in figure 4.2, is used within the multi-flow control experiments.
Figure 12.3: Parts per Tool Profiles for the Three Tooling Scenarios
12.3.5. Rough Cut Plan

A rough cut plan is defined as a requirement for processing a number of orders in the machining cell during a manufacturing horizon. In the multi-flow control experiments, rough cut plans are configured in the form of a number of ‘joblists’. A joblist is an unsequenced string of jobs where a job is defined as a requirement for a quantity of a unique part type to be completed by a specific due date. A job consists of a number of transfer batches, and therefore, the processing of a job may require a number of pallet visits to the machines. The following information is provided in the joblists for each individual job:

- a job identification and description;
- a part type and a batch quantity of parts;
- the total machine cutting time required by the job; and
- an earliest launch date and due date associated with the job.

The joblist characteristics can be viewed in terms of a profile, as illustrated in figure 12.4, which identifies the range of the total cutting times of jobs included in the joblist. The joblist characteristics are directly influenced by the range of the part types and batch sizes in a flexible batch machining application. The following joblist profiles are defined to be used in multi-flow experiments, as outlined in section 12.4.5:

i) short cutting times, representing applications with small batch sizes.
ii) long cutting times, representing applications with medium batch sizes.
iii) mixed cutting times, representing application with small to medium batch sizes.

![The Total Machine Cutting Times Required by Each Job](image)

**Figure 12.4**: An Example of a Joblist Profile
12.4. Generation of a Number of Data Sets for the Multi-Flow Control Experiments

One of the most important issues that ensures an efficient and effective series of experiments leading to logical and useful new knowledge, is the identification of appropriate initial data sets. The generation of these data sets has been carefully investigated. Furthermore, the industrial collaborators of the multi-flow control research programme (see section 5.4) have provided invaluable input to this data generation task, to ensure that:

i) the adopted data values relate closely to those in existing flexible batch machining applications.

ii) a realistic range of flexible batch machining applications is represented by the various data sets.

This work on the syntheses of these data sets has been a joint effort between Mr. P. Coleman and the author, and therefore, similar data sets are used in the computer based experiments of both research theses (Coleman 1996). The summary of the various data values adopted in these data sets is shown in table 12.1 and is outlined below.

12.4.1. Data Values Relating to Business Configurations

The multi-flow control experiments are based on manufacturing horizons (MH) of a week, where a work pattern of three shifts (8 hours each) per day and seven days a week production is envisaged for machines in the cell. A maximum workload capacity of 90% is allowed and three distinct policies are used to associate launch dates and due dates to the jobs. These policies are:

i) **due date interval 1 (DDI 1)**: where the launch dates of all jobs in the joblist are the start of MH and their due dates are the end of MH, representing the applications where jobs can be processed in any order throughout the MH.

ii) **due date interval 2 (DDI 2)**: in this policy the starting dates of all jobs in the joblist are the start of MH, with a unique daily due date assigned to each job, representing applications where jobs can be started at any time during the MH, but must be finished before specific completion dates.
<table>
<thead>
<tr>
<th><strong>DATA SETS</strong></th>
<th><strong>DATA VALUES</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Related to Business Configurations</td>
<td></td>
</tr>
<tr>
<td>manufacturing horizon</td>
<td>1/2, 1, 2 weeks</td>
</tr>
<tr>
<td>due date intervals</td>
<td>DDI 1, DDI 2, DDI 3 (see section 12.4.1)</td>
</tr>
<tr>
<td>work patterns</td>
<td>8 hours a shift, 3 shifts a day, 7 days a week</td>
</tr>
<tr>
<td>maximum workload capacity</td>
<td>90 - 95 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Related to Part and Tool Matrix</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>no. of part types</td>
<td>300</td>
</tr>
<tr>
<td>no. of tool types</td>
<td>150</td>
</tr>
<tr>
<td>range of cutting times per part (minutes)</td>
<td>10 - 120</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Related to Part and Fixture Matrix</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>no. of fixture types</td>
<td>20</td>
</tr>
<tr>
<td>fixture capacity</td>
<td>1, 2 or 4 parts</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Related to Cell Configuration</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>no. of machines</td>
<td>2, 4, 8</td>
</tr>
<tr>
<td>no. of part transporters</td>
<td>1</td>
</tr>
<tr>
<td>no. of tool transporters</td>
<td>1</td>
</tr>
<tr>
<td>no. of loading stations</td>
<td>2</td>
</tr>
<tr>
<td>no. of fixturing stations</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Related to Rough Cut Plan</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>joblist profiles</td>
<td>JP1 (short jobs), JP2 (long jobs), JP3 (mix jobs)</td>
</tr>
<tr>
<td>range of cutting times per job (hours)</td>
<td>JP1 (2 - 6), JP2 (12 - 16), JP3 (2 - 16)</td>
</tr>
<tr>
<td>max-min part batch sizes</td>
<td>JP1 (2 - 24), JP2 (12 - 44), JP3 (2 - 44)</td>
</tr>
<tr>
<td>no. of jobs in each joblist</td>
<td>JP1 (153 jobs), JP2 (46 jobs), JP3 (88 jobs)</td>
</tr>
</tbody>
</table>

Table 12.1: Adopted Data Values for Multi-Flow Control Experiments
i) **due date interval 3(DDI3)**: where a unique starting date and due date are assigned to every job, representing applications where raw material is delivered to the cell in some sequence at certain times and jobs must finish before the completion dates.

12.4.2. **Data Values Relating to the Part and Tool Matrix**

A part and tool matrix containing 300 part types and 150 tool types is generated. The cutting times per part of different part types vary between 10 - 120 minutes. The range of part types in this matrix is divided into three groups to represent the tooling scenarios described in section 12.3.1.

12.4.3. **Data Values Relating to Part and Fixture Matrix**

A range of 20 fixture types is created to be used with the 300 part types. These fixture types can represent both specially designed fixtures and modular fixtures. Each fixture has a capacity of 1, 2 or 4 parts. The number of parts on a fixture is related to the individual cutting times of the parts. In the case of part types with cutting times of less than 20 minutes, 4 parts are loaded on a fixture. For part types with a processing times of 20-45 minutes, two parts are loaded on a fixture, and finally for part types with cutting times of greater than 45 minutes, only one part is loaded on a fixture. In a similar manner to tooling scenarios, to represent various fixturing scenarios, the range of 300 part types are divided into three groups, with different parts per fixtures profiles.

12.4.4. **Data Values Relating to Cell Configuration**

Three cell configurations containing 2, 4 and 8 identical machining centres are used in the multi-flow control experiments. These cell configurations also include:

- 1 part transporter and 1 tool transporter;
- 2 loading stations, with an average of 0.5 minutes for loading and transportation time of each transfer batch; and
- 2 fixturing and defixturing stations, with an average of 1 minute for fixturing operations of each transfer batch.
12.4.5. Data Values Relating to Rough Cut Plans

Based on each of the three distinct joblist profiles, described in section 12.3.5, a joblist is generated, as shown in table 12.1. The joblists vary in terms of the number of jobs included, the cutting times per job and the part batch sizes. The profiles for these joblists is illustrated in figure 12.5. The adopted data values for each of these joblists are shown in table 12.1, and are:-

i) joblist profile 1(JP1) : based on short cutting times, ranging between 2-6 hours, and small batch sizes of 2-24 parts. This joblist consists of 153 jobs.

ii) joblist profile 2(JP2) : based on long cutting times, ranging between 12-16 hours, and medium batch sizes of 12-44 parts. This joblist consists of 46 jobs.

iii) joblist profile 3(JP3) : based on a mixture of cutting times, ranging between 2-16 hours, and small to medium batch sizes of 2-44 parts. This joblist consists of 88 jobs.

12.5. The Implementation of the Experiments

Based on the data values discussed in section 12.4, there can be a large number of data sets varying in terms of due date intervals, cell configurations and joblist profiles adopted in each case. In addition, these data sets are the initial input data to the different experiments based on various planning strategies, job allocation policies and sequencing rules. Therefore, a systematic approach has been identified to implement every experiment, as shown in figure 12.6. As it can be seen, the implementation of every multi-flow control experiment involves the following two main stages :-

i) specification of a particular data set which commences with selecting one of the joblists(described in section 12.4.5) and applying one of policies discussed in section 12.3.1 to associate a launch date and due date to every job. Then, a cell configuration based on 2, 4 or 8 machines in the cell is selected to generate the input files required by the multi-flow controller.

ii) selection of one of the operational modes of the multi-flow controller based on workpiece, fixture or tool dominated planning strategies, as described in section 8.6. Finally, a job allocation policy and a sequencing rule related to the selected planning strategy are adopted to generate the schedules.
i) The Jobs With Short Cutting Times of 2-6 Hours  
Joblist Profile 1 - 153 Jobs

ii) The Jobs With Long Cutting Times of 12-16 Hours  
Joblist Profile 2 - 46 Jobs

iii) The Jobs With Mix Cutting Times of 2-16 Hours  
Joblist Profile 3 - 88 Jobs

Figure 12.5: The Joblist Profiles 1, 2 and 3
Figure 12.6: A Systematical Approach for the Implementation of the Multi-Flow Control Experiments
Chapter 13

THE PROGRAMME OF EXPERIMENTS AND ANALYSIS OF THE RESULTS

13.1. Introduction

This chapter describes the programme of the experiments undertaken for the multi-flow control research, together with a critical analysis of the results of these experiments. The initial part of the chapter describes the manufacturing performance measures selected to examine the efficiency of the multi-flow planning strategies and outlines the programme of experiments which are based on these performance measures. The major part of the chapter interrogates the outputs of the experiments, using these manufacturing performance measures to highlight the new knowledge provided by the research, through a number experimental observations. These experimental observations are utilised in chapter 14, to suggest a number planning and control rules to be used by a cell manager in conjunction with the multi-flow controller.

13.2. Manufacturing Performance Measures

Each multi-flow control experiment produces a huge amount of output data which can be interrogated based on a large number of performance measures such as the size of work-in-progress queues, resource utilisations, mean flow time of jobs, number of tardy jobs, tool inventory requirements, the number of tooling activities in the tool room, tool transportation requirements, tool exchange activities at machines, fixture inventory requirements, the number of fixturing activities related to fixture assembly and disassembly operations. In order to be able to effectively and efficiently describe and analyse the results of the experiments, from this large number of manufacturing performance measures, a limited set of critical measures have been adopted to highlight
the performance of the multi-flow planning strategies in various flexible batch machining scenarios. These manufacturing measures can be used as indicators to a wider range of performance measures as described later in this chapter, and are listed below:

i) the number of toolkit exchange activities in the cell.
ii) the total quantity of fixtures of various types required.
iii) the balance of workload assigned to the machines.
iv) the number of tardy jobs.

13.2.1. The Number of Toolkit Exchange Activities in the Cell

In the multi-flow control experiments, based on the adopted job allocation policy, a cluster of jobs, a single job or a portion of a single job is assigned to a machine at a time. It is assumed that the toolkit required to process the entire job cluster, the job or a portion of the job can be transported and loaded onto the machine prior to the start of machining operations. Therefore, based on the adopted planning strategy a job may require one or several toolkit exchange activities. It should be noted that the word 'toolkit' in this performance measure can refer to a full toolkit or a differential toolkit (partial toolkit), based on the adopted tool exchange policy (see section 4.5.1). This performance measure identifies the number of toolkits that have to be exchanged during a manufacturing horizon, and therefore, is also an indication to both:

i) the cost of required cutting tools, as the larger number of toolkits reflects a higher likelihood of duplication of cutting tools on the machines and a higher number of partially worn tools (see section 8.5.2); and
ii) the cost of manual tooling requirements, as tool transportation and tool replacement activities are often carried out by an operator.

13.2.2. Total Quantity of Fixtures of Various Types Required

The total quantity of fixtures of various types required throughout a manufacturing horizon is the sum of the maximum number of fixtures of a particular type required at any time. The maximum number of fixtures of a particular type required at any time is the sum of the number of fixtures loaded on the machines (fixtures in use) at any time and those required at fixturing stations to prepare the next transfer batch for the machines, in order to
be able to avoid machine down time due to delays in fixturing operations. As stated in chapter 11, the fixturing cost is mainly due to the initial cost of fixtures and the cost of manual fixturing activities, as unlike the cutting tools, fixtures are assumed not to have any consumable / durable components. As a result, this performance measure is adopted to indicate:-

i) the possible delays expected by lack of fixture availability in the case of specially designed fixtures; and

ii) the number of required fixture assembly and disassembly activities in the case of modular fixtures (see fixturing practices in section 11.5.1).

12.2.3 The Balance of Workload Assigned to the Machines

This is a well established performance measure which is frequently adopted in production scheduling research as a basis for measuring the effectiveness of a planning strategy. It identifies the difference between the lowest and the highest workload, in terms of the number of machining(cutting) hours, assigned to every machine in the cell for a manufacturing horizon. This performance measure can also be used as an indicator to the machine utilisation and the length of makespan time(period between the start time of the first job to the finish time of the last job in the joblist), required for a joblist.

12.2.4 The Number of Tardy Jobs

This is one of the most important performance measures used in contemporary research, as it is an indicator to the critical issue of meeting completion dates which is the main manufacturing objective in the majority of flexible batch machining applications. As a result, the multi-flow control research has carefully investigated the issue of tardy jobs, resulting in the combined machine loading job allocation policy, and has used this performance measure to analyse the performance of other job allocation policies. A job can be late by as little as one minute to hours within a schedule. However, in the multi-flow control experiments, the jobs that are late by at least a period equal or greater than the processing time of a single transfer batch are defined to be tardy jobs and are included in this performance measure.
13.3. Definition of the Manufacturing Parameters Used in the Data Analysis

In order to be able to analyse and describe the experimental results, the following manufacturing parameters have been defined, and are depicted in figure 13.1:-

MH : manufacturing horizon (e.g. a week or 168 hours).
M : number of machines.
CAP : total machining capacity available in a MH, i.e. :

\[
CAP = MH \times M
\]

(e.g. 168 * 4 = 672 hours for a 4 machine cell in a week).

\[\sum WL\] : Total workload allocated for a MH (e.g. 604 hours in a week)
WLavg : Average workload (i.e. number of machining hours) assigned per machine for a MH.

\[
WL_{avg} = \frac{\sum WL}{M}
\]

(e.g. 604 / 4 = 151 hours per machine in a week).

WLP : a percentage of total machining capacity representing the total workload for a MH, i.e.:

\[
WLP = \frac{\sum WL}{CAP} \times 100
\]

(e.g. 604 / 672 * 100 = 90% for a 4 machine cell in a week).

S : slack per machine for a MH, i.e.:

\[
S = \frac{CAP}{M} - WL_{avg}
\]

(e.g. 672 / 4 - 151 = 17 hours slack per machine, 90% workload in a week).

I : number of due date intervals within a MH (e.g. seven daily due date intervals in a week).

J : number of jobs for a MH.

TJ : number of tardy jobs in a MH
In a similar manner the following parameters are defined for a due date interval, as illustrated in figure 13.1:-

\[ T(i) : \text{length of a due date interval (e.g. 24 hours), so that} \]
\[ MH = \sum_{i=1}^{n} T(i) \]

\[ \text{CAP} (i) : \text{machining capacity for a due date interval i.e.:} \]
\[ \text{CAP} (i) = T(i) \times M \]

(e.g. \(4 \times 24 = 96\) hours for a 4 machine cell with daily due dates).

\[ \text{WL} (i) : \text{workload assigned per machine for a due date interval.} \]

\[ \text{WLP} (i) : \text{a percentage of total machining capacity representing the total workload for a due date interval.} \]

\[ S (i) : \text{slack per machine for a due date interval.} \]

\[ J (i) : \text{number of jobs for a due date interval.} \]
In addition the following machining parameters are defined and used in the analysis of experimental results:

\[ C_{\text{max}} \] maximum length of cutting time assigned to a machine.

\[ C_{\text{min}} \] minimum length of cutting time assigned to a machine.

\[ C_{\text{avg}} \] average of \( C_{\text{max}} \) and \( C_{\text{min}} \)

It should be noted that the \( C_{\text{max}} \) and \( C_{\text{min}} \) represent the maximum and minimum machining times of a transfer batch, an entire job or a cluster of jobs assigned to a machine at a time, when using the multi machine loading, single machine loading or cluster based machine loading job allocation policies, respectively.

### 13.4. The Programme of Experiments

The multi-flow control experiments aim to examine and measure the performance of various planning strategies against a number of different flexible batch machining scenarios. However, there is an enormous number of possible permutations for these experiments, based on different data sets and various planning strategies. Furthermore, it is the critical comparison of the results of various subsets of these experiments that provides a better understanding of the performance of the planning strategies, and therefore, a structured framework for the implementation of these experiments can play a vital role in the overall analysis of the results. Thus, a programme of experiments has been developed in order to be able to effectively and efficiently highlight the new knowledge provided by the research through these experiments.

The multi-flow controller supports two categories of the 'predictive' and 'reactive' planning strategies. The manufacturing performance of the reactive planning strategies, namely those based on the combined machine loading(CML) and fixture availability based(FAB) job allocation policies cannot be measured in the same manner as those of predictive planning strategies.

For example, in the case of CML, the jobs are allocated in the first instance, based on the single machine loading(SML) policy, and if there are any late jobs, then CML is used as a reactive function to split the batches, in order to avoid producing any late jobs. Therefore, the performance measure relating to the number of late jobs cannot
meaningfully be used in conjunction with the CML policy. Similarly, in the case of the
FAB policy, the total quantity of available fixtures is a predefined constant value, and
therefore, the fixture inventory performance measure cannot be used as the basis of
comparison of this planning approach with other planning strategies. As a result, the
multi-flow control experiments are solely concerned with the study of the performance of
the predictive planning strategies, namely those based on the multi machine
loading(MML), single machine loading(SML) and the cluster based(CLS) job allocation
policies.

The structure of the analysis of the multi-flow control experimental results is based
on this programme of experiments. The four performance measures, defined in section
13.2, are used to compare the manufacturing performance and highlight the advantages
and disadvantages associated with the each of the planning strategies. Subsequently, the
programme divides the experiments into four major subsets, each concerned with the study
of one of the manufacturing performance measures, as shown in table 13.1. These subsets
of experiments and the major issues of investigation considered in each case are listed
below:-

i) the comparison of tooling requirements based on workpiece and tool dominated
planning strategies. This subset of experiments compares the number of toolkit
exchange activities required by the workpiece and tool dominated strategies, based
on different job allocation policies, joblist characteristics and cell configurations.

ii) the comparison of fixturing requirements based on workpiece and fixture
dominated planning strategies. This subset of experiments compares the total
quantity of fixtures of various types required by the workpiece and fixture
dominated strategies, based on different job allocation policies, joblist
characteristics and cell configurations.

iii) the measurement of the effects of workpiece, fixture and tool dominated planning
strategies on the issue of balancing the workload of machines, based on various job
allocation policies, joblist characteristics, and cell configurations.

iv) the identification of the influences of workpiece, fixture and tool dominated
planning strategies on the number of tardy jobs, based on different due date interval
policies, job allocation policies, and joblist characteristics.
The workpiece dominated strategy is used in each study as the basis of comparison, because this strategy is the most commonly adopted planning approach in flexible machining applications. A large number of experiments, based on the various planning strategies and data sets (defined in section 12.4) are carried out. The number of experiments considered in this thesis is equal to the total number of possible permutations for the parameters of the job allocation policies (JAP), the joblist profiles (JP), cell configurations (CC) and due date intervals (DDI), i.e. :-

\[ \sum EXP = \text{No. JAP} \times \text{No. JP} \times \text{No. CC} \times \text{No. DDI} \]

\[ \sum EXP = 4 \times 3 \times 3 \times 3 = 108 \]

The results of these experiments are analysed and described in the remaining sections of this chapter.
13.5. Analysis of the Results Relating to the Number of Toolkit Exchange Activities (No. TEA)

The first subset of experiments, considers the influences of job allocation policies related to workpiece and tool dominated strategies, namely the multi machine loading (MML), single machine loading (SML), and the cluster based machine loading (CLS), on the number of required toolkit exchange activities (see figure 11.1). It should be noted that clearly in this subset of experiments, the CLS policy constructs the job clusters based on the commonality of the tool requirements of jobs. In order to be able to carry out a comparison of the number of required toolkit exchange activities, the schedules for joblist profiles 1, 2 and 3 based on the end of manufacturing horizon due date interval (i.e DDI 1, see table 12.1) for the 2, 4 and 8 machine cell configurations, are generated using these three job allocation policies. The number of required toolkit exchange activities required in each case for the various job allocation policies, joblist profiles and cell configurations are shown in table 13.2.

<table>
<thead>
<tr>
<th>Reference Number of Major Issue of Investigation</th>
<th>M</th>
<th>Joblist Profile</th>
<th>J</th>
<th>No TEA (MML)</th>
<th>No TEA (SML)</th>
<th>No TEA (CLS)</th>
<th>Ratio of No TEA SML : MML</th>
<th>Ratio of No TEA CLS : MML</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>JP 1</td>
<td>153</td>
<td>306</td>
<td>153</td>
<td>13</td>
<td>1 : 2</td>
<td>1 : 23.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>92</td>
<td>46</td>
<td>7</td>
<td>1 : 2</td>
<td>1 : 13.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>176</td>
<td>88</td>
<td>9</td>
<td>1 : 2</td>
<td>1 : 19.5</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>JP 1</td>
<td>153</td>
<td>515</td>
<td>153</td>
<td>19</td>
<td>1 : 3.4</td>
<td>1 : 27.1</td>
</tr>
<tr>
<td>Toolkit Exchange Activities (No TEA)</td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>184</td>
<td>46</td>
<td>11</td>
<td>1 : 4</td>
<td>1 : 16.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>332</td>
<td>88</td>
<td>14</td>
<td>1 : 3.8</td>
<td>1 : 23.7</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>JP 1</td>
<td>153</td>
<td>889</td>
<td>153</td>
<td>23</td>
<td>1 : 5.8</td>
<td>1 : 38.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>359</td>
<td>46</td>
<td>11</td>
<td>1 : 7.8</td>
<td>1 : 32.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>542</td>
<td>88</td>
<td>15</td>
<td>1 : 6.2</td>
<td>1 : 36.1</td>
</tr>
</tbody>
</table>

Table 13.2: The Experimental Results Relating to the Number of Toolkit Exchange Activities (NoTEA)
A comparison of the number of toolkit exchange activities required by the MML, SML and CLS, job allocation policies, for the applications with 2, 4 or 8 machine cells is shown in figure 13.3. Figure 13.4 illustrates a comparison of the ratio of the required number of toolkit exchange activities when considering two cases of the SML versus MML policies and the CLS, versus MML policies. The analysis of the results of this subset of experiments, summarised in table 13.2, highlights the following:-

i) **the influence of job allocation policy on No. TEA**: regardless of joblist characteristics or cell configuration, MML requires the highest and CLS, the lowest number of toolkit exchange activities to process a joblist, as illustrated in figure 13.2. Additionally, SML requires a lower number of toolkit exchange activities than those required by MML, but is higher than those required by CLS, as shown in figure 13.2. This in turn, indicates that MML always results in the highest tooling cost, whereas CLS, always provides the most economical tooling solution to process a joblist.

ii) **the influence of cell configurations on No. TEA**: regardless of joblist characteristics, the number of toolkit exchange activities required by SML to process a joblist remains constant in cells with different numbers of machines, as shown in figure 13.2. In comparison, the number of toolkit exchange activities required by CLS, increases by a small factor in cells with a higher number of machines. However, the number of toolkit exchange activities related to MML, is significantly increased in cells with a higher number of machines, as illustrated by figure 13.2. This indicates that the tooling costs when using SML, and to some extent CLS, remains constant for various cell configurations, whereas MML results in a huge increase in the tooling costs of the larger cells.

iii) **the influence of joblist characteristics on No. TEA**: regardless of cell configuration, the ratio of the number of toolkit exchange activities required when considering SML versus MML remains more or less constant for different joblist profiles, as illustrated in figure 13.3. However, in the case of CLS, versus MML, this ratio significantly increases for the joblist profiles with a higher number of jobs, as shown in figure 13.3. This indicates that a bigger saving in tooling costs can be achieved by CLS, in cases where there are a large number of short jobs, processed within the MH.
Figure 13.2: The Number of Toolkit Exchange Activities Required by the MML, SML and CLS Job Allocation Policies in a 2, 4 and 8 Machine Cells
Figure 13.3: The Ratio of the Required Number of Toolkit Exchange Activities for SML versus MML, and CLS versus MML Policies in a 2, 4 and 8 Machine Cells
13.6. Analysis of the Results Relating to Total Quantity of Fixtures (TQF)

In a similar manner, the second subset of experiments investigates the influences of the job allocation policies related to the workpiece and fixture dominated planning strategies, namely the MML, SML and CLSf on the minimisation of fixture inventory requirements. Obviously, in this subset of experiments, the CLSf job allocation policy forms job clusters based on the commonality of fixturing requirements of the jobs. A joblist consists of a string of jobs, each of which comprises of a fixed number of transfer batches, depending on the size of part batches included in the jobs. Each transfer batch requires a fixture for its machining operations. Therefore, the total number of fixtures used of various types for a particular joblist is a constant value, and is equal to the sum of the numbers of all the transfer batches of the jobs included in the joblist. However, depending on the adopted planning strategy, this fixture usage throughout the manufacturing horizon can be either the frequent use of a small number of fixtures or an infrequent use of much large number of these fixtures, as illustrated in figure 13.4. As an example of the patterns of fixture usage, the figure 13.4 illustrates the usage of the fixture type F203 for joblist profile 2 in a 4 machine cell over a manufacturing horizon, based on the MML, SML and CLSf.

The Fixture Usage Over Manufacturing Horizon Using the MML, SML & CLS Policies

Fixtuer type F203 / Fixture Capacity = 2
Joblist Profile 2 - 4 Machine cell

Figure 13.4: The Usage of Fixture Type 203 for Joblist Profile 2 Over a Manufacturing Horizon, Based on The MML, SML and CLS Policies
Clearly, MML has resulted in an infrequent use of a large number of fixtures of this type over a series of short periods of time. Whereas, the CLS\(_f\) policy by assigning all the jobs within the joblist requiring this fixture type to a single machine, has provided a frequent use of a much smaller number of fixtures of this type over a long period of time. SML, like CLS\(_f\), assigned an entire job to a machine, and therefore, should provide a similar pattern of fixture usage. However, as can be seen from this example, as jobs are not grouped together based on their fixture requirements in SML, it is likely that two or more machines in the cell require the same fixture type during a short period throughout a manufacturing horizon. Therefore, in this example, SML has resulted in a fixture usage not as efficient as that provided by CLS\(_f\), but not as infrequent or inefficient as MML. It should also be noted that in this example, the maximum number of fixtures required of the type F203 by MML, SML and CLS\(_f\) are 8, 6 and 2 fixtures, respectively. As stated earlier, the total quantity of fixtures required of various types is the sum of the maximum number of fixtures for every fixture type used in the joblist. In order to obtain a broader understanding of fixturing requirements, the schedules for joblist profiles 1, 2 and 3 based on the end of manufacturing horizon due date interval (i.e. DDI 1) for the 2, 4 and 8 machine cell configurations, are generated using these three job allocation policies, and the results relating to fixture inventory requirements are shown in table 13.3.

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Major Issue of Investigation</th>
<th>M</th>
<th>Joblist Profile</th>
<th>TQF (MML)</th>
<th>TQF (SML)</th>
<th>TQF (CLS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Total Quantity of Fixtures of Various Types Required (TQF)</td>
<td>2</td>
<td>JP 1</td>
<td>153</td>
<td>52</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>36</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>44</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>JP 1</td>
<td>153</td>
<td>76</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>72</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>78</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>JP 1</td>
<td>153</td>
<td>126</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>128</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>140</td>
<td>44</td>
</tr>
</tbody>
</table>

**Table 13.3** : The Experimental Results Relating to the Total Quantity of Fixtures of Various Types Required

169
A comparison of the number of the total quantity of fixtures of various types required by the MML, SML and CLSf job allocation policies, for the applications with 2, 4 or 8 machine cells is shown in figure 13.5. The analysis of the results of these subset of experiments, summarised in table 13.3, highlights the following:-

i) *the influence of job allocation policy on TQF*: regardless of joblist characteristics or cell configuration, MML requires the highest and CLSf results in the lowest total quantity of fixtures of various types required to process a joblist, as illustrated in figure 13.5. Additionally, SML requires the total quantity of fixtures of various types that is lower than those required by MML, but is higher than those required by CLSf as shown in figure 13.5. This in turn, indicates that MML always results in the highest fixturing cost, whereas CLSf always provides the most economical fixturing solution to process a joblist.

ii) *the influence of cell configuration on TQF*: regardless of joblist characteristics, the total quantity of fixtures of various types required by SML and CLSf to process a joblist increases by a small factor in cells with a higher number of machines, as shown in figure 13.5. In comparison, the total quantity of fixtures of various types required by MML, is significantly increased in the cells with a higher number of machines, as illustrated by figure 13.5. This indicates that the fixturing costs when using SML and CLSf remains more or less constant for various cell configurations, whereas MML results in a huge increase in the fixturing costs of the larger cells.

iii) *the influence of joblist characteristics on TQF*: the number of transfer batches within a job can be influential when using MML within the different cell configurations. The jobs with a high number of transfer batches can be divided between more machines in larger cells, resulting in a higher total quantity of fixtures required. Whereas, the short jobs with smaller number of transfer batches are divided across a smaller number of machines(even in larger cells i.e. with 8 machines). This is highlighted by the large difference in fixturing requirements of the JP 2(i.e. the joblist with long jobs), based on MML, in the 2 and 8 machine cells. As it can be seen from table 13.3, the same rate of increase has not been required for the fixturing requirements of JP 1(i.e. the joblist with short jobs) in 2 and 8 machine cells.
The Total Quantity of Fixtures of Various Types Required By MML, SML and CLS
Joblist Profiles 1, 2 and 3 - Weekly Due Date Intervals
2 Machine Cell

The Total Quantity of Fixtures of Various Types Required By MML, SML and CLS
Joblist Profiles 1, 2 and 3 - Weekly Due Date Intervals
4 Machine Cell

The Total Quantity of Fixtures of Various Types Required By MML, SML and CLS
Joblist Profiles 1, 2 and 3 - Weekly Due Date Intervals
8 Machine Cell

Figure 13.5: The Total Quantity of Fixtures of Various Types Required by the MML, SML and CLS Job Allocation Policies in a 2, 4 and 8 Machine Cells
13.7. Analysis of the Results Relating to WorkLoad Balancing (WLB)

In theory within machining applications, the optimum workload balance is achieved when an equal amount of machining (cutting) times is assigned to every machine in the cell. However, in reality due to the main reasons of the complex process routes and the wide range of operations and cutting times included in different jobs within the joblists, the likelihood of achieving such an optimum workload balance remains very low. In the application of FMC with a number of identical machines where there are not any process routes defined for the jobs, it is only the range of cutting times included in jobs that are assigned to the machine at a time which influences the workload balance achieved by various planning strategies. As a result in such applications, the difference between the lowest and highest workload, in terms of the amount of machining (cutting) times, assigned to every machine in the cell for a manufacturing horizon can vary between zero (representing the optimum workload balance scenario) and a period equal to the maximum cutting times ($C_{\text{max}}$), representing the worst possible workload balance scenario, as shown in figure 13.6 (Bellman et al. 1982). This maximum length of cutting time assigned to a machine at one instance depends on the following factors:

i) the joblist characteristics: as the length of the jobs included in each joblist can vary in different applications.

ii) the adopted job allocation policy: as MML assigns a portion of a job (i.e. a transfer batch), SML assigns an entire job, and CLS (i.e. the CLS, and CLS$J$) assigns a cluster of jobs to a machine at a time.

Therefore in theory, the joblist profile with the longest jobs (i.e. joblist profile 2), and the job allocation policy which assigns the longest cutting time at a time to a machine, namely CLS (which assigns a cluster of jobs to a machine at a time), should provide the worst workload balance scenario. The schedule patterns generated by the three job allocation policies for joblist profile 2 in a 4 machine cell, are depicted in figure 13.7. Clearly, as it can be seen, using MML due to the relatively small cutting times (of transfer batches) has resulted in the best workload balance in this case. On the other hand, $CLS_t$ due to the large cutting times included in the job clusters produces the worst schedule in terms of workload balancing. The experimental results relating to the workload balance of schedules generated for joblist profiles 1, 2 and 3 in the 2, 4, and 8 machine cells are summarised in table 13.4.
i) The Optimum Workload Balance Scenario

Start of DD (i)                End of DD (i)

Percentage Workload (i)

<table>
<thead>
<tr>
<th>MC1</th>
<th>J23</th>
<th>J1</th>
<th>J37</th>
<th>J12</th>
<th>J25</th>
<th>J32</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC2</td>
<td>J3</td>
<td>J31</td>
<td>J7</td>
<td>J18</td>
<td>J22</td>
<td></td>
</tr>
<tr>
<td>MC3</td>
<td>J13</td>
<td>J33</td>
<td>J15</td>
<td>J2</td>
<td>J24</td>
<td></td>
</tr>
<tr>
<td>MC4</td>
<td>J9</td>
<td>J11</td>
<td>J27</td>
<td>J20</td>
<td>J26</td>
<td>J16</td>
</tr>
</tbody>
</table>

ii) The Worst Work Balance Scenario

Start of DD (i)                End of DD (i)

Percentage Workload (i)

<table>
<thead>
<tr>
<th>MC1</th>
<th>J23</th>
<th>J1</th>
<th>J37</th>
<th>J12</th>
<th>J25</th>
<th>J32</th>
<th>J5 (C max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC2</td>
<td>J3</td>
<td>J31</td>
<td>J7</td>
<td>J18</td>
<td>J22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC3</td>
<td>J13</td>
<td>J33</td>
<td>J15</td>
<td>J2</td>
<td>J24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC4</td>
<td>J9</td>
<td>J11</td>
<td>J27</td>
<td>J20</td>
<td>J26</td>
<td>J16</td>
<td></td>
</tr>
</tbody>
</table>

Figure 13.6: The Best and the Worst Workload Balance Scenarios within FMC applications
i) The Multi Machine Loading (MML)

![Diagram of MML](image1)

ii) The Single Machine Loading (SML)

![Diagram of SML](image2)

iii) The Cluster Based Machine Loading (CLS)

![Diagram of CLS](image3)

Figure 13.7: The Scheduling Patterns Generated by the MML, SML, and CLS Job Allocation Policies
A comparison of the difference in the workload of machines based on the MML, SML, CLS, and CLSy job allocation policies, for the applications with 2, 4 or 8 machine cells is shown in figure 13.8. The analysis of the results of this subset of experiments, summarised in table 13.4, highlights the following:

i) **the influence of job allocation policies on WLB**: regardless of joblist characteristics or cell configuration, MML always produces the lowest difference in workload of machines, as illustrated in figure 13.8. On the other hand, CLS (i.e. both CLS, and CLSy) results in the highest difference in workload of machines, and in comparison, CLSy provides an even worse result than those of CLS, as shown in figure 13.8. Finally, SML often results in a difference of workload higher than those of MML, but lower than those of CLS, as shown in figure 13.8.

ii) **the influence of joblist characteristics on WLB**: regardless of cell configuration, the joblist profiles which includes shorter jobs (namely JP1) with smaller $C_{\text{avg}}$ (i.e. average of $C_{\text{min}}$ and $C_{\text{max}}$) results in the least difference in workload of machines when using SML or CLS, as shown in table 13.3 and figure 13.5. On the other hand, the joblist profile with the largest $C_{\text{avg}}$, namely JP 2, provides the highest difference in workload of machines. This indicates that the most optimum achievable workload balance is directly related to the value of $C_{\text{avg}}$, when using SML and CLS.

### Table 13.4: The Experimental Results Relating to Workload Balancing

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Major Issue of Investigation</th>
<th>$M$</th>
<th>Joblist Profile</th>
<th>Difference in Workload MML(Hrs)</th>
<th>Difference in Workload SML(Hrs)</th>
<th>Difference in Workload CLS(Hrs)</th>
<th>Difference in Workload CLSy(Hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Workload Balancing (WLB)</td>
<td>2</td>
<td>JP 1</td>
<td>0.8</td>
<td>3.5</td>
<td>6.7</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>1.3</td>
<td>9.2</td>
<td>10.7</td>
<td>15.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>0.7</td>
<td>4.8</td>
<td>8.9</td>
<td>12.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>JP 1</td>
<td>0.9</td>
<td>4.2</td>
<td>6.5</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>1.5</td>
<td>12.1</td>
<td>12.1</td>
<td>13.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>0.7</td>
<td>5.6</td>
<td>7.4</td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>JP 1</td>
<td>0.8</td>
<td>5.1</td>
<td>7.5</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>1.4</td>
<td>10.8</td>
<td>12.9</td>
<td>14.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>1.1</td>
<td>5.5</td>
<td>8.2</td>
<td>10.8</td>
</tr>
</tbody>
</table>
The Difference in Workload Based on MML, SML, CLS, and CLSf Job Allocation Policies

**2 Machine Cell**

![Graph showing the difference in workload based on MML, SML, CLS, and CLSf for 2 machine cells.](image)

**4 Machine Cell**

![Graph showing the difference in workload based on MML, SML, CLS, and CLSf for 4 machine cells.](image)

**8 Machine Cell**

![Graph showing the difference in workload based on MML, SML, CLS, and CLSf for 8 machine cells.](image)

**Figure 13.8:** The Difference in Workload Based on the MML, SML, CLS, and CLSf Policies in the 2, 4 and 8 Machine Cells
13.8. Analysis of the Results Relating to the Number of Tardy Jobs (No. TJ)

The final subset of experiments examines the influence of the multi-flow planning strategies on the number of tardy jobs produced in a wide range of flexible batch machining scenarios. As stated earlier, in these experiments a job which is failed to meet its due date by a period equal or greater than the machining time of a single transfer batch, is referred to as a tardy job. This is due to the fact that with the combined machine loading (CML) policy, the jobs can be divided into a number of smaller transfer batches and assigned to different machines, in order to avoid lateness of jobs. However, the smallest unit that a job is allowed to be divided into is a single transfer batch, and therefore, if a job is late by a period smaller than the machining time of a single transfer batch the CML policy could not be used.

It should also be noted that the number of tardy jobs in each experiment must be considered in conjunction with the total number of jobs within the joblist used in that experiment. For example, in the case based on joblist profile 1 with 153 jobs, the adoption of a planning strategy which results in generating 10 tardy jobs (i.e. 6.5% of total jobs), maybe acceptable. However, if the same number of tardy jobs was generated in the case based on joblist profile 2 with 46 jobs (i.e. 22% of total jobs), the schedules would not be acceptable. Therefore, a parameter termed percentage of tardy jobs (PTJ) is used in the analysis of results of this subset of experiments to compare the performance of the various planning strategies. This parameter is equal to:

\[ PTJ = \frac{\text{No. TJ}}{J} \times 100 \]

Three due date interval policies are implemented within this subset of experiments, namely DDI 1, DDI 2, and DDI 3 (see section 12.4.1). The schedule patterns generated by these three due date interval policies for joblist profile 3 in a 4 machine cell are illustrated in figure 13.9. Clearly, as it can be seen, the DDI 1 is the least restrictive policy in terms of job allocation process, as jobs can start and finish in any order throughout the week, resulting in the least number of tardy jobs. On the other hand, the DDI 3 is the most restrictive policy as jobs not only have to be finished by the end of certain due date interval but also they cannot be started before the start of that due date interval, and therefore, resulting in the largest number of tardy jobs (these jobs are shaded in see figure 13.9).
i) Schedule Pattern Using DDI 1 Policy

![Image of Schedule Pattern Using DDI 1 Policy]

ii) Schedule Pattern Using DDI 2 Policy

![Image of Schedule Pattern Using DDI 2 Policy]

iii) Schedule Pattern Using DDI 3 Policy

![Image of Schedule Pattern Using DDI 3 Policy]

Figure 13.9: Schedule Patterns Generated Based on the SML Job Allocation Policy and Using the DDI 1, DDI 2 and DDI 3 Policies
In general, the following factors are the major reasons which could result in producing tardy jobs within a schedule:

i) the workload allocated to a due date interval through the aggregate planning process is more than the total capacity available within the due date interval. The investigation of the performance of the aggregate planning strategies is outside the scope of these thesis, and therefore, all the multi-flow control experiments are based on a 90-95% workload capacity.

ii) the difference in the workload assigned to the individual machines in the cell by a planning strategy has resulted in one or more machines to finish well in advance of the due date but others failing to finish on time, as shown in figure 13.10.

iii) the implementation of a job allocation policy such as the cluster based policy restricts the sequence with which jobs are processed, and could result in a large number of tardy jobs, as illustrated in figure 13.11.

In figure 13.11 the jobs in the joblists with daily due dates are grouped based on their tool commonality requirements, to form 6 job clusters. However, as it can be seen while allocating these job clusters to the machine, some of the jobs (e.g. J16 and J25 in the job cluster 4, and J15, J17 and J27 in the job cluster 6) cannot even start to be processed before their due dates, and therefore, the entire job is late. On the other hand, there are a few jobs (e.g. J28, J24, J23), due to the long cutting times included in a job cluster, are partially late. Therefore, in theory within the multi-flow control experiments, the scenarios that are based on the use of CLS, joblist profile 2 which consists of the longest jobs (see section 13.7 on the influences of joblist characteristics on workload balancing) and DDI 3 which is the most restrictive due date interval policy, should produce the largest number of tardy jobs.

In order to be able to carry out a comparison of the performance of the multi-flow planning strategies with respect to the various due date interval policies, the schedules for joblist profiles 1, 2 and 3 within the 2, 4 and 8 machine cells, based on the MML, SML, CLS, and CLSf job allocation policies, using DDI 1, DDI 2 and DDI 3 have been generated. The results relating to the number of tardy jobs generated in each experiment, are summarised in table 13.5.

A comparison of the percentage of tardy jobs (i.e. the PTJ parameter) by the MML, SML, CLS, and CLSf, for the joblist profiles 1, 2 and 3 in the applications with 2, 4 or 8 machine cell, based on the DDI 1, DDI 2 and DDI 3 policies, is illustrated in figures 13.12,
13.13 and 13.14. The analysis of the results of this subset of experiments, shown in table 13.5, highlights the following:

i) \textit{the influence of due date intervals on No. } T_f \textit{: regardless of job allocation policies or joblist characteristics, as expected, } DDI 1 \textit{results in the least number of tardy jobs. This is clearly shown in figure 13.12, where in few scenarios and only the cluster based job allocation policies have resulted in a small number of tardy jobs. On the other hand, the use of } DDI 3 \textit{has resulted in the largest number of tardy jobs as indicated by figure 13.14, where in the majority of scenarios almost all of the job allocation policies have produced a number of tardy jobs. In comparison, the schedules based on } DDI 2 \textit{, have a fewer number of tardy jobs than those based on } DDI 3 \textit{, and yet still, they have a significantly higher number of tardy jobs than those based on } DDI 1. \textit{This indicates that the selection of due date intervals can severely restrict the range of possible planning strategies with which schedules can be generated.}

ii) \textit{the influence of job allocation policy on No. } T_f \textit{: regardless of the due date interval policies, the joblist characteristics or the cell configurations, as expected } MML \textit{results in the least number of tardy jobs, as illustrated in figures 13.12, 13.13 and 13.14. This also indicates that the } MML \textit{policy results in the least work in progress and mean flow time of jobs. On the other hand, the cluster based job allocation policies(i.e. both the } CLS\gamma \textit{ and } CLS\delta \textit{) generate the highest number of tardy jobs, as illustrated in figures 13.12, 13.13 and 13.14. This is due to the restrictions in the sequence with which jobs can be processed(see figure 13.11), and that cluster based policies often result in a large difference of workload of machines(see section 13.7 on the influences of job allocation policies on workload balancing). Additionally in every experiment, } SML \textit{has resulted in a higher number of tardy jobs than those of } MML, \textit{but fewer than those produced by the cluster based policies, as shown in figures 13.12, 13.13 and 13.14. This is because, as indicated in section 13.7, } SML \textit{results in a higher differences in workload of machines than those of } MML, \textit{and therefore, a higher number of tardy jobs than those by } MML. \textit{However, } SML \textit{does not restrict the sequence of processing the jobs in the same manner to that of cluster based job allocation policies, and therefore, produces fewer tardy jobs than the cluster based policies.}
the influence of joblist characteristics on No. TJ: regardless of due date interval, job allocation policy or the cell configuration, the joblist profile which includes shorter jobs(namely JP1) with smaller $C_{avg}$ (i.e. average of $C_{min}$ and $C_{max}$) results in the least number of tardy jobs, and the joblist profile with the largest $C_{avg}$, namely JP 2, provides the highest number of tardy jobs, as shown in figures 13.12, 13.13 and 13.14. This indicates that the number of generated tardy jobs using any of the planning strategies is directly related to the ratio of the value of $C_{avg}$ and the length of due date intervals (i.e. $C_{avg} / T (i)$). Therefore, the higher values of this ratio result in the larger number of tardy jobs while using any of the planning strategies.
Figure 13.10: Tardy Jobs Due to the Difference in the Workload Assigned to the Machines

Figure 13.11: Tardy Jobs Due to the Use of Cluster Based Job Allocation Policy
<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Major Issue of Investigation</th>
<th>$M$</th>
<th>Due Date Interval</th>
<th>Joblist Profile</th>
<th>$J$</th>
<th>No. TJ MML</th>
<th>No. TJ SML</th>
<th>No. TJ CL$\text{I}$</th>
<th>No. TJ CL$\text{f}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 1</td>
<td>153</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 1</td>
<td>153</td>
<td>0</td>
<td>1</td>
<td>21</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>0</td>
<td>3</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>0</td>
<td>2</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 1</td>
<td>153</td>
<td>0</td>
<td>7</td>
<td>43</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>1</td>
<td>14</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>0</td>
<td>10</td>
<td>36</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 1</td>
<td>153</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 1</td>
<td>153</td>
<td>0</td>
<td>1</td>
<td>32</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>0</td>
<td>5</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>0</td>
<td>2</td>
<td>19</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 1</td>
<td>153</td>
<td>0</td>
<td>11</td>
<td>49</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>2</td>
<td>17</td>
<td>19</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>1</td>
<td>14</td>
<td>33</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 1</td>
<td>153</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 1</td>
<td>153</td>
<td>0</td>
<td>2</td>
<td>37</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>0</td>
<td>7</td>
<td>15</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>0</td>
<td>3</td>
<td>23</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 1</td>
<td>153</td>
<td>0</td>
<td>15</td>
<td>61</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 2</td>
<td>46</td>
<td>3</td>
<td>19</td>
<td>21</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JP 3</td>
<td>88</td>
<td>2</td>
<td>18</td>
<td>37</td>
<td>52</td>
</tr>
</tbody>
</table>

Table 13.5: The Experimental Results Relating to the Number of Tardy Jobs
Figure 13.12: The Percentage of Tardy Jobs Based on MML, SML, CLS₁ and CLSᵢ in 2, 4 and 8 Machine Cells, Using the DDI 1 Policy
The Percentage of Tardy Jobs Based on MML, SML, CLSt and CLSf Policies
Joblist Profiles 1, 2 and 3 - DDI 2 Policy
2 Machine Cell

The Percentage of Tardy Jobs based on MML, SML, CLSt and CLSf Policies
Joblist Profiles 1, 2 and 3 - DDI 2 Policy
4 Machine Cell

The Percentage of Tardy Jobs Based on MML, SML, CLSt and CLSf Policies
Joblist Profiles 1, 2 and 3 - DDI 2 Policy
8 Machine Cell

Figure 13.13: The Percentage of Tardy Jobs Based on MML, SML, CLSt and CLSf in 2, 4 and 8 Machine Cells, Using the DDI 2 Policy

185
Figure 13.14: The Percentage of Tardy Jobs Based on MML, SML, CLS, and $CLS_f$ in 2, 4 and 8 Machine Cells, Using the DDI 3 Policy
Chapter 14

CONCLUDING DISCUSSION

14.1. Introduction

This chapter discusses the contributions of the research reported in this thesis, and brings together a number of the major research issues, in order to allow a set of conclusions to be formulated. The research has been carried out in two phases, namely:

i) the realisation of a suite of software modules to demonstrate and investigate the proposed novel planning and control structure, reported in chapters 7-11; and

ii) the design and implementation of a large number of computer-based experiments, to assess the effectiveness and efficiency of the novel planning strategies generated by the research, reported in chapters 12 and 13.

The initial part of the chapter reviews the research concepts and provides comments on the effectiveness of software modules generated to examine these concepts. The final part of the chapter utilises the experimental observations outlined in chapter 13 to provide a number of planning rules to be used in conjunction with the multi-flow controller.

14.2. Realisation of an Interactive Multi-Flow Control Structure

The literature survey in chapter 2, and in particular the specific quotations from references provided in section 5.2, have illustrated the emergence of a common view that the planning and control of the flows for workpieces, fixtures and cutting tools within machining facilities must be more closely linked. This research has investigated the requirements for design and specification of such a common planning and control environment, resulting in the implementation of the 'multi-flow controller'.
The recent research and developments in cell control, and in particular that of the 'Leitstand' initiative in Europe, has indicated a trend away from the 'more automated' control structures to 'more interactive' ones. This has resulted in the utilisation of graphical-based interfaces within control systems, in order to allow for rapid interactions and ease of use within the shop floor environment. Although, the design and specification of the multi-flow controller was carried out independently from the 'Leitstand' work, there is a remarkable similarity between the major modules of a leitstand system, described in section 2.2.5, namely the database manager, scheduler generator, schedule editor, evaluation component and graphical interface, with those of the multi-flow controller, namely the manufacturing database, multi-flow scheduler, production sequence editor, multi-flow simulation model and multi-flow control user interface. This proves that the work by the two independent research programmes into requirements for interactive cell control has generated similar specifications.

Finally, due to the pressures of the world market for staying competitive in terms of providing a wide range of products at lowest possible cost, and being flexible towards changes in customer demands, this research has identified that any futuristic planning and control structure must not only utilise any off-line optimisation procedures such as the use of clustering algorithms for part, tool and fixture groupings, but must also have real-time capabilities to deal with the dynamic needs of manufacturing systems. As a result, the multi-flow control research has integrated the production scheduling and production activity control to provide a flexible structure, where a hybrid approach capable of utilising the advantages offered by both off-line and on-line techniques, can be implemented.

14.3. Parallel Generation of Schedules for Workpieces, Tools and Fixtures

As the core module of the multi-flow control, a scheduling system was required to be able not only to generate schedules for jobs(workpiece schedule), but also the schedules required for the cutting tools and fixtures. The generation of a formal tool schedule and fixture schedule organises the activities in the tool room and fixturing stations much more effectively, which in turn, harmonises the interactions of the three principal flows within the machining cell. The research has investigated a novel approach to generate these schedules simultaneously, in order to minimise the time taken and manual planning effort.
required to develop these schedules. In order to achieve this, a scheduling model was required to represent the machining cell activities in much more detail than those of existing schedulers. To generate such a scheduling model, simulation techniques have been identified by the research as the only viable and suitable tool to be used. The simulation based ‘multi-flow scheduler’ generated by the research, as described in chapter 8, has demonstrated the potential advantages for the concept of the ‘parallel generation of schedules’.

14.4. Decision Support for the Cell Manager

The software modules of the multi-flow controller have been designed and implemented to act as an advisory system to the cell manager. The multi-flow controller supports a wide range of planning strategies varying in scheduling constraints, job allocation policy and sequencing rules. To aid the cell manager in selecting the most appropriate planning strategies for specific production requirements, a range of manufacturing performance measures has been identified. A simulation model has been designed and implemented, as described in chapter 9, to provide the cell manager with these performance measures based on a set of planning decisions. The role of the multi-flow simulation models has not been defined as a part of every schedule generation process, but as a decision support tool which the cell manager can utilise as often as required.

14.5. An Information Model to Support the Multi Flow Controller

One major issue that needs to be considered in every scheduling process, is the time required to generate the schedules. Scheduling algorithms and procedures, due to the complexity of mathematical calculations involved, require significant computing power and often take a long time to generate schedules. In addition, these procedures need to handle a large amount of orders, process and product data. Therefore, to keep the schedule generation time to an acceptable period, it was identified that a fast and efficient information management system was required as one of the modules of the multi-flow controller. Furthermore the multi-flow scheduler, in addition to the common planning information related to jobs, requires data on tool and fixture requirements. An information
model based on the data requirements of the multi-flow controller has been developed to identify this additional data and relates them to the common planning information in a logical manner, as shown in figure 10.3.

The tooling and fixturing information is often kept in a number of files within different software packages such as CTMS, and CAFP systems. In a complete CIM structure, the multi-flow controller can access these data files via appropriate information gateways. However, for the purpose of the research reported in this thesis, a manufacturing database has been designed and implemented, based on the data structure contained in the multi-flow control information model, as described in chapter 10. This database has also been used to integrate the other modules of the multi-flow controller, and can provide the most up-dated information to the cell manager, as and when required.

14.6. Planning Strategies for Economic Manufacture

In most manufacturing applications, production objectives can vary frequently from meeting delivery dates (regardless of manufacturing cost) to the most economical methods of production. In addition, manufacturing companies are expected to produce a wide range of part types over a short period. As a result, a larger number of cutting tools and fixtures and related tooling and fixturing activities are required to be controlled in this short period. Therefore, any reduction in tool and fixturing requirements, not only has a direct effect on the manufacturing cost, but also could result in reductions in machine down time due to delays in tool and fixture availability.

The multi-flow controller has provided the flexibility of being able to adopt a number of novel tool dominated and fixture dominated planning strategies for economy in tooling and fixturing cost, or to select the more costly workpiece dominated strategies to meet the rapid completion dates of jobs, as described in chapter 11. This flexibility is particularly advantageous in applications where the job throughput requirements for a manufacturing horizon changes significantly on a regular basis. Typical examples of such applications are small manufacturing companies that are used as subcontractors by larger businesses. The selection of one of these planning strategies is left with the cell manager based on the specific short term manufacturing requirements.
14.7. Design and Implementation of Computer-Based Experiments

In the experimentation stage of the research, it was identified that in order to test and validate the research concepts, and to measure the performance of the multi-flow planning strategies against various manufacturing scenarios, a variety of manufacturing challenges were required. These manufacturing challenges must differ in terms of business configurations, manufacturing data relating to parts, tools and fixture types, machining operations and cell configurations. This variety of manufacturing challenges could not have been provided through a limited number of industrial case studies. As a result, a comprehensive programme of computer-based experiments has been designed and implemented to highlight the new knowledge provided by the research. This was achieved by synthesising a large number of data sets based on a wide range of manufacturing scenarios, as described in chapter 12. Furthermore, a structured programme of experiments was developed to effectively and efficiently analyse the results of these experiments, as described in section 13.3. The experimental studies have been concerned with the study of the performance of the multi-flow planning strategies, namely those based on the multi machine loading(MML), single machine loading(SML) and the cluster based(CLS) job allocation policies.

14.8. Analysis of the Results of the Experiments

The results of the experiments could have been interrogated based on a large number of manufacturing performance measures generated by the multi-flow simulation model. In order to effectively and efficiently compare the performance of the planning strategies, from this large number of performance measures, a limited set of critical measures has been adopted. These critical measures, namely the number of toolkit exchange activities, the total quantity of various fixture types, the balance of workload assigned to the machines and the number of tardy jobs, have been used as indicators to a wider range of performance measures, as described in section 13.2. The observations made based on the results of the experiments, outlined in sections 13.4 - 13.8, have proved the following planning rules.
14.8.1 Planning Rules Concerning the Cluster Based Policies

The use of the two cluster based job allocation policies, namely the tool cluster based policy (CLS_t) and fixture cluster based policy (CLS_f), significantly reduce the tooling and fixturing requirements of processing a specific joblist. This reduction of tooling and fixturing requirements is even greater in the applications with larger machining cells (4-8 machines) and in the scenarios where a larger number of short jobs are needed to be processed. However, the clustering algorithms used within the multi-flow controller for CLS_t and CLS_f, produce greater difficulties in balancing the workload of the machines. This lack of workload balancing is more significant in applications with larger machining cells and in scenarios where a small number of long jobs are required to be processed. In addition, the use of cluster based job allocation policies in applications with restricted due date intervals results in a larger number of tardy jobs. This number of tardy jobs is even higher in scenarios where in addition to a completion date, a starting date is also specified for each job. This is due to two reasons, firstly the resequencing of the jobs into a number of job clusters severely restricts the order in which jobs can be processed (see figure 13.11). Secondly, the failure in balancing the workload results in one or more machines finishing well in advance of the due date, but others failing to finish on time. In general, the results of experiments have shown that the use of the cluster based policies is most advantageous in applications:

i) where a larger number of short jobs are required to be processed.
ii) with larger machining cells (4-8 machines).
iii) where jobs can be processed in any order throughout the manufacturing horizon, with no intermediate starting dates or due dates.
iv) where interleaving jobs can be added to the machines with the least workload throughout a manufacturing horizon.

14.8.2 Planning Rules Concerning the Multi Machine Loading Policy

The use of the multi machine loading (MML) policy significantly reduces the work-in-progress inventory and enables a balanced workload to be assigned to the machines, regardless of the size of the cell. Furthermore, MML provides flexibility to generate schedules with hardly any tardy jobs for applications with very restricted due date intervals. However, MML significantly increases the tooling and fixturing requirements.
for processing a specific joblist. This increase of tooling and fixturing requirements is not as significant in the applications with smaller machining cells (2 machines) and in scenarios where a small number of long jobs are required to be processed. In general, the research has proven that the use of MML is most advantageous in applications:

i) where a low work-in-progress is highly desirable due to the high cost of raw material or shortage of space.

ii) where jobs need to be processed in a very restricted order due to a specific pattern for the starting dates and completion dates of the jobs.

iii) with smaller machining cells (2 machines).

iv) where a small number of long jobs, i.e. small number of larger part batches, are required to processed.

14.8.3 Planning Rules Concerning the Single Machine Loading Policy

In terms of the potential manufacturing performance, the single machine loading (SML) policy falls in between MML and CLS, based on all the critical performance measures considered in the experiments. In every scenario, SML could not provide quite the same efficiency in minimisation of the tooling and fixturing requirements as CLS, but resulted in significantly less tooling and fixturing requirements than those of MML. On the other hand, SML could not achieve the balance of the workload possible through the use of MML, but resulted in a lower difference of workload in comparison to the schedules generated by CLS. Similarly, in terms of the number of tardy jobs, the use of SML does not result in a large percentage of tardy jobs in applications with restricted due date intervals, as is the case for CLS. But, in applications with a high ratio of $C_{avg}$ and the length of due date intervals (i.e. $C_{avg} / T(i)$), the use of SML was not as efficient as that of MML. In any case, the use of SML has two significant advantages over the use of CLS and MML, namely:

i) with cluster based policies the clustering algorithm is applied to a part and tool matrix or to a part and fixture matrix to group the jobs based on either their tooling requirements or their fixturing requirements. Therefore, for example with CLS$_T$, it cannot be guaranteed that fixture inventory requirements is minimised. Similarly, the CLS$_F$ does not ensure the rationalisation of tool usage. However, although SML cannot provide the same efficiency in terms of minimisation of tooling and fixturing requirements, when considered individually with CLS$_T$ or CLS$_F$, the use of
Chapter 14

SML results in a simultaneous reduction of both tool and fixture requirements when compared with MML.

ii) Unlike MML which has a better manufacturing performance in smaller cells, or the use of CLS which is more advantageous in larger cells, SML can be used in any size of cell with very similar manufacturing performance.

Based on these two SML characteristics, the research has concluded that SML should be used as the *de facto*(default) job allocation policy within the multi-flow controller. The decision should be made by the cell manager, at the start of a planning phase to divert from this policy to :-

- MML if low work-in-progress is desirable, or a restriction in the order with which jobs must be processed has been imposed by a starting date or a due date.
- CLS if there is a high level of commonality in the tooling or fixturing requirements of jobs, with no due date restrictions.
- CML if there is a limited number of tardy jobs when using SML.
- FAB if there is a restriction on the availability of required fixtures of various types.
Chapter 15

CONCLUSIONS

15.1. Introduction

The conclusions drawn from the research and computer-based experiments are presented in this chapter.

15.2. Conclusions

The conclusions drawn from this research are as follows:

i) An integrated structure for the planning and control of workpieces, fixtures and cutting tools has been proposed, and shown to have a strong potential for the harmonisation of these three material flows within flexible machining cells. A hybrid approach has been utilised for the design and implementation of this novel control structure, which is capable of taking advantage of benefits offered by both the off-line optimisation planning and on-line dynamic control techniques.

ii) The design and specification of the multi-flow control structure has identified the need for an interactive approach to cell control, in order to maximise its potential capabilities and flexibility. Thus, a suite of software modules, termed the multi-flow controller, has been realised to act as an advisory system to interact with the cell manager, and to incorporate the most updated information on cell status and localised knowledge for refining schedules.

iii) This concept of ‘parallel generation of schedules’ introduced by the research, provides a solution to minimise the time and manual planning effort required for producing schedules, and reduces the source of operational errors, caused by the independent/unsynchronised planning of the three related principal flows. This
research concept has been achieved through utilisation of the recent advancements in simulation based scheduling and information technology. Thus, as the main core of the multi-flow controller, a simulation based scheduling system has been designed and implemented which is capable of simultaneous generation of tool schedules and fixture schedules, in addition to the common workpiece schedules.

iv) The use of simulation techniques as a decision support facility in planning and control procedures has been demonstrated. A multi-flow simulation model has been shown to be a powerful method for measuring the manufacturing performance of machining cells. Furthermore, the capability of introducing randomness via statistical distributions in this simulation model, has proved to be vital in gaining an insight into cell performance based on possible manufacturing disturbances such as machine breakdowns, shortage of materials or tools.

v) The feasibility of the implementation of such a multi-flow control structure is only seen possible with the aid of a fast and efficient data manager. The research has defined a dual role for an information model in a neutral format of an EXPRESS data model, namely in the design and implementation of the manufacturing database, and in the integration of the multi-flow controller into a CIM structure using STEP standards.

vi) The research has identified a flexible framework of planning strategies, and has investigated an approach where production objectives can vary from meeting delivery dates (regardless of manufacturing cost) to the most economical methods of production. A range of novel job allocation policies has been proposed to provide the flexibility of being able to adopt tool dominated and fixture dominated planning strategies for economy in tooling and fixturing cost, or to select the more costly workpiece dominated strategy, to meet the rapid completion dates of jobs.

vii) A systematic approach for the design and implementation of a series of computer-based experiments has been proposed and shown to be a powerful method in providing a range of manufacturing challenges required to examine the performance of various planning strategies. The potential effectiveness of such experiments depends on the synthesis of a number of data sets that closely relates to data values in existing flexible batch machining applications and represents a wide range of manufacturing challenges in terms of business configurations,
manufacturing data relating to parts, tools and fixture types, machining operations and cell configurations. However, the enormous number of possible permutations of these data sets has highlighted the necessity for a structured implementation programme in such experimental studies.

viii) In order to be able to effectively analyse the results of the experiments, a limited set of critical manufacturing performance measures has been identified. The analysis of the results based on these measures, namely the number of toolkit exchange activities, the total quantity of various fixture types, the balance of workload assigned to the machines and the number of tardy jobs, has proved the suitability of a number of planning rules relating to CLS, MML and SML job allocation policies for various manufacturing scenarios.

ix) Experimental observations have shown that the use of the cluster based policies is most advantageous in applications: where a larger number of short jobs are required to be processed; with larger machining cells(4-8 machines); where jobs can be processed in any order throughout the manufacturing horizon, with no intermediate starting dates or due dates or no penalties for having late jobs; and where interleaving jobs can be added to the machines with the least workload throughout a manufacturing horizon.

x) The research has demonstrated that the use of MML is most advantageous in applications: where low work-in-progress is highly desirable due to the high cost of raw material or shortage of space; with smaller machining cells(2 machines); where jobs need to be processed in a very restricted order due to a specific pattern for the starting dates and completion dates of jobs; and where small number of larger part batches, are required to processed.

xi) Based on the overall experimental results it has been shown that SML should be used as the de facto (default) job allocation policy within the multi-flow controller. The decision should be made to divert from this policy to: MML if low work-in-progress is desirable or a restriction in the order with which jobs must be processed has been imposed by a starting date or a due date, CLS if there is a high level of commonality in the tooling or fixturing requirements of jobs, CML if there are a limited number of tardy jobs when using SML, and finally FAB if there is a restriction on the availability of required fixtures of various types.
Chapter 16

FURTHER WORK

16.1. Introduction

This chapter suggests a number of work areas based on the wide range of research issues reported in this thesis, as the most valuable extensions to the scope of the research.

16.2. Scheduling Rules Related to Transporters

The extension of the context of the multi-flow scheduling work to include issues relating to the planning of transporters, is seen as an important line of progress for the research. The publications by Ulusoy and Bilge(1993), Sabuncuoglu and Hommertzheim(1992), King and Wilson(1991) provide a number of scheduling rules related to transporter flow which can be included in the scheduling model of the multi-flow controller. This would enable the multi-flow scheduler to simultaneously generate transporter schedules, in addition to, the workpiece, tool and fixture schedules. Inclusion of constraints relating to transporters would also provide the opportunity to explore the possibility of generation of a job allocation policy based on transporter availability.

16.3. Application of the Multi-Flow Controller within Traditional Manufacturing Systems

Although the research reported in this thesis has investigated the potential advantages of a multi-flow control structure in modern flexible machining cells, the basic research concepts and planning strategies can be applied to the applications of jobshops and more conventional flexible manufacturing facilities with non-identical machines. In fact, the
harmonisation of the three principal flows within more traditional manufacturing systems may prove to be more fruitful in terms of savings in operational costs and increase production output through higher resource utilisation.

16.4. Generation of a Cost Model Based on the Multi-Flow Planning Strategies

Within the reported research the savings in manufacturing cost have been measured indirectly based on the reduction of tooling and fixturing requirements. However, this can be significantly enhanced by consideration of costing information such as the cost of tools and fixtures, cost of manual fixturing and tooling activities per unit time, cost of machine down times per unit time, financial penalties involved in having late jobs, etc. The generation of a cost model based on the multi-flow planning strategies allows the manufacturing performance to be measured based on a total cost which can be a very desirable data item for any cell manager.

16.5. Integration of the Multi-Flow Controller in a CIM Structure

The design and specification of the multi-flow controller has been carried out so it fits into the CIM concept by connecting the scheduling module with the shop floor data collection facilities and related CAD/CAM software modules. The generation of the multi-flow control information model in the form of the EXPRESS data model, allows appropriate information gateways to be designed for the multi-flow controller, using the emerging manufacturing integration standards based on the STEP physical file formats, as outlined in appendix 4.

16.6. Utilisation of Advanced Clustering Algorithms

The use of cluster algorithms in the multi-flow control research has been based on the previous research at Loughborough University (de Souza 1988, Ozbayrak 1993) which utilises the established Rank Order Cluster Algorithm (King 1980). However, recent
research by Macchiaroli and Riemma (1994), Shargal et al. (1995) and Arizona et al. (1995) has suggested more modern clustering algorithms which are applied in different applications. Therefore, further enhancement in tool and fixture dominated strategies may be achieved by investigation of these existing clustering algorithms to identify a procedure which provides similar (or improved) tooling reduction and allows the job clusters to be formed in such a way that more balanced workloads are assigned to machines.

16.7. Software Implementation of the Combined Machine Loading Policy

The concept of combined machine loading, described in chapter 11, was investigated in the later part of this research. Although, this novel policy has not been investigated exhaustively, it shows significant potential for future planning and control procedures. Due to time constraints on the multi-flow control research programme, it was not possible to develop a software implementation for this policy. At present, the task of identifying the jobs to be divided and split into part batches, needs to be carried out manually by the cell manager. However, it is feasible to develop a software routine that having allocated the jobs based on the single machine loading policy, identifies the late jobs and uses an algorithm to split part batches as and when required. Further consideration is also required to explore alternative selection rules used to identify the jobs which must be divided, besides those that are suggested by this research.
REFERENCES


Anon, 1986, Modular fixtures for special parts, American Machinist & Automated Manufacturing, June, 82-84.


French, S., 1982, Sequencing and scheduling: An introduction to the mathematics of the job shop, (West Sussex: Ellis Horwood Ltd).


Herman, J., Safka, Z., 1982, Dynamic rescheduling of operations - a computer approach to production control, Engineering Costs and Production Economics, 131-139.


References


Lundrigan, R., 1986, What is this thinking called OPT?, Production and Inventory Management, 27 (2), 2-12.


References


Painter, C.W., April 1987, Last rites for MRP, Production Engineer, 33-34.


Rahimifard, S., Newman, S.T., Bell, R., 1992, Data requirements for the design and
modelling of flexible machining cells, *Proceedings of the 8th International
Conference on Computer-Aided Production Engineering*, V.C. Venkatesh & J.A.
Rajgopal, J., Bidanda, B., 1991, On scheduling parallel machines with two setup classes,
Ram, B., Sarin, S., Chen, C.S., 1990, A model and a solution approach for the machine
loading and tool allocation problem in a flexible manufacturing system,
Randhawa, S.U., McDowell, E.D., 1990, An investigation of the applicability of expert
system to job shop scheduling, *International Journal of Man-Machine Studies*,
32, 203-213.
Ranky, P.G., 1988, A generic tool management system architecture for flexible
manufacturing systems (FMS), *Robotica*, 6, 221-234.
Ranky, P.G., 1990, Flexible Manufacturing Cells and Systems in CIM, (Guildford-UK:
CIMware Limited).
Raynolds, R.F., McMahon, J.A., 1987, FMS scheduling with an expert system,
*Proceedings of the CASA/SME Flexible Manufacturing Systems Conference*,
87-102.
analysing tool management issues in FMS, *International Journal of Production
Research*, 30 (6), 1427-1440.
Rogers, P., Flanagan, M.T., December 1991, On-line simulation for real-time scheduling
Rogers, P., Williams, D., Wesley, P., 1990, Object oriented modelling for the design and
scheduling of flexible machining cells incorporating a tool management,
*Proceedings of the 1st International conference on Artificial intelligence and


The CIMulation Centre, 1994, The PREACTOR user manuals, *The CIMulation Centre*, Chippenham - UK.


Appendix 1

A USER GUIDE FOR THE MULTI-FLOW CONTROLLER

A1.1. Introduction

This appendix provides an overview of the software implementation of the multi-flow controller. It briefly describes the commercial software packages used to generate the modules of the multi-flow controller, namely the PREACTOR scheduling system and ARENA simulation package. A description of the specially designed user interface of the multi-flow controller, with its set of menus, is also provided in this appendix.

A1.2. The Multi-Flow Controller

The multi-flow controller consists of three software modules, as illustrated in figure A1.1, namely the multi-flow scheduler, the multi-flow simulator and manufacturing database. The issues involved in the design, specification and functionality of these modules are discussed in chapter 8, 9 and 10, respectively. These three modules are integrated using a specially designed, menu driven, user interface, as shown in figure A1.2. This user interface allows orders(jobs) to be entered directly from a MRP system or similar software package and schedule to be generated, approved and amended, as and when required. The main menu of this user interface consists of the following options, as shown in figure A1.3, used to :

- **Scheduling Menu**: load the multi-flow scheduler
- **Simulation Menu**: load the multi-flow simulator
- **Database Menu**: access the manufacturing database
- **Exit Multi-Flow Controller**: end the use of the multi-flow controller
Figure A1.1: The Software Modules of the Multi-Flow Controller
Figure A1.2: The User Interface of the Multi-Flow Controller

Figure A1.3: The Main Menu of the Multi-Flow Controller
A1.3. The Multi-Flow Scheduler
The multi-flow scheduler has been developed using the PREACTOR scheduling software (The CIMulation Centre, 1994). PREACTOR is a simulation based scheduling system and has a modular structure of functionality, named accordingly PREACTOR 200, 300, 400 and 500. It starts at its lowest level of functionality with PREACTOR 200 which supports a limited number of the most common sequencing algorithms. In PREACTOR 300, this list of sequencing rules are expanded. PREACTOR 400 and 500 have a simulation model which allows user defined sequencing rules to be implemented, and enables schedules to be generated based on a combination of such rules (i.e. multi criterion scheduling). The PREACTOR 400 version has been used to generate the scheduling model of the multi-flow controller. The PREACTOR 400 consists of the following software modules:

- **Production Order Editor**: where Orders(jobs) data are entered and edited. This editor consists of a table with a number of columns which stores various pieces of information such as, job description, batch size, list of operations, starting date and due date for each job.

- **Production Sequencer**: Where sequencing rules are applied to the jobs in an unallocated queue. Every manufacturing resource (e.g. machining centre) is represented via a window which is divided into time buckets (e.g. hours, days). Shaded time buckets indicate the times that the resource is not available (e.g. out of shift, broken down) and blank time buckets represent the period when the resource is available to carry out its processing function. The joblist is represented by a window, labelled ‘unallocated jobs’ and jobs are depicted via icons appearing in this window.

- **Schedule Editor**: This consists of a graphical editor where outputs from the production sequencer are formatted in the form of Gantt charts. The Gantt charts can also be converted into work-to-lists and saved in appropriated data files which are downloaded to the shop floor.

- **Shift Pattern Editor**: which records the information such as the length of each shift which could be different for the various days of the week (e.g. weekends), short breaks (e.g. launch hours, setting up times) and pre-planned maintenance activities.

- **System Status Editor**: The latest data on the system status is maintained in this module and used to amend / update the schedules, as and when required.
The scheduling menu of the multi-flow controller, illustrated in figure A1.4, consists of the following options:

- **View/Edit Joblist**: to enter and edit job information, as shown in figure A1.5.
- **Select Planning Strategy**: to choose a planning strategy for the generation of schedules, as shown in figure A1.6.
  - **Workpiece Dominated**: as shown in figure A1.7.
    - Multi Machine Loading Job Allocation
    - Return to Planning Strategy Menu
  - **Tool Dominated**: as shown in figure A1.8.
    - Cluster Based Job Allocation
    - Single Machine Loading Job Allocation
    - Combined Machine Loading Job Allocation
    - Return to Planning Strategy Menu
  - **Fixture Dominated**: as illustrated in figure A1.9.
    - Cluster Based Job Allocation
    - Fixture Availability Based Job Allocation
    - Return to Planning Strategy Menu
  - Return to Scheduling Menu
- **View Schedules**: to see the Gantt Charts, as shown in figure A1.10, and to generate the work-to-lists, as illustrated in figure A1.11.
  - Parts versus Machines Schedule
  - Machines versus Jobs Schedule
  - Parts versus Toolkits Schedule
  - Toolkits versus Machines Schedule
  - Parts versus Fixtures Schedule
  - Fixtures versus Machines Schedule
  - Return to Scheduling Menu
- **Save Schedules**: to store the schedules in data files.
- **View/Edit Shift Pattern**: to maintain the information relating to shift patterns.
- Return to the Main Menu
Figure A1.4: The Scheduling Menu of the Multi-Flow Controller

Figure A1.5: The Joblist Editor of The Multi-Flow Controller
Figure A1.6: The Planning Strategy Menu of the Multi-Flow Controller

Figure A1.7: The Workpiece Dominated Scheduling Menu of the Multi-Flow Controller
Figure A1.8: The Tool Dominated Scheduling Menu of the Multi-Flow Controller

Figure A1.9: The Fixture Dominated Scheduling Menu of the Multi-Flow Controller
Figure A1.10: The Gantt Chart Menu of the Multi-Flow Controller

Figure A1.11: An Example of The Work-to-List Generated by the Multi-Flow Controller
A1.3. The Multi-Flow Simulator

The commercial simulation software ARENA (Systems Modeling 1994), has been utilised to construct the multi-flow simulation model. ARENA is based on the SIMAN simulation language, and is an object oriented software package. The simulation models are constructed in ARENA using a set of Application Solution Templates (AST) which are a number of commonly used simulation routines. A number of these templates are selected from a set of specially designed menus and linked together in a specific sequence to form the logic of the simulation model. A graphical animation of the simulation model can be generated, based on the logic specified by the model, as illustrated in figure A1.9. Furthermore, statistical graphs, charts and tables can be included in the working space of an ARENA simulation model. One of the main advantages of ARENA is that a model can be developed in a fraction of time required to generate the same model, using a simulation languages such as SIMAN.

The manufacturing resources modelled in the multi-flow simulation model, shown in figure A1.12, are as follows.

- **part storage area**: divided into an arrival section for raw material and a section for finished parts which are returned from the machining cell having been machined.
- **fixture / defixture area**: this is an area where fixtures are stored and workpieces are mounted or removed from the fixtures.
- **load / unload station**: used to load or unload workpieces onto/from part transporter.
- **part transporter**: workpiece handling device used to transport workpiece to/from machining centres.
- **machining centres**: these are divided into part buffer, machining area and tool magazine so that the three activities of part load/unloading, machining operations and tool exchange can be modelled.
- **tool transporter**: used to transfer cutting tools to/from the machines.
- **cell tool store**: a tool store dedicated to the cell which receives fresh tools and returns the used tools to/from the central tool store.
Figure A1.12: Manufacturing Resources Modelled By the Multi-Flow Simulator

The simulation menu of the multi-flow controller contains the following options, as shown in figure A1.13:-

- **Convert Scheduling Files for Simulator**: file translator used to link the scheduler to the simulator.
- **Convert Simulation Files for Scheduler**: file translator used to link the simulator to the scheduler.
- **Load Multi-Flow Simulation Model**: starts the execution of the simulator.
- **Return to the Main Menu**

These options are used to load and execute the simulation model to obtain the manufacturing performance measures based on a set of planning decisions.
A1.4. Manufacturing Database

The PREACTOR scheduling software provides facilities to develop customised database which are automatically integrated with the scheduler. These facilities contain a data configuration language, using which the data structure and data relationships can be defined. Based on these data configuration files a database containing a number of tables is generated. Figure A1.14 illustrates an example of the definition of a table within the manufacturing database, namely the operations table, using the PREACTOR data configuration language.

The codes related to the definitions of the tables are converted into a set of computer screen windows, which are divided into rows and columns, using a graphical editor. Furthermore, each row is connected to a dialogue screen which includes a number of data fields. The manufacturing information is entered into the database, by typing the various data values in these data fields, as shown in figure A1.15. The manufacturing database is totally integrated with other modules of the multi-flow controller, so that the initial input data is automatically extracted and a range of outputs is stored within the database.
Appendix I

```
Number, 0, INTEGER, PRIMARY KEY | HIDDEN:
Operation Id, 0, STRING, FREE FORMAT (10) | UNIQUE:
Operation Description, 0, STRING, FREE FORMAT (30) | UNIQUE:
Toolkit Req., -1, STRING, DATABASE(Toolkits(Toolkit Id)); ALLOW UNSPECIFIED:
Fixture Req., -1, STRING, DATABASE(Fixtures(Fixture Id)); ALLOW UNSPECIFIED:
Resource Group, 1, STRING, DATABASE(Resource Group(R.G Description));
Resources, -1, MATRIX, AUTO LIST(Resource Group(Resources Included));
Pattern, 1, STRING, TABLE(Patterns); PATTERN | GANTT CONTROL | DIALOG
ONLY:
Set-up Time, 0.006945, DURATION, DURATION | SEQ CHANGEOVER | DIALOG
ONLY:
Op Time, 0.006945, DURATION, DURATION | CONDITIONAL "ENTRY>0":
Set-up time, 0, MATRIX | DURATION,
AUTO DIMENSION(From,Products(Name). To, Products(Name)) | SEQ
CHANGEOVER:
```

Figure A.14: The Definition of the Operations Table of the Multi-Flow Controller

```
; Format 6
; Operation Id, Operation Description, Fix, Def, LD, UNLD, Tool Id, Toolkit Req., Fixture Req., Resource Group, Resources, Pattern, Set-up Time, Op Time

t
Figure A.15: The Operations Table of The Manufacturing Database

241
The database menu of the multi-flow controller consists of the following options, as shown in figure A1.16:

- *Edit / View Parts*
- *Edit / View Tools*
- *Edit / View Toolkit*
- *Edit / View Fixtures Types*
- *Edit / View Operations Lists*
- *Edit / View Machines*
- *Edit / View Machine Groups*
- *Edit / View Calendar States*
- *Return to the Main Menu*

Options within this menu enable the user to access the various tables within the manufacturing database to enter and edit any data items relating to the modules of the multi-flow controller.

*Figure A1.16*: The Database Menu of the Multi-Flow Controller
A1.5. Generation of Schedules Using the Multi-Flow Controller

The multi-flow controller assumes that a rough cut plan in the form of a job list is offered to the scheduler (via MRP or equivalent). This job list is entered using the joblist editor, and is initially considered by the cell manager prior to the start of the manufacturing horizon. The cell manager then, selects strategies for the provision of parts, fixtures and cutting tools. The strategies are used in the multi-flow scheduler to generate the individual schedules for the three principal flows. The proposed schedules are then, down loaded to the multi-flow simulation model which provides output to the cell manager. This gives the cell manager insight into the potential performance of the cell and allows him to make valued judgements on whether the schedules should be down loaded for implementation. Based on the approved schedules, a number of work-to-lists for various resources are generated. Furthermore, the cell manager at the start of specific short term time intervals(e.g. a day or a shift) reviews a range of issues such as the progress of the schedules during the previous interval, requirements for the introduction of new jobs and any other possible manufacturing disturbances(e.g. breakdowns and shortage of materials, fixtures and tools). Any required modification to the short term schedules is then carried out by the cell manager.
Appendix 2

THE ROLE OF SIMULATION IN OPERATIONAL PLANNING AND CONTROL OF FLEXIBLE MACHINING CELLS

A2.1. Introduction

This paper was presented in the 'Winter Simulation Conference' (WSC'95), held in Arlington-USA (Rahimifard and Newman 1995). The various methods of utilising the simulation models to solve the operational planning and control problems of machining facilities, are described in detail. The paper also discusses the use of simulation models within the multi-flow controller as a:-

i) scheduling model;

ii) decision support tool; and

iii) cell mimic.
THE ROLE OF SIMULATION IN OPERATIONAL PLANNING AND CONTROL OF FLEXIBLE MACHINING CELLS

Shahin Rahimifard
Stephen T. Newman

Department of Manufacturing Engineering
Loughborough University of Technology
Loughborough, U.K.

ABSTRACT

The use of simulation as a solution to the operational planning and control problems of flexible machining cells is now well established. This paper describes the role of simulation models as: a decision support tool, a scheduler and as an aid to develop appropriate control procedures. To illustrate the ideas presented, a novel framework for the simultaneous management and control of parts, fixtures and cutting tools is outlined which is termed multi-flow control. Three simulation models have been designed and implemented to carry out specific tasks within this framework. These models and their respective functionality are also described in this paper.

1 INTRODUCTION

Simulation models have been used extensively for the purpose of design and analysis of Flexible Machining Cells (FMC) (Mertines and Wieneke-Toutouxi 1991). There has been a number of benefits reported in the use of simulation as a design tool (Tempelmeier 1992). These reported benefits include:

- rapid development of cell designs resulting in reduction of design cost.
- selection of an optimum design among a number initial configurations.
- the concept of 'getting it right first time' to reduce the initial cost of machining cells.

The successful use of simulation as a design tool has encouraged researchers to investigate into possible ways and methods of using these models for planning, scheduling and control (Steeke 1988). More recently, the area of real-time control of manufacturing cells using simulation models has been the subject of a number of research projects (Manivannan and Banks 1991).
Planning, scheduling and control of production systems is a problem of well known complexity. Among the various manufacturing activities, these problems have been the areas with the largest proportion of research and development projects in recent years. This is due to the significant financial incentives for manufacturing companies to constantly improve their manufacturing practices (Grant and Clapp 1988).

This paper describes how the flexibility offered by simulation models can be utilised to improve efficiency and productivity of FMC. The initial part of the paper identifies some of the FMC operational problems in the areas of production strategy selection, scheduling, and cell control. The latter part of the paper describes a novel framework for the simultaneous scheduling and control, of parts, fixtures and cutting tools, termed multi-flow control, to highlight the effective use of simulation in solving the operational problems of a FMC.

2 OPERATIONAL PLANNING AND CONTROL OF FMC

The need for an efficient production management and control system has further increased with the introduction of the flexible machining facilities. In these highly automated systems a number of CNC machine tools are closely linked via work and tool handling facilities, operating under the supervisory control of a computerised cell controller. A typical representation of such a cell is illustrated in Figure 1.

An FMC presents several operating problems that were not encountered in conventional manufacturing systems because of the tightly controlled environment in which they operate (Gupta et al. 1993). These operational problems, together with how simulation models are used to solve them, are discussed in the following sections.

![Figure 1 - A Block Diagram Representation of a Flexible Machining Cell](image-url)
2.1 Simulation Based Planning and Scheduling

The daily operation of a FMC involves the process of a manufacturing plan, by converting a list of jobs to finished/machined parts. There are a number of tasks involved in generation of daily manufacturing plans such as batching (lot sizing) of total orders into manageable partitions, routing parts through machining cells, producing a dispatching list for the load and unload stations, and sequencing the operations within jobs.

The scheduling task is one part of the manufacturing planning and control process. Scheduling is required whenever a set of resources in the manufacturing system must be shared to make a variety of different products during the same time period. The objective of manufacturing scheduling is the allocation of machines and other resources to jobs, or operations within jobs, and the subsequent time-phasing of these jobs on individual machines. The scheduling policies, constraints and requirements vary significantly between different manufacturing applications. As a result, the majority of schedulers developed are designed to suit a particular application such as discrete part manufacture, the process industry, assembly of PC boards, etc.

Simulation has been traditionally utilised in the area of scheduling as the means of validating the robustness of a generated schedule before it is released to the manufacturing system. Simulation models, by introducing variability with the use of statistical distributions and random numbers, have had the capability to predict bottlenecks, queuing problems, over utilisation of resources, etc.

More recently, the flexibility of some of the more established simulation languages have been used to develop models that act as a scheduler (Kachitvichyanukul 1991) and generate the work list sequence. The flexibility of simulation allows the modelling of an application with various levels of detail and tailoring schedulers for very complex scenarios. Typical examples are where part operation routing is particularly complicated in a multi-cellular environment or for applications in the process industry where time constraints are very restricted.

2.2 Simulation as Decision Support Tool

Planning and scheduling of flexible machining cells is a very demanding task involving significant decision making based on a number of manufacturing parameters and variables, some of which are illustrated in Figure 2.
A large number of conflicting constraints and manufacturing goals such as meeting due dates, minimising inventory and operation costs, maximising the utilisation of resources and achieving a balanced work load across the resources make the planning task a very complex decision problem. In applications with large numbers of jobs, a wide variety of part types, cutting tools and fixture types, 4-8 CNC machines and very tight due dates; the effect of some of these decisions are vital, but not easily realised. For these complexities and the unpredictable nature of production systems, it has been virtually impossible to develop a fully automated planning, scheduling and control system. This highlights the important role of decision makers and the effect of their decisions.

In addition, there is an ever increasing number of production strategies being introduced to minimise the throughput time and production costs, to maximise the use of resources, and to achieve higher efficiency and productivity. Therefore, the decision maker in charge of operational planning should have the facilities available to test and analyse alternative plans based on various strategies and decision scenarios to obtain confidence that the proposed plan is executable.

Simulation models have been used widely as decision support tools to provide answers for the ‘what if’ queries. These models enable users to realise the effect of a set of decisions on the system under evaluation. Furthermore, they allow the assessment of the performance under a set of different operational strategies and the selection of the most appropriate ones for a particular application.
2.3 Simulation in Control of FMC

The control function within a FMC is the implementation of a specific production schedule, continuously monitoring the state of the system and the progress of the schedule. This has to be able to take steps to overcome problems introduced by changes in the system status (e.g., machine breakdowns) or interrupts to the schedule (e.g., shortage of raw material and tools). The problem of schedule adherence has been the subject of many research projects with various solutions been suggested (Cheng and Gupta 1989).

One of these solutions is the real-time control of manufacturing systems. With real-time control there is a need for a detailed model of the manufacturing system which has been integrated via a computer network to the physical resources on the shop floor. This model receives information on system status through shop floor data collection facilities and issues appropriate corrective instructions to overcome any possible problems (Smith et al. 1994). Knowledge based models and simulation models have been used to set-up the real-time control systems. The success of such a system relies very much on the design of the information structure and the quality of information being exchanged between the control system and the shop floor.

Developing the most suitable recovery procedures for operational changes and interrupts requires a significant number of experiments with various sets of constraints and alternative decision scenarios. Simulation is the most effective tool in such situations.

3 MULTI-FLOW CONTROL FRAMEWORK

Multi-Flow Control (MFC) has become the in-house research terminology for the simultaneous scheduling and control of the parts, fixtures and cutting tools within flexible batch machining facilities. MFC aims to generate knowledge and generic techniques/solutions to harmonise the interactions between the three principal flows by short term control and planning of these flows.

Traditionally, manufacturing control systems have always been concerned with the flow of workpieces through production systems and the importance of the effective management of cutting tools and fixtures has been neglected. The cost of cutting tools is a significant component both in the initial capital investment and operational costs of machining facilities. A number of researchers have addressed the general tool management problem (Gray et al. 1993). However, none of the research work has identified a structure to provide an adequate basis for short term scheduling and control of...
tool flow at the machining cell level i.e. identification of the precise time and a workstation where a collection of tools (referred to as a toolkit) is required.

Fixtures have a greater role in the daily operation of FMC than their traditional use in the jobshop environment (Grippo et al. 1988). For example, the utilisation of unmanned machines requires workpieces to be rigidly secured on a work holding devices. Furthermore, at times, with latest CNC machine tools capable of machining complex curved surfaces, the workpiece needs to be accurately positioned with respect to machining surfaces. As a result, a number of special design fixtures have been developed which can be used with a limited number of part types. Therefore, effective management of fixtures within FMC play a vital role on the overall performance of such systems. However, the published research on the use of fixtures has mostly focused on the design of fixtures with little emphasis given to the management of fixture flow within FMC.

To overcome these problems, a unique structure of software modules, termed the multi-flow controller, has been designed and implemented to regulate the flow of parts, fixtures and cutting tools in a flexible machining environment. These modules are integrated around a manufacturing database. The multi-flow control framework does not aim to automate the control procedure but to act as an ‘advisory system’ to the person responsible for decision making. This decision maker is referred to as the ‘Cell Manager’. The MFC assumes that a rough cut forward planning projection in the form of a job list is offered to the scheduler (via a MRP or equivalent). This job list is initially handled by the cell manager which will recommend strategies for the provision of parts, fixtures and cutting tools.

Figure 3 : Overview of Multi-Flow Control Framework
The strategies are offered to a multi-flow scheduler which in turn generates a short term schedule for the three principal flows. The proposed schedules are then, down loaded to a simulation model which provides output to the cell manager. This gives the cell manager insight into the potential performance of the cell and allows him to make valued judgements on whether the schedules should be down loaded for implementation. An overview of the multi-flow control framework is shown in Figure 3. The role of simulation models used within these framework are described in more detail below.

### 3.1 Multi-Flow Scheduler

As a part of the MFC prototype software, a novel scheduler is required to generate schedules not only for jobs to be processed in a machining cell but also for the cutting tools and fixtures required by those jobs. Research issues involved in the design and implementation of such a scheduler is described elsewhere (Rahimifard and Newman 1995). One of the principal issues involved, is the selection of a scheduling approach to develop the scheduler. A simulation-based approach was identified to be the most flexible and powerful technique for the development of this scheduler.

As a result, a simulation based multi-flow scheduler has been developed that simultaneously generates short term schedules for the three principal flows. A commercial simulation based scheduling software, termed PREACTOR (The CIMulation Centre 1994) has been used as the basis to develop the multi-flow scheduler. The primary inputs to this scheduler being an unsequenced list of jobs for a specified manufacturing horizon and the machining cell status at the start of this horizon and the primary outputs are three individual and synchronised schedules for the control of the principal flows.

### 3.2 Multi-Flow Simulator

A multi-flow simulation model is designed and implemented as a part of the MFC, to model the part, fixture and cutting tool flows around a machining cell. The commercial simulation software ARENA (Systems Modeling 1994), has been utilised to construct this simulation model. The multi-flow simulator is designed to act as a flexible decision support system which can be used in many ways. It can simply execute schedules generated by the multi-flow scheduler on a deterministic mode, to produce manufacturing performance measures (e.g. resource utilisation, queue/buffer sizes) and act as a window through which consequences of the decisions made during the planning and scheduling
stages can be realised. Alternatively, the multi-flow simulator can be used to measure the effect of some of the constraints such as transportation or temporary buffer storage capacity which might not have been considered in the first stage of manufacturing planning.

3.3 Machining Cell Mimic

It is obvious that the research ideas behind the solutions of short term control of the three flows need to be tested and validated, before it can be widely accepted and adopted. Originally, it was envisaged that an actual machining installation would be used to carry out a number of experiments. However, it became clear that the access to such an installation with appropriate configuration, that challenged the research ideas will not be possible. Therefore, an experimental simulation model, termed the machining cell mimic (MCM) which represents a specific cell configuration, is utilised to validate the MFC research ideas. A number of defined manufacturing disturbances (machine breakdowns, shortage of parts and cutting tools) are also modelled.

The primary inputs to the MCM are a set of approved schedules for the three flows generated by the MFC prototype software and the machining cell status. The primary outputs from the MCM are reports on the progress of jobs, resources status and delays that are caused by the introduction of the manufacturing disturbances. These outputs provide the initial machining cell status to be used for the planning of the next manufacturing period.

4 CONCLUDING REMARKS

Simulation has seen a significant use in the design of flexible machining installations. This paper highlights a range of operational problems experienced with these types of systems and provides a further use for exploiting simulation in the operational planning and control of such a facilities to overcome these problems. Furthermore it has identified how simulation models can be used within a novel framework for the control of the flows of parts, fixtures and cutting tools within FMC. This multi-flow control framework harmonises the interactions between these three principal flows by enabling the preparation of fixturing and cutting tool requirements prior to the start of the production period.
ACKNOWLEDGEMENTS

This work has been carried out as a part of a Governmental funded (the Control, Design and Production Group of the Engineering Physical Science Research Council) research programme, entitled "Multi-Flow Control to Improve Flexible Batch Manufacturing Performance". The authors would like to acknowledge the work of the LUT FMS Research group and the supporting work of the industrial collaborators namely, The CIMulation Centre Ltd, ISIS Informatics Ltd, Camtek Ltd and Cincinnati Milacron UK Ltd.

REFERENCES

Cheng, T.C.E., Gupta, M.C. 1989. Survey of scheduling research involving due date determination decisions, European Journal Operational Research, 156-166.

Grant, H., Clapp, C., 1988, Making production scheduling more efficient helps control manufacturing costs and improve productivity, Industrial Engineering, 20, 54-62.


The CIMulation Centre. 1994. PREACTOR user manual, The CIMulation Centre, Chippenham, Wiltshire, U.K.

AUTHOR BIOGRAPHIES

SHAHIN RAHIMIFARD is a Research Associate in the Department of Manufacturing Engineering at Loughborough University of Technology. He received a B.Sc. degree in Computing and Mathematics from Brighton University and his M.Sc. in Computer Integrated Manufacture (CIM) from Loughborough University. His research interests are in information modelling and system integration, simulation, scheduling, and control of manufacturing systems.

STEPHEN T. NEWMAN is a Lecturer in the Department of Manufacturing Engineering at Loughborough University of Technology. He received a B.Sc. degree in production technology in 1982 from the University of Aston, Birmingham, and his Ph.D. degree in design of flexible machining facilities. His research interests are in scheduling and control of machining systems, cutting tool management and computer numerical control of machine tools.
Appendix 3

PLANNING AND CONTROL OF FIXTURE FLOW WITHIN FLEXIBLE MACHINING SYSTEMS

A3.1. Introduction

This paper was presented in the ‘Sixth International Conference on Flexible Automation and Intelligent Manufacturing’, held in Atlanta-USA (Rahimifard and Newman 1996b). The various issues related to the fixture dominated planning strategies, such as fixture designs, fixturing practices, fixturing activities, and the appropriate job allocation policies are described in detail in this appendix.
ABSTRACT: The efficient management of fixture flow within flexible machining facilities plays a vital role in the overall performance of such systems. In this paper, the authors identify three distinct fixturing practices that are commonly adopted in modern machining facilities. These fixturing practices are based on the use of specially designed fixtures and modular fixtures. Furthermore, planning strategies based on ‘finite’ and ‘infinite’ fixture capacity for use in each of these fixturing practices are presented. These planning strategies are implemented within a novel ‘multi-flow scheduling system’ which is capable of producing schedules for the flows of workpieces, cutting tools and fixtures. In addition, this scheduling system incorporates the latest techniques offered through the use of ‘clustering algorithms’ for the allocation of jobs, so that the cost of cutting tools and fixtures requirements are minimised. These job allocation rules, termed ‘tool oriented’ and ‘fixture oriented’, together with the functionality of the multi-flow scheduling system are also described in this paper.

1. INTRODUCTION

Within machining facilities, fixtures are the workholding devices upon which workpieces are mounted before being sent to a machine tool for their machining operations. There are an enormous number of fixture designs, varying in shape, size, capacity and number of working faces. These fixture designs are based on the shape, size and machining requirements of parts, together with the size and the configuration of machining centres (e.g. horizontal or vertical machines). Fixtures are usually clamped on a pallet before being transferred to the machines. Based on the size of pallets, fixtures, workpieces and machines, there could be one or more fixtures loaded onto a pallet. These fixtures can be temporarily loaded or permanently attached depending on the number of available pallets and fixtures (Solot 1990). As a result, the nature and number of fixturing activities required within a machining system can vary significantly based on the pallet, fixture and part configuration.

Grippo (Grippo et al. 1988) has identified that fixturing methodologies and technologies have remained relatively stagnant in comparison to the significant advancements evidenced in the rapidly evolving electronics and machine tool industries. In recent years, the published research on the use of fixtures has mostly focused on the design of
fixtures (Siong et al. 1992, Nee et al. 1992). In particular, the use of computer aided design (CAD) for fixture design has been investigated by a number of researchers (Ngoi and Leow 1994, Dai and Yuen 1995). However, the published research in the area of fixturing has given little emphasis to the management of fixture flow within machining facilities.

The work reported in this paper is a part of a nationally funded research programme which aims to investigate the application of a ‘multi-flow scheduling system’ based on a novel concept for the simultaneous generation of schedules for the flows of workpieces, fixtures and cutting tools within a flexible machining system. The main focus of the paper is the issues involved in the planning and control of fixture flow in modern machining facilities. The initial part of the paper reviews common fixture designs and various fixturing activities. The main body of the paper identifies three distinct and common fixturing practices and describes the planning strategies developed to be used in each of these fixturing practices. Finally, the later sections of the paper briefly outlines the functionality of the ‘multi-flow scheduling system’ with its novel tool oriented and fixture oriented job allocation rules and highlights how these planning strategies are implemented to generate fixture schedules that regulate the fixture flow within flexible machining systems.

2. THE ISSUES RELATED TO FIXTURE FLOW

The fixture flow within machining systems and the level of manual requirements for fixturing operations are directly influenced by a number of factors such as the type of fixture used, number of fixturing activities required and number of parts mounted on a fixture. These factors are described in more detail below.

2.1. Fixture Design

Fixture designs can be divided in two main categories :-

2.2.1. Specially designed fixtures: These fixtures are designed to be used with one or a family of part types and could have a capacity of one or more parts. They have a fixed configuration (i.e. shape and size) and are often used in flexible batch machining cells where a limited range of part types are machined in medium to large batches over a long time period. These types of fixtures offer high accuracy in positioning the workpieces, reliability over a long period, the minimum time period for fixturing and defixturing operations and possibility of maximising the machining time per machine setup with multi parts per fixture. However the specially designed fixtures have the following disadvantages ; a complex, time consuming and expensive design procedure, high initial cost per fixture and can be obsolete through the changes in part designs.

2.2.2. Modular fixtures: These fixtures consist of a mounting plate or a mounting block together with various clamps, nuts, screws, pins and supporting arms which are used in different combinations to produce a number fixture configurations that can securely hold a range of part types. The fixture configurations are initially designed and photographed. The fixture configuration pictures, together with the list of required components and instructions for rebuilding are used to generate a series of assembly cards.
which will be used to rebuild the fixture configurations. These type of fixtures are used in machining applications with small to medium batches with a large variety of part types and offer reduction in the initial design cost, flexibility in production (i.e. infinite fixture capacity - see section 3.2) and reusability for new part designs (i.e. they do not become obsolete). The disadvantages associated with the use of modular fixtures are as follows; they require the time consuming fixturing activities of fixture assembly and fixture disassembly, they require a more frequent recalibration activity than specially designed fixtures and they cannot always be effectively used to maximise the machining time per machine setup, specially with multi-parts per fixture.

2.2. Fixturing Activities

Fixturing activities can be classified as follows:-

i) *Fixturing operation*: mounting (securing) one or more workpieces onto a fixture.

ii) *Defixturing operation*: removing one or more machined parts from a fixture.

iii) *Fixture assembly*: building up a combination of mounting plates or mounting blocks together with clamps, supporting arms, pins, nuts and screws to assemble a particular fixture configuration.

iv) *Fixture disassembly*: Breaking down a fixture configuration into its basic elements.

v) *Fixture calibration*: measurement of distances, setups and positions on a fixture.

vi) *Fixture load*: loading/clamping a fixture onto a pallet.

In the applications with specially designed fixtures, a quantity of every fixture type is stored in the fixture store. These fixtures are withdrawn from the store as and when required and are returned to the store, following a defixturing operation. In applications with modular fixtures a fixture configuration has to be assembled for a particular part type, before workpieces can be mounted and sent to the machines. The activities of fixture assembly and fixture disassembly usually require a much longer period to be carried out. Therefore, a different set of strategies for planning and management of the fixturing activities should be adopted with modular fixtures. Typical activities for the flows of fixtures and workpieces while using modular fixtures is illustrated in figure 1. Clearly, the main difference with the use of modular fixtures is that of activities related to fixture assembly and fixture disassembly which will not be required with specially designed fixtures. However, in some machining applications using modular fixtures, the various fixture configurations are often constructed in some quantities and are stored. These fixture configurations are then withdrawn from the store similar to the specially designed fixtures and are used as and when required without the need for fixture assembly or fixture disassembly operations. Clearly, this would eliminate the need for fixture assembly and fixture disassembly activities associated with modular fixturing. In addition, unlike specially designed fixtures these fixture configurations will not be obsolete and can eventually be broken down and reused for new part designs. Obviously, this method of using modular fixtures introduces the need for extra fixture inventory and requires a larger space to store the pre-assembled fixtures. These fixturing practices are described with an aid of a rule set associated to each fixturing practice in section 3.1.
3. PLANNING AND CONTROL OF FIXTURE FLOW

The use of flexible machining systems is now common place within many manufacturing companies, providing fixtures with a new role than their traditional use in the jobshop environment. For example, specially designed fixtures have been developed to maximise the possible machining time per machine setup(with multi-parts per fixture), allowing for a longer unmanned production period. These specially designed fixtures can be used with a limited number of part types, or even at times with one part type. Alternatively, the use of modular fixtures have gained enormous popularity in recent years(Pandey and Ngamvinijsakul 1995, Shirinzadeh et al 1995). However, modular fixtures have to be assembled and setup, before workpieces can be mounted on them. This operation of assembling modular fixtures is time consuming and needs to be properly planned, with a low level of manning such as in a flexible machining system. Therefore, the effective management of fixtures within flexible machining systems plays a vital role in the overall performance of such facilities.

3.1. The Fixturing Practices within Flexible Machining Systems

Through consideration of the operational procedures of a large number of flexible machining installations, three distinct and common fixturing practices have been identified and are modelled within the multi-flow scheduling system(see section 4). These fixturing practices represent the various methods for the use of modular fixtures and specially designed fixtures, as discussed in section 2.2. These fixturing practices and their related rule sets are described below.
3.1.1. \textit{Fixturing practice 1}: This category of fixturing practice includes flexible machining applications where specially designed fixtures are used and a limited quantity of every fixture type is available. The rule set relating to this fixturing practice is as follows:

i) let $FT_1, FT_2, \ldots, FT_n$ represent the range of available fixture types, and
ii) let $Q_1, Q_2, \ldots, Q_n$ the quantities available for each fixture type.
iii) if a job $J_i$ requires $FT_i$ then let $Q_i = Q_i - 1$.
iv) start a fixturing operation and send the fixture and the workpiece(s) to a machine or a temporary buffer.
v) on completion of the machining operations of the job $J_i$ return the machined part(s) and the fixture to the fixturing station.
vii) start the defixturing operation and send the machined part(s) to the part warehouse and the fixture to the fixture store.
vi) if $Q_i$ is required by next job or $Q > 1$ then goto iii) else,
ix) start a fixture disassembly operation and let $Q = Q + 1$ and goto iii).

3.1.2. \textit{Fixturing practice 2}: This category of fixturing practice includes flexible machining applications where modular fixtures are used and the total number of available fixtures is very limited. Therefore, fixture assembly and fixture disassembly activities take place frequently to accommodate the requirements for various fixture configurations. The rule set related to this practice is as follows:

i) let $FC_1, FC_2, \ldots, FC_n$ represent the range of available fixture configurations, and
ii) let $Q$ the total quantity of available fixture sets.
iii) if a job $J_i$ requires $FC_i$ then let $Q = Q - 1$.
iv) if $FC_i$ is not available in the store start a fixture assembly operation, else goto v)
v) start a fixturing operation and send the fixture and the workpiece(s) to a machine or a temporary buffer.
vii) on completion of the machining operations of the job $J_i$ return the machined part(s) and the fixture to the fixturing station.
viii) if $FC_i$ is required by next job or $Q > 1$ then goto iii) else,
ix) start a fixture disassembly operation and let $Q = Q + 1$ and goto iii).

3.1.3. \textit{Fixturing practice 3}: This category of fixturing practice includes flexible machining applications where modular fixtures are used and a number of fixture configurations are constructed and stored. The fixture assembly and fixture disassembly activities do not take place frequently, unless as a result of the introduction of a new part design or a new fixture configuration. The rule set related to this fixturing practice is as follows:

i) let $FC_1, FC_2, \ldots, FC_n$ represent the range of pre-assembled fixture configurations, and
ii) let $Q_1, Q_2, \ldots, Q_n$ the quantities available for each fixture configurations.
iii) if a job $J_i$ requires $FC_i$ then let $Q_i = Q_i - 1$.
iv) start a fixturing operation and send the fixture and the workpiece(s) to a machine or a temporary buffer.
v) on completion of the machining operations of the job $J_i$ return the machined part(s) and the fixture to the fixturing station.
vi) start the defixturing operation and send the machined part(s) to the part warehouse and the fixture to the fixture store.

vii) if $Q_i = 0$ and a job is waiting for $F_{C_j}$ then start a fixture disassembly operation to convert $F_{C_i}$ to $F_{C_j}$ and let $Q_i = Q_i + 1$ and goto iii), else

viii) let $Q_i = Q_i + 1$ and goto iii).

3.2. Fixture Planning Strategies

One of the major objectives of the multi-flow scheduling research has been to develop a number of fixture planning strategies for the most effective use of fixtures in each of the fixturing practices, stated in section 3.1. These fixture planning strategies are developed so that:-

i) the number of fixture activities required for a manufacturing task is minimised.

ii) the machining system can efficiently operate with minimum fixture inventory.

iii) both i) and ii) can be achieved without compromising the workpiece throughput requirement.

The fixture planning strategies are divided into two categories

3.2.1. Finite fixture capacity planning: This strategy is associated with specially designed fixtures where the limitation on the quantity of fixtures available of a specific type becomes a scheduling constraint. The finite fixture capacity planning strategy utilises the common work oriented scheduling rules for the assignments of jobs to machines(Gupta 1989). However, when the number of required fixtures of a particular type exceeds the quantity available, the start of next job requiring the fixture type is delayed until a fixture becomes available.

3.2.2. Infinite fixture capacity planning: This strategy is associated with modular fixtures where the quantity of fixtures available for a particular type(configuration) is not limited to a constant number, and therefore the fixture quantity is not a scheduling constraint. However, in such cases the number of allowed fixture configurations and their conversion frequency can have a significant effect on the required total fixturing activities and fixture inventory.

4. MULTI-FLOW SCHEDULING SYSTEM

The review of planning and control procedures of flexible machining systems has indicated that tooling and fixturing requirements are often planned independently from the work(master) scheduler, and usually at a much later period, sometimes just prior to start of a production shift. As a result, inadequate warning is given to the tool room/store and fixturing stations for cutting tool and fixture requirements, with little or no time to prepare. This lack of preparation time leads to delays in machine down time and bottlenecks in tool building, tool pre-setting, tool procurement and fixturing activities. As a result, a need has been identified for the research into an integrated planning and environment where issues involved in the short term planning and scheduling of the flows of workpieces, fixtures and cutting tools can be addressed simultaneously(Rahimifard and Newman 1996).
'multi-flow scheduling system’ has become the research terminology used for such a planning environment. This research work aims to generate knowledge and generic techniques / solutions to harmonise the interactions between these three principal flows within machining cells. These generic techniques are based on the latest advancement in the area of planning and control through utilisation of simulation models (Rahimifard and Newman 1995). However, the multi-flow scheduling research does not aim to automate the decision making procedure involved in planning and control, but to act as an ‘advisory system’ to the person responsible for decision making, referred to as the ‘cell manager’, as illustrated in figure 2.

![Diagram](image)

**Figure 2.** An overview of the multi-flow scheduling concept

### 4.1. Job Allocation Rules

Three modes of operation are implemented within the multi-flow scheduling system based on workpiece, fixture and tool oriented job allocation rules. The cell manager selects one of these modes for generation of the triple flow schedules, depending on the specific requirements of a manufacturing horizon. Alternatively where appropriate, schedules based on the three approaches can be generated and analysed to select the one which produces the best manufacturing performance (Rahimifard and Newman 1996). These modes of operation are described in more detail below.

**4.1.1. Workpiece oriented job allocation rules:** This is primarily concerned with the generation of schedules for the most effective flow of workpieces through the machining cell. An extensive list of workpiece oriented scheduling rules is published by Gupta (Gupta et al. 1989). A subset of these scheduling rules representing the most commonly used
rules such as First In First Out (FIFO), Earliest Due Dates (EDD), Jobs Priorities (JP), Processing Time of jobs (PT), Number of Operations per job (NOP), are implemented within the multi-flow scheduling system.

4.1.2. Tool oriented job allocation rules: With the tool oriented job allocation approach, the emphasis is put on the minimisation of cutting tool requirements. This is achieved by utilisation of a clustering algorithm which is applied to the part and tool matrix to form a cluster of jobs that have similar tool requirements (de Souza and Bell 1991). The jobs within these individual job clusters are sequenced based on the earliest due dates before or another sequencing being allocated to a specific machine or a group of machines in the machining system.

4.1.3. Fixture oriented job allocation rules: The fixture oriented job allocation approach utilises a clustering algorithm where jobs with common fixturing requirements are grouped to form a series of job clusters. The jobs within a job cluster are then sequenced based on the earliest due date or another sequencing rule, before being allocated to a machine or a group of machines within the machining cell. The use of the fixture oriented job allocation policy results in a significant reduction of required fixturing activities and fixture inventory to carry out a list of manufacturing tasks. Furthermore, these potential benefits can be achieved for any of the three fixturing practices, described in section 3.1. For example, in applications with specially designed fixtures (i.e. fixturing practice 1), grouping of jobs with common fixture requirements and allocating them to a machine or a subset of available machines will reduce the total fixture inventory requirements. Alternatively, in applications where fixture assembly and disassembly are carried out frequently because of the limited total number of available fixture sets (i.e. fixturing practice 2), the use of a fixture oriented job allocation policy will reduce the frequency of fixture assembly and fixture disassembly requirements.

4.2. Workpiece, Cutting Tool and Fixture Schedules

Based on the selected planning strategies and job allocation rules, schedules for the flows of workpieces, fixtures and cutting tools are generated, analysed and approved by the cell manager. The schedules can be generated either in the format of Gantt Charts and/or work-to-lists. Currently, six different forms of Gantt Charts (or work-to-lists) are produced by the multi-flow scheduling system as the schedules for workpieces, fixtures and cutting tools flows. These Gantt Charts are derived from a unique manufacturing plan for a specific production period and provide scheduling information in a particular format which can be useful to carry out a specific task of the overall machining system operational procedures. These Gantt Charts and their suggested usage are described in detail elsewhere (Rahimifard and Newman 1996) and are listed below:-

i) Part types versus machines (workpiece flow)
ii) Machines versus jobs (workpiece flow)
iii) Part types versus toolkits (tool flow)
iv) Toolkits versus machines (tool flow)
v) Part types versus fixtures (fixture flow)
vi) Fixture versus machines (fixture flow)
Figure 3. Fixture types versus machines (fixture flow schedule)

The part types versus fixtures schedule is used in the fixturing/defixturing area as a set of instructions to mount the workpieces on the appropriate fixtures. It identifies the time that a fixture of a particular type is used so the required fixturing activities can be carried out prior to the start times of jobs. The fixture versus machines schedule, shown in Figure 3, is used to organise the flow of fixtures between machines and the load/unload stations.

5. CONCLUSIONS

The modern competitive world market has pressurised manufacturing companies to frequently change their product designs and to introduce new products. These continuous changes in product designs, in the context of machining facilities has resulted in adoption of modular fixtures over a more traditional specially designed fixtures. At the same time, the applications of flexible machining system has provided new challenges in the use of fixtures. These automated facilities with a low level of manning demand a reduction in the manual requirements of fixturing activities, and that these fixturing activities be planned and carried out in advance of the required time for the maximum production output.

The multi-flow scheduling research has investigated the application of simultaneous generation of schedules for the flows of workpieces, cutting tools and fixtures within flexible machining cells to harmonise the interactions between these flows. Furthermore, this research has identified three distinct fixturing practices and developed appropriate planning strategies for effective management of fixture flow. In addition, a novel approach, termed fixture oriented, for allocation of jobs based on the commonality of their fixturing requirement has been implemented within the multi-flow scheduling system. The fixture oriented job allocation rule will significantly reduce the number of required fixturing activities and can result in a lower level of fixture inventory requirements.
6. ACKNOWLEDGEMENT

This work has been carried out as a part of a Governmental funded research programme from the Control, Design and Production Group of the Engineering Physical Science Research Council, entitled “Multi-Flow Control to Improve Flexible Batch Manufacturing Performance”. The authors would like to acknowledge the work of the LUT FMS research group and the supporting work of the industrial collaborators namely, The CIMulation Centre Ltd, ISIS Informatics Ltd, Camtek Ltd and Cincinnati Milacron UK Ltd.

7. REFERENCES


Appendix 4

A METHODOLOGY TO DEVELOP EXPRESS DATA MODELS

A4.1. Introduction

This paper was published in the ‘International Journal of Computer Integrated Manufacturing’ (Rahimifard and Newman 1996a). Through various methods and techniques for information modelling, a methodology has been developed to generate a complete and accurate data model in EXPRESS for a system from its original data requirements. The paper provides a description of this methodology in which some of the advantages of well-established techniques in software engineering, namely IDEF0 and YOURDON are utilised. This methodology has been used to develop the EXPRESS data model for the multi-flow controller, as outlined in appendix 5.
A METHODOLOGY TO DEVELOP EXPRESS DATA MODELS

S. Rahimifard* & S.T. Newman*1

Abstract

In recent years the development of the formal data specification language EXPRESS, by the STEP committee, has been a significant advance towards a computer-interpretable form of data model. One of the major advantages of having the data model in this form is that it can be tested, validated and then translated into a format convenient to the users and system requirements. Through evaluation of various methods and techniques for information modelling, a methodology has been developed to generate a complete and accurate data model in EXPRESS for a system from its original data requirements. The methodology aims to utilise some of the advantages of well established methods and techniques in software engineering, namely IDEFO and YOURDON together with advancements in information exchange which have become available through the EXPRESS language and its supporting software tools. This paper describes the stages involved in the data modelling methodology and highlights the logical connections between these stages. The information obtained in each stage can easily be used as the starting point for the next one in order to generate an EXPRESS model.

1. Introduction

Effective information exchange is the key to integrated manufacturing. Integration of the manufacturing functions is one of the best ways to achieve higher productivity, reduce the design, planning, manufacturing and delivery time, and to improve the overall performance of a factory (Chadha et al. 1991). Information systems are increasingly playing an important role towards the integration of the manufacturing functions. Information/data models are constructed to understand the requirements, specification and the functionality of such information systems. The information generated during the specification, design and manufacture of a product is used for many purposes. The use may involve many computer systems, including some that may be located in different organisations or even on

1 * Department of Manufacturing Engineering, Loughborough University of Technology, UK.
remote sites. Thus the need to have information models in a computer-interpretable form will become vital in the future (Kusiak 1992).

Several tools and modelling methodologies have been developed to facilitate the design and generation of information models for complex manufacturing environments. However, none of these tools and methodologies provide a systematic structure that can be used for the development of information models from start to finish (Chadha et al. 1991, Czernik and Quint 1992). Most of these techniques and methodologies have used some kind of graphical representation of a system where data elements, data flows and to some extent the functionality of the system can be illustrated through a set of diagrams. These diagrams are helpful in visualisation and comprehension of the information structure. However, these diagrams cannot easily be coded, compiled and converted into a format suitable for computers.

In order to be able to exchange information there is a need for the data that represents the information together with the interpretation rules. To exchange information reliably, all parties in the communication process need to be operating with the same set of interpretation rules, thus it is necessary to reach agreement on these rules. A number of attempts have been made to define standards to be used for the information exchange. In recent years the activity of STEP (STandard for the Exchange of Product data model) committee has been predominate. As a result, a set of part documents have been produced, known as the ISO 10303-series standard, an overview of which is provided in section 2.

The work reported in this paper describes the utilisation of ISO 10303-series standard within one of the sub projects of a European research programme, entitled EUREKA-FORCAST (Flexible Operational Real-time Control And Scheduling Tools). An overview of the structure of FORCAST is given in section 3 with a summary of the role of sub project 4 provided in section 4. The main part of the paper describes the data modelling methodology for the development of EXPRESS models, with the final sections of the paper illustrating the utilisation of these models for the integration of different software products via SQL (Standard Query Language). The authors would like to acknowledge that during the preparation of this paper a number of other methodologies and software tools have been developed to aid in generation of EXPRESS models and the use of STEP standards.
2. ISO 10303-series standards - An Overview

The STEP initiative is a multi-national effort directed at facilitating the creation of a standard to exchange product design, manufacturing and supporting data (Yang 1991). STEP is the name of a set of documents which are known as the ISO 10303-series standards (ISO 1992). PDES is an activity which is contributing to STEP (Kiggans 1991), the PDES acronym is Product Data Exchange using STEP. Additionally, ISO/STEP is the informal name used for the international organisation ISO/TC184/SC4 and its related working groups, the developers of the standard (Kusiak 1992).

The objective of this standard is to provide a mechanism that is capable of describing product data throughout the product life cycle, independent from any particular computer system. The nature of this description enables mechanisms to be defined for physical file exchange, for database implementation, and for direct access to product data by application programs.

ISO 10303 uses a formal data specification language, EXPRESS, to specify the representation of product information (ISO 1993). The syntax of a number of computer programming languages have contributed to EXPRESS including principally Ada, C, C++, Modula-2, Pascal and SQL. Some novel facilities have been invented to make EXPRESS more suitable for the job of describing a standard information model.

The use of a formal language enables consistent representation of information within data models. The approach for representation is to provide one definition of the product data common to many applications. These common representations can be tailored to meet the needs of specific applications. The use of EXPRESS models specified in ISO 10303 is defined by mapping from the EXPRESS language onto the formal language or formal notation used for the particular application.

The problem of modelling information, although to some extent similar, is not the same as for designing a database. EXPRESS is not a database design language and it is not an executable language. Special purpose tools are required to make EXPRESS models suitable for application software development. The generation of such tools has been the focus of many research and development projects and a number of tools such as syntax checker, semantic checker, translators and populators have already been developed (NIST 1991, CADDETC 1993).
3. FORCAST Project

The FORCAST project began in April 1991 for two years, following a 6 month feasibility study in 1990 which established the need and specific requirements for the project (The CIMulation Centre 1990. There were seventeen industrial and academic collaborators, covering four European countries. The overall project aim was to provide both manufacturing and process based companies with software tools, mechanisms and standards for the integration of production planning and control systems with simulators, and to introduce an open environment in which control, scheduling and simulation tools may be effectively integrated to improve and support reliable control of manufacturing operations (Parsons et al. 1992).

FORCAST comprised of six sub projects, as illustrated in Figure 1. Sub projects 2-5 tackled 'niche' areas of manufacturing such as the application of simulators, schedulers, controllers and mimics. Sub project 1 concentrated on investigating business needs and specifying the requirements for the support tools, and sub project 0 was responsible for the development of a neutral form for information exchange between sub projects.

Figure 1: FORCAST Project Structure
One of the major objectives of FORCAST was to develop a standard for the implementation of interconnected modules and functions between schedulers, simulators, control systems and other software packages developed in 'niche' sub projects(Godwin and Saunders 1993). This was to be achieved by providing sub project 0 with a data model of software systems used in each sub project in a specific format, as illustrated in Figure 2. Through evaluation of a number of tools and methodologies, the EXPRESS language was seen to be a suitable tool to construct these data models. The data models were then to be analysed and converted to a neutral format, termed the FORCAST standard which was then to be used by the sub projects for the information transfer.

Figure 2: Schema Used to Develop FORCAST Standards

4. Sub Project 4 of FORCAST

Sub project 4 was concerned with the interfacing of tool requirements with simulation and scheduling. Tool in this case, refers to cutting tools as used in machining cell environments. A research programme in the area of tool management had been carried out by the Tool Management Research Group at Loughborough University and as a result a number of software tools were developed to aid the designers of machining cell in designing an appropriate tooling management system. This termed the Tool Management Planner(TMP) software, consists of five modules(de Souza et al. 1991), namely:-
i) Expert Scheduler
ii) Computer-Aided Cluster Analysis
iii) Tool Requirement Planner
iv) Tool Strategy Selector
v) SIMAN Tool Flow Models

The Expert Scheduler is a knowledge based system that generates a job list based on initial job information from orders and some manufacturing goals, specified by the user on an interactive basis. The Tool Requirement Planner module calculates the tooling requirement of the jobs according to a number of workpiece-oriented tooling issue strategies, namely kitting, differential kitting and single tooling (de Souza et al. 1991), whilst the Computer-aided Cluster Analysis module calculates the tooling requirements for a tool-oriented tooling issue strategy, namely the tool clustering (de Souza and Bell 1991). The tooling requirements for all these strategies are compared in the Tool Strategy Selector module, in relation to alternative manufacturing goals such as maximum machine utilisation and minimum throughput time. Having compared the tooling requirements for various strategies in relation to manufacturing goals, a strategy is advised by the Tool Strategy Selector to be the most suitable tooling issue management strategy for a particular application. The selected strategy is then used in the appropriate SIMAN (Pegdon et al. 1990) tool flow model to simulate the operation of the manufacturing facility for the purpose of validation, and to ensure that manufacturing goals such as due dates for parts are met. The flow chart in Figure 3 shows the sequence of the use for these modules.

The objectives of sub project 4 were to provide a comprehensive data definition and data model from the tooling viewpoint in manufacturing to be used for development of the FORCAST standards. Data models can be constructed with various levels of detail. The original data models required to generate the core of the FORCAST standard, however, needed to include at least the following:

- a detailed list of all data elements used by the system.
- representation of the flow of data between the sub systems of this system.
- a clear knowledge of functions and procedures that would update the raw data to the required information.
In the construction of an EXPRESS data model for these software modules, a problem presented itself in deciding the best method to collect all the necessary information before the generation of EXPRESS code. As a result, a data modelling methodology has been designed and tested as outlined below.

5. Data Modelling Methodology (DMM)

As previously mentioned, the development of EXPRESS models requires a preparation stage by which all the relevant information required to develop the actual code is collected, formatted and documented so that it can be used by the programmer or the code generator. Through evaluation of various methods and techniques for information modelling, a methodology has been developed to generate a complete and accurate data model in the EXPRESS language for a system from its original data requirements. The methodology aims to utilise some of the advantages of the well established methods and techniques in software engineering, namely IDEF0 and YOURDON together with advancements in information exchange which have become available through the EXPRESS language and

Figure 3: Tool management Planner System Structure
its supporting software tools. It should be noted that this methodology was not developed to replace any of the other information modelling methodologies, such as IDEF0 and YOURDON, but to highlight the effective use that maybe achieved by the utilisation of these methodologies in a logical manner/order.

The steps involved in the DMM are interconnected in that the information contained in each stage can be used as a starting point for the process of the next stage. Although the development of diagrams and tables required in each stage is relatively straightforward, a working knowledge of both the IDEF0 and YOURDON methodologies is necessary. The stages of DMM are shown in Figure 4 and are summarised as:-

i) identification of the data requirements for the system using input/output diagrams.
ii) construction of a data index.
iii) modelling of the information flows using IDEF0 diagram.
iv) specification of the functionality of the system using the YOURDON methodology.
v) specification of entity relationships via an express-g diagram.
vi) development of the data model in express using the information collected in the five previous stages.

![Figure 4: Data Modelling Design Methodology](image)
These stages are further explained below with the aid of the example of the TMP system.

5.1. Data Requirements (Input/Output Diagrams)

The first stage of DMM is the identification of the data requirements which is of paramount importance in the design and analysis of any system. Inevitably the generation of the data requirements will always start with the production of a list of inputs and outputs to and from the system. This list of I/O to/from the system might not provide an accurate explanation of the system behaviour, but it clarifies many aspects about system functionality. In Figure 5 a simple and yet effective method is used to summarise I/O to/from the TMP system. This method is used to identify the I/O requirements for each module within the TMP.

![Figure 5: Summary of Input / Output Data to / From Tool Management System](image)

5.2. Data Index

In many systems there are overlaps between the initial data requirements of the sub-systems. It is also possible for the output of one of the sub-systems to become the input to another. Therefore, having all the data elements tabulated in a format shown in Figure 6, helps to identify the commonality of the inputs to the sub-systems and the flow of data between them. In Table 1, the first column consists of a list of all of the inputs and outputs of the modules of the TMP system taken from I/O diagrams. All the software modules considered are shown across the first row of the table. Then, an 'i' or 'o' is used in the appropriate column to indicate that a data element is an input to or an output from the modules. This data index, also contains an initial indication of the manner in which data elements must be grouped together for effective information management.
<table>
<thead>
<tr>
<th>Data elements</th>
<th>SIMAN</th>
<th>TRP</th>
<th>CACA</th>
<th>SCHED</th>
<th>TSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning horizon</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>No. of jobs</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Job priorities</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Machine group</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>No. of machines in each group</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Transporter type</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>No. of transporters</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Transfer batch size</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Part types</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Max. no. of sub operations allowed</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Operations and sub-operations per part</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Duration for each sub-op</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Tool type for each sub-op</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Pallet type</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Retention time</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>No. tools in each kicluster</td>
<td>i</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tool types in each kicluster</td>
<td>i</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total no. of tool types</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Tool life</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Max. permissible tool life</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Machine utilization</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average machine utilization</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Animation of model layout</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process batch size</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>No. of machines visited per job</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Pallet capacity</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Average tool change time</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Primary tool store capacity</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Cost of individual tools</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Total no. of tools used</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Total no. of sister tools used</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total tool life used</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of tool kicluster</td>
<td>o</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total tooling cost</td>
<td>o</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of required tool clusters</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starting time of the first jobs</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Machine type</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Transporter capacity</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Machine loadunload times</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Tool loadunload times</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Palletizingdepalletizing times</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Average transport times for parts</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Average transport times for tools</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Cell job list</td>
<td>o</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Workstation job list</td>
<td>o</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starting times of the jobs</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finishing times of the jobs</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tooling traffic</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td>i</td>
</tr>
<tr>
<td>Best tooling strategy for overall system</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Best tooling strategy for a cell</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Best tooling strategy for a workstation</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Best tooling strategy for related batch</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Justification of a selected strategy</td>
<td>o</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SIMAN: Simulation models
TRP: Tool requirement planner module
CACA: Computer-aided cluster analysis module
SCHED: expert scheduler module
TSS: Tool strategy selector module

Table 1: Data Index, Table of Input and Output Data for TMP system
5.3. IDEF0 Diagrams

A number of methods and techniques have been used in the 70's and 80's to help system designers in the task of specification, design and analysis. IDEF0 is one of the most popular methods because it is easy to comprehend and its hierarchical approach has the ability to model a system in many levels of detail (Colquhoun and Baines 1991, Colquhoun et al. 1988). In order to establish the relationship between data elements, the data flows in the system has to be considered. In addition to data flows, the control parameters, variables and software tools are some of the other important criteria that need to be modelled. IDEF0 diagrams are particularly suitable to represent these criteria. Figure 6 is an example of an IDEF0 diagram that has been developed for the TMP system based on the information obtained from the I/O diagrams and the data index. However, while considering complex systems the number of arrows in IDEF0 diagrams can lead to confusion and difficulties. The functionality of the system, i.e. how the raw data gets converted into the required information, is not modelled in IDEF0. IDEF1 and IDEF1x (Chadha et al. 1991) were developed to help these shortcomings, but they have not gained the same popularity of IDEF0.

![Figure 6: Data Flow Between Sub-systems of Tool Management Planner System](image)

**Figure 6**: Data Flow Between Sub-systems of Tool Management Planner
5.4. YOURDON Methodology

The YOURDON methodology has been utilised as a part of the DMM to describe the functionality of a system. Three forms of diagrams have been used, namely the context diagram, the state transition diagram and the data flow diagram. The context diagrams in the YOURDON methodology, identify the data interactions between a system and its user and therefore highlights the user interface requirements. The state transition diagrams and the data flow diagrams of YOURDON are designed to aid the modelling of the functionality of a system (Yourdon 1989).

A set of YOURDON diagrams for the TMP system are show in FIGURE 7 and 8. The calculation of tool requirements for an application, as mentioned in section 3, is done in two stages for the tool-oriented and workpiece-oriented strategies. Therefore, these have been represented in different state transition diagrams and data flow diagrams. The information contained at this stage of the DMM is used to aid in the generation of the EXPRESS-G diagram, described below.

![State transition Diagrams for calculating Tool Requirements](image)

![Data Flow Diagrams for calculating Tool Requirements](image)

Figure 8: Yourdon Diagrams for Calculation of Tool Requirements
Context Diagram For The Tool Management Planner System

State Transition Diagram For The Tool Management Planner System

Data Flow Diagram For The Tool Management Planner System

Figure 7: YOURDON Diagrams for Tool Management Planner
5.5. EXPRESS-G Diagram

In recent years the popularity of Object Oriented Programming (OPP) in the area of software engineering has experienced a significant increase (Booch 1991). Within the OOP environment, the definition of the relationship between an entity and its attributes is of paramount importance. The definition of these relationships is only possible through the comprehension of the logic and functionality of a system. EXPRESS-G is a graphical representation of the entity and attribute relationships (ISO 1993), where an attribute can be of a pre-defined type or a type defined by the user of the system. In EXPRESS-G diagrams, entities are represented by a box and attributes are lines that connect the entity box to attribute types. Information and knowledge obtained from previous stages of the DMM have been used to produce the EXPRESS-G diagram, illustrated in Figure 9. In this diagram, the boxes representing tool, part, jobs, machines, etc are entities and those containing time, id-type, integer, string, etc are attribute types whereas lines connecting these are the attributes of the entities considered. These entities and their attribute are extracted from I/O diagrams and the data index and the entity relationships are identified using the IDEF0 and YOURDON diagrams. An example of how an entity and its attributes and relationships are defined in EXPRESS code using information collected in these stages of the DMM is given in section 5.6.

![Express-G Diagram](image-url)

**Figure 9**: Express-G Diagrams for Tool Management Planner
5.6. EXPRESS Code

The DMM has been examined by developing an EXPRESS model for the TMP software. The I/O diagrams together with the data index are used to define the schema and its entities and attributes. The data flow, data relationship and functionality represented in IDEFO, YOURDON and EXPRESS-G diagrams are used in the definition of type, supertypes, functions and procedures in the EXPRESS code.

As an example, let us consider the generation of EXPRESS codes for the entity tool which for the obvious reason is one of the main entities in the data model. From the data index, it is clear that tool type and tool life are the attributes of the entity tool. The IDEFO and state transition diagram indicate that before being able to calculate tool requirements a schedule must be produced. This introduces two new attributes of load_time and unload_time for tool. Selection of a tooling issue strategy is based on the cost of tools and number of tool changes (see Figure 6) which will from other attributes, namely the tool cost and tool traffic. The definition in EXPRESS language is as follows:

```
ENTITY Tool;
    Tool_Type : ID_Type; (* ID-Type is defined as STRING
(5)*)
    Tool_Life : Time;
    Load_Time : Time;
    Unload_Time : Time;
    Tool_Traffic : Integer;
    Tool_Cost : Currency;
END_ENTITY
```

The state transition diagram, identifies that tool requirements are calculated in two steps, firstly for the tool-oriented issue strategy where tool sets are called tool clusters, and then for the workpiece-oriented strategies where tool sets are referred to as tool kits. Therefore, a tool-set is defined as a supertype which has the subtypes kit and cluster :-

```
ENTITY Tool_Set;
    ABSTRACT SUPERTYPE OF (Kit AND Cluster);
    Tool_Set_ID : ID_Type;
    Tools : SET [O:?] OF Tool;
END_ENTITY;
```
ENTITY Kit ;  
(* is a collection of cutting tools required to machine a single part type*)
SUBTYPE OF (Tool_Set);
END_ENTITY ; 

ENTITY Cluster  
(* is a collection of tools required to machine a number of part type*)
SUBTYPE OF (Tool_Set) ;
    Retention_Time : Time ; (Min Period of time, for which the cluster is left on the machine (idle) *)
END_ENTITY ; 

It can be seen that all the information and knowledge required to construct the EXPRESS model can be extracted, step by step, from information contained in the various stages of the DMM. In fact the development of EXPRESS code can be done by a different person, who has not worked closely with system, providing each stage of the methodology is properly documented. 

The EXPRESS model can be useful in a number of ways. One of the major advantages of having the data model in a computer-interpretable form is that it can be tested, validated and then converted into a more convenient format according to the user and system requirements. Typical converted formats of an EXPRESS model are; data structure in an include file used by C programs, SQL codes which form the basis of a database structure, or classes of objects that can be used in OOP environment. The following two examples in section 6 and 7 describe the use made of the EXPRESS models in Sub Project 4 of the FORCAST project.

6. Database Design Using EXPRESS Models

Information management systems are an integral part of most software systems. The design and specification of DBMS's can be very complex and a time consuming process. Development of a data model is similar to the design of a database. Furthermore, there is a close relationship between the structure of a data model and that of the corresponding database. This has been recognised by the development committee of the EXPRESS language and those users of the language. Therefore, various sources are developing
translators (NIST 1990, Rutherford Appleton Laboratory 1992) for EXPRESS that would convert EXPRESS code to their corresponding code in SQL.

One such translator was used to convert the EXPRESS model of the TMP system into a set of corresponding SQL code. The result is a series of 'create' commands in SQL which have been used to produce a database structure to be populated with case study data for testing of the TMP system. The database consists of some fifteen tables corresponding to the entities in the EXPRESS model. These tables are capable of storing initial information required by the TMP system and holds the output produced by its software modules.

7. Integration and Interfacing Using EXPRESS Models

One part of the work of sub project 4 was to link simulation software produced in sub project 4 with scheduling software of the sub project 2. In discussions with other sub projects, which were also linking their software together, it was identified that STEP physical files (Altermueller 1988) were being used as a means of file transfer.

In the case of integration between software tools where neither of the tools have the capability to directly use the STEP physical files, as is the case for information transfer between software of sub project 4 and 2, conversion of ASCII files into STEP files would not have helped, but added to the complexity of the issues involved. Therefore, a different approach to information transfer was planned using EXPRESS models. This approach has utilised a Relational Database produced by translating the EXPRESS schema of the data to be transferred into corresponding SQL codes (Rahimifard and Newman 1994). These SQL codes formed the structure of a database used to store the information to be passed between the software tools, namely the SIMAN Tool Issue Strategy Selector (STISS) (TMS Research Group 1993) and the PREACTOR (The CIMulation Centre 1994) scheduler, as illustrated in Figure 10.

This approach was tested by passing a limited amount of information generated by the simulation models to the scheduler. An EXPRESS schema has been developed for the part information contained in the job list used by STISS, together with some information on the tooling requirements of the jobs. This EXPRESS schema was translated into SQL. The SQL codes were used to form a database structure. The part and tool information produced by STISS were entered into the database and then the appropriate files, in the
format required by PREACTOR were generated. The major advantage of this approach is that in the process of information transfer a database is produced which can store the information as it is being transferred.

![Diagram](image)

**Figure 10**: Information Transfer Between Sub-project 2 and 4 via a Relational Database

8. Conclusions

A series of work packets have been carried out in each of the sub projects of the FORCAST project to develop the fundamental requirements for the initial core of the FORCAST standards. These work packets have concentrated primarily on the utilisation of the latest technology in the area of information modelling and information exchange offered through the development of ISO 10303 standards by the STEP committee. The result has been the development of a number of data models in the EXPRESS language by various sub projects which form the core of the FORCAST standards.

A methodology has been developed to produce EXPRESS models based on initial data requirements of a system. Based on this methodology a number of EXPRESS models have been developed for the area of tool management in flexible manufacturing systems. These models were then translated into SQL codes to produce a database structure. Using
an EXPRESS schema for database design, a number of tool flow simulation models and scheduling system have been integrated. This integrated software environment will be used for further research into the scheduling of parts, fixtures and cutting tools within flexible machining cells.

9. Acknowledgements

This work has been carried out as a part of a European research programme, entitled Eureka 358 FORCAST (Flexible Operational, Real-time Control and Scheduling Tools). Funding in UK was partially provided by the Department of Trade Industry. The authors would like to acknowledge the work of the LUT TMS Research group and the supporting work of participants in sub project 0 and 2 of the FORCAST project.

10. References

CADDETC, 1993, DECEXPRESS, CADDETC Ltd, Leeds, UK.


NIST, EXPRESS Toolkit, *National Institute of Standards and Technology*, U.S.A.


Rutherford Appleton Laboratory, 1992, Code Generation to Produce SQL statements for the direct implementation of a relational database from an EXPRESS model, *Rutherford Appleton Laboratory*, Oxon, UK.

The CImulation Centre, 1994, PREACTOR User Manuals, *The CImulation Centre*, Chippenham, UK.


Appendix 5

AN EXPRESS DATA MODEL FOR THE MULTI-FLOW CONTROLLER

A5.1. Introduction

This appendix provides the EXPRESS data model generated for the multi-flow controller, using the methodology described in appendix 4.

A5.2. EXPRESS Language

Several tools and modelling methodologies have been developed to facilitate the design and generation of information models for complex manufacturing environments, such as the multi-flow controller. Most of these techniques and methodologies, such as IDEF0 or YOURDON methodologies, have used some form of graphical representation of a system where data elements, data flows and to some extent the functionality of the system can be illustrated through a set of diagrams. These diagrams are helpful in visualisation and comprehension of the information structure. However, they cannot easily be coded, compiled and converted into a format suitable for computers. A number of attempts have been made to define standards to be used for information exchange. In recent years the activity of STEP (STandard for the Exchange of Product data model) committee has been predominate. As a part of these standards, a formal data specification language, termed EXPRESS has been developed which is a significant advance towards a computer-interpretable form of data model. The research reported in this thesis has defined a dual role for an information model based on the data requirements of the multi-flow controller, in a neutral format of an EXPRESS data model. Firstly, the data structures contained in the information model have been utilised to design and implement a manufacturing database as one of the modules of the multi-flow controller. Secondly, this EXPRESS data model can be used as the basis of integration of the multi-flow controller into a CIM structure using STEP standards, as previously outlined in appendix 4.
5.3. EXPRESS Model

Title : Multi-Flow Controller
Description : The information model to support an integrated structure for the planning and control of flexible machining cells
Version : 6.4
Author : S. Rahimifard

Include 'inc.es'

SCHEMA Multi-Flow Controller ;

REFERENCE FROM General ;

Type
  ID_Type = STRING(24) ;
END_Type ;

Type
  (* a set of tools are transported together to a machine, and parts are mounted on a fixture before being transported *)
  Transportable_Items = Enumeration of (Toolkit, Fixture) ;
END_Type ;

ENTITY Joblist
  (* a list of orders for a quantity of a unique part type to be completed by a specific due date *)
  Job_ID : ID_Type ;
  Priority : INTEGER ;
  Part_Type : ID_Type ;
  Batch_Size : INTEGER ;
  Operation_No : INTEGER ;
  Operation_ID : ID_Type ;
  Lot Number : INTEGER (* Lot Number = Transfer Batch *) ;
  Toolkit_ID : ID_Type ;
  Fixture_ID : ID_Type ;
  Machine_ID : ID_Type ;
Preferred_Machine : STRING(10) ;
Op_time : REAL ;
Start_Date : Time ;
Due_Date : Time ;
END_ENTITY

ENTITY Part
(* a part type is used to refer to a component or a sub-assembly *)

Part_Type : ID_Type ;
Part_Description : STRING(30) ;
Part_Ops : LIST [1 : ?] of Operation ;
(* part_operation refers to a list of all sub-operations required to machine
a part type *)

Tools_Required : Set of [1 :?] of Tool ;
Fixture_Required : Set of [1 :?] of Fixture ;
END_ENTITY ;

ENTITY Tool
(* a tool in this information model refers to a tool assembly consisting at least of a
tool holder, a cutting tip holder and a cutting tip *)

Tool_Type : ID_Type ;
Tool_Description : STRING(30) ;
Tool_Life : Time ;
(* Tool life can be based on a time period, e.g. 90 mins, or a number of parts that
can safely machined with a tool, e.g. 35 parts *)

Tools_Used_In : LIST of [1 :?] of Toolkit ;
END_ENTITY ;

ENTITY Toolkit
(* a collection of tools required to process a transfer batch, a job or
a cluster of jobs *)

Toolkit_ID : ID_Type ;
Toolkit_Description : STRING(30) ;
Tools_Included : Set [1 :?] of Tool ;
Part_Used_With : LIST of [1 :?] of Part ;
END_ENTITY ;
ENTITY Fixture
    Fixture_Type : ID_Type ;
    (* fixture type can refer to specially designed fixtures or Modular fixtures *)
    Fixture_Description : STRING(30) ;
    Quantity_Available : INTEGER ;
    (* with modular fixtures, quantity refers to maximum number of fixtures that can
    be assembled with available fixturing elements *)
    Part_Used_With : LIST of [1:?] of Part ;
END_ENTITY ;

ENTITY Transporter
    Transporter_Type : ID_Type ;
    (* transporter can be used for movement of fixtures i.e. parts, or toolkits i.e. tools *)
    Transporter_Description : STRING(30) ;
    (* a transporter can be an automatic material handling, e.g. an AGV or robot, or
    a manual material handling, e.g. an operator used for transportation of tools *)
    Transporter_Contents : Transportable_Items ; (* Fixture or Toolkit *)
    Transporter_Capacity : INTEGER ;
    Quantity_Available : INTEGER ;
    Load_Unload_Time : Time ;
    Speed : REAL ;
END_ENTITY ;

ENTITY Operation
    (* a list of machining process requiring a set of tools to machine a part type *)
    Operation_ID : ID_Type ;
    Operation_Description : STRING(30) ;
    Toolkit_Required : Set of [1:1] of Toolkit ;
    Fixture_Required : Set of [1:1] of Fixture ;
    Sub_Ops_Included : LIST of [1:?] of Sub_Operation ;
    (* operations are divided into a number of sub-operations, in order to be able to
    monitor the tool life *)
    Op_Setup_Time : Time ;
    Op_Time : Time ;
END_ENTITY ;
ENTITY Sub_Operation

(* a machining process requiring a single tool type *)

Sub_Operation_ID : ID_Type ;
Sub_Operation_Description : STRING(30) ;
Tool_Required : Set of [1:1] of Tool ;
Sub_Op_Setup_Time : Time ;
Sub_Op_Time : Time ;

(* sub-operation time is used to plan and monitor the tool life *)
END_ENTITY ;

ENTITY Machine

(* machines can be of identical make, or different makes but identical machining capabilities *)

Machine_ID : ID_Type ;
Machine_Description : STRING(30) ;
Tool_Magazine_Capacity : INTEGER ;
Pallet_Capacity : INTEGER ;
Machine_Setup_Time : Time
END_ENTITY ;

ENTITY Machine_Group

Machine_Group_ID : ID_Type ;
Machine_Group_Description : STRING(30) ;
Machines_Included : LIST of [1:?] of Machine ;
END_ENTITY