Resource selection and route generation in discrete manufacturing environment

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RESOURCE SELECTION AND ROUTE GENERATION IN DISCRETE MANUFACTURING ENVIRONMENT

BY

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Dedicated to God, the Virgin, my parents,
my sister and brother, my brother-in-law,
my nephew and Adnan.

Declaration

I hereby declare that the work reported in this thesis has not been previously submitted for any degree. All material in this thesis is original except where indicated by reference to other work.

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ABSTRACT

When put to various sources, the question of which sequence of operations and machines is best for producing a particular component will often receive a wide range of answers. When the factors of optimum cutting conditions, minimum time, minimum cost, and uniform equipment utilisation are added to the equation, the range of answers becomes even more extensive. Many of these answers will be 'correct', however only one can be the best or optimum solution.

When a process planner chooses a route and the accompanying machining conditions for a job, he will often rely on his experience to make the choice. Clearly, a manual generation of routes does not take all the important considerations into account. The planner may not be aware of all the factors and routes available to him. A large workshop might have hundreds of possible routes, even if he did 'know it all', he will never be able to go through all the routes and calculate accurately which is the most suitable for each process - to do this, something faster is required.

This thesis describes the design and implementation of an Intelligent Route Generator. The aim is to provide the planner with accurate calculations of all possible production routes in a factory. This will lead up to the selection of an optimum solution according to minimum cost and time. The ultimate goal will be the generation of fast decisions based on expert information.

Background knowledge of machining processes and machine tools was initially required, followed by an identification of the role of the knowledge base and the database within the system. An expert system builder, *Crystal*, and a database software package, *DBase III Plus*, were chosen for the project.

Recommendations for possible expansion of and improvements to the expert system have been suggested for future development.

ABBREVIATIONS

AI	Aritificial Intelligence
ASRS	Automated Storage and Retrieval System
BOM	Bills of Material
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacture
CAPM	Computer-Aided Production Management
CAPP	Computer-Aided Process Planning
CIM	Computer-Integrated Manufacturing
CPN	Coloured Petri Nets
CRP	Capacity Requirements Planning
DBMS	Database Management System
DCA	Design Compatibility Analysis
DDBMS	Distributed Database Management System
DFA	Design for Assembly
DFM	Design for Manufacture
DNC	Direct Numerical Control
FDL	Function Description Language
FMS	Flexible Manufacturing System
GPN	General Petri Nets
GT	Group Technology
JIT	Just in Time
KBS	Knowledge-Based System
MCKS	Multiple Cooperative Knowledge Sources
MPC	Manufacturing Planning and Control
MPS	Master Production Scheduling
MRP	Manufacturing Resource Planning
NC	Numerical Control
PAC	Purchasing and Production Activity Control
RCCP	Rough Cut Capacity Planning
SFC	Shop Floor Control
SMED	Single Minute Exchange of Dies
UPN	Updated Petri Nets
WIP	Work-In-Progress

NOTATION

α	cost of setting up and operating a specific process
ρ	material density
β	process specific total tooling cost for an ideal design
t_0	change over time
t_{t_C}	cutting time
f_t	feed per revolution per teeth
C_1	hourly machine rate
n_p	number of passes
n_t	number of teeth on cutter
t_2	processing/machining time
t_i	setup time / component changing time
t_3	tool changing time
t_c	tool changing time
C_t	tool cost
t_T	total transportation time
T_h	workpiece handling time
C_B	cost per batch
C_{B_P}	cost per batch for processing
C_P	cost per part
x_T	cost rate of transportation equipment
C_o	direct labour wage / productive hour cost for the machine and operator
$L_{x,y}$	distance value between two consecutive machines in a route
f_{dt}	drilling of tapping feed rate
f_m	feed rate
$t_{2_{Final}}$	final processing / machining time
C_2	hourly settinfg rate
T_M	machine tolerance
C_{B_M}	material cost per batch
t_{2_R}	retrieve tool / retrack time
T_{th}	tool handling time per workpiece

C_B	total cost per batch
C_{B_T}	transportation cost for batch
$C_{T_{x,y}}$	transportation cost from machine x to machine y
$t_{f,Exit}$	transportation time from last machine to exit point
$t_{x,y}$	transportation time from machine x to machine y
$T_{t_{x,y}}$	travel time between machines x and y
C_u	unit cost
s_{TR}	velocity of transportation equipment
C_{batch}	cost per batch
$L_{Entry,1}$	distance value between entry point and machine 1
$L_{f,Exit}$	distance value between last machine and exit point
s_{Rapid}	rapid feed rate
$t_{Entry,1}$	transportation time from entry point to machine 1
$t_{Tran_{Entry,1}}$	transportation time including loading and unloading times between entry point and machine 1
$t_{Tran_{x,y}}$	transportation time including loading and unloading times between machine x and machine y
$t_{Tran_{f,Exit}}$	transportation time including loading and unloading times between last machine and exit point
$t_{L/U_{Entry,1}}$	work handling equipment loading and unloading time between entry point and machine 1
$t_{L/U_{f,Exit}}$	work handling equipment loading and unloading time between lasst machine and exit point
$t_{L/U_{x,y}}$	work handling equipment loading and unloading time between machine x and machine y
$C_{component}$	cost per component
A	approach of cutter
a	machine identificator in setup 1
$a1$	distance on x axis between entry point and first machine
$a2$	distance on x axis between two machines

a3	distance on *x* axis between last machine and exit point
b	batch size
b	machine identificator in setup 2
b1	distance on *y* axis between entry point and first machine
b2	distance on *y* axis between two machines
b3	distance on *y* axis between last machine and exit point
c	machine identificator in setup 3
Cc	relative cost associated with producing different geometries by various processes
Cf	relative cost associated with obtaining a specified surface finish
Cft	the higher of *Cf* and *Ct*, but not both
Cm	cost of material per unit volume
Cmp	relative cost associated with material-process suitability
Cs	relative cost associated with achieving component section reduction/thickness
Ct	relative cost associated with obtaining a specified tolerance
d	diameter of drill
D	maximum cutter diameter / diameter being cut
Dc	component general maximum outside diameter / diameter being cut
Dw	diameter of material piece
f	last machine in each route / feed rate of spindle and shaft / feed rate
H	depth of hole to be drilled / hours per shift
h	time to setup for a batch
Hc	component height
Hs	cycle hours
i	machine number
k	number of operations
L	component length as a factor of the maximum cutter diameter / length of cut for metal cutting (length of shaft)
Lc	component length
Lw	length of material piece
m	material cost per part
m	number of machines required
Mc	manufacturing machining cost
MCc	material cost per component
MCw	material cost per unit weight

MLT	manufacturing lead time
MTBF	mean time between failures
MTTR	mean time to repair
N	lot number
n	spindle rotation / number of operations required to achieve the finished component
N	spindle speed (rotary cutting speed)
N	total component demand
Nm	number of operations or machines
O	overtravel of cutter
P	machine power
p	pitch
Pc	basic processing cost
PC	production capacity
Q	batch size
q	scrap rate
R	metal removal rate
Rc	relative cost coefficient
Rp	production rate
s, s_z, s_R, s_n	feed rate
SU	setup hours for operation as recorded from data tables
Sw	number of shifts per week
T	machining time
T	process time in seconds for processing an ideal component by a specific process
t	time to machine one part
T	tool life
Tc	component tolerance
Tm	actual machining time
Tmax	tool life corresponding to maximum production rate
Tno	non-operation time
To	operation time
Tp	production time
Tsu	setup time
Tu	time to produce a workpiece
u	table feed

U	utilisation
v	cutting speed
V	volume of material required
Vc	component volume / peripheral velocity of surface
Vmax	maximum velocity
Vmin	minimum velocity without revenue considerations
Vw	volume of material piece
W	number of work centres
Wc	component weight
WDc	component width
WIP	work in progress
x	machine cost rate
z	number of teeth

CONTENTS

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CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW

In every successful organization there are two basic characteristics. The first one is the way in which the resources are allocated in order to achieve results, especially in the short term, maintaining a strict management over its utilisation. The second is related to its extent of innovation, trying always to find new methods to learn from experience. As R.E.J. Roberts [92] stated, innovation means "new ideas implemented successfully", and it is a very important element of strategy, while management is defined as "the achievement of objectives through the proper combination of the work of others". Combining innovation with management in the design and production phases, one tries to achieve a strategic management method in order to increase the actual competitiveness of a business, "without losing control over current operations nor endangering corporate performance" [92].

In defining a project, there are certain things like identification of problems, needs, opportunities, and integration of critical elements, that should be taken into consideration in order to reach the objectives proposed. Besides this, another relevant factor is the definition of a team with frequent meetings and information exchange with regular 'cross-functional contact', having at the same time free flow of information (See Figure 1). For this project, this team will be conformed by experts from both the design and process planning areas.

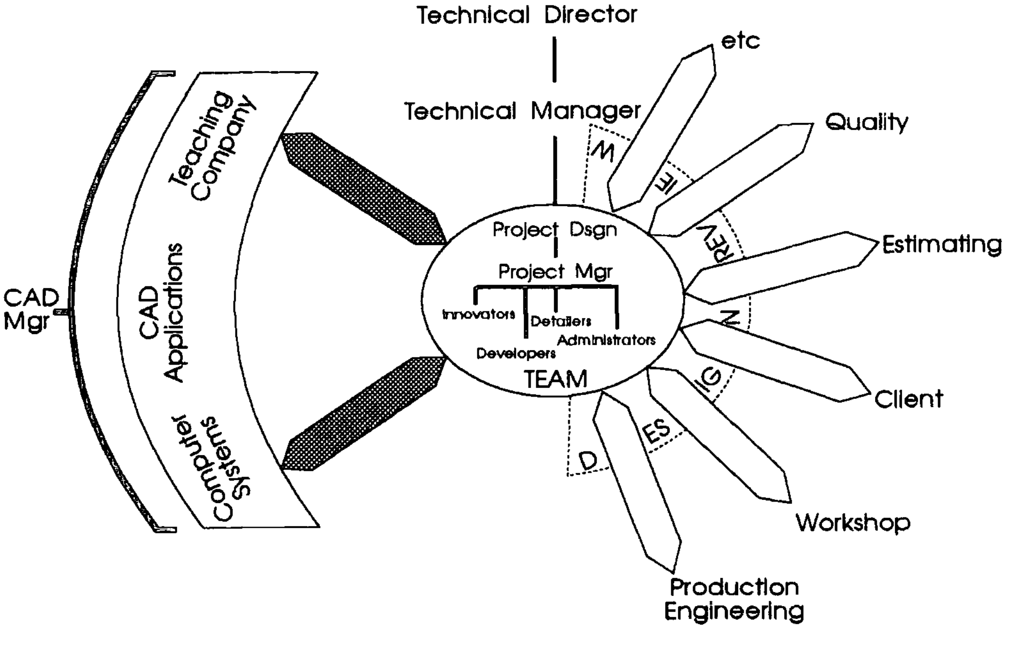


Figure 1. Design Team Structure and Interfaces

The project aims to develop a route generator for machined components. The idea is to develop a general design of a part, and identify the resources available to manufacture it, in accordance with the design and the related specifications. Since this process can increase the manufacturing cost, this is a factor that must be taken into consideration. This basic design is sent to the process planning participant, who takes into account the manufacturing considerations and generates a list of generic manufacturing processes required for producing it. Then, the designer and planner use the decision support system described herein to generate the production routes and calculate the corresponding lead times and costs. The result of this process is that the process planning is performed at the same time as the design process.

The designers can have feedback from the system at all the stages of the design process. This strongly reduces the design and process planning lead times and increases the efectiveness of detailed process planning decisions.

The IRG System

The decision support system described herein is the IRG (Intelligent Route Generator) system. This system is composed of algorithms, knowledge bases, and databases.

Various databases are used throughout, including machines and components databases. The system is knowledge-based, and so its predictions should become more accurate as the amount of information available to the system is increased.

Overview of the Thesis

The main body of the thesis is composed of seven main chapters:

Chapter one is this introduction. An explanation of the need for and aims of this project is provided. Chapter two presents some material about information technology and manufacturing systems.

Chapter three is a general description and explanation of the philosophy of the Intelligent Route Generator.

Chapter four outlines the initial investigation into the problem and the solutions chosen, by means of a knowledge-based system for route generation in discrete manufacturing, described in detail by a heuristic algorithm.

Chapter five describes the production concepts and mathematical models used in the project. Chapter six demonstrates the functionality and uses of the system, through a discussion of some case studies.

Finally, chapter seven concludes the main body of the report with conclusions and recommendations for further work.

Following the main body of the report are two further sections, the references and the appendices.

Information technology concepts such as manufacturing strategies and simultaneous/concurrent engineering are the basis for the development of a decision support system. IRG is an idea generated from knowledge-based design methodologies and resource allocation strategies. Its interface with planning constraints controlled by MRP, CRP, MPS, and MPC provides with intelligent decisions regarding managerial needs. It is an approach which improves manufacturing performance based on reduced lead times and costs. In order to achieve this, it is necessary to integrate concepts such as production systems, machine tools, and manufacturing layouts. The theoretical background of these concepts is presented in this chapter and Chaper 2.

1.1 MANUFACTURING STRATEGIES

"The introduction of new products or changed products demands flexibility and presents a wide range of management challenges" [108]. Design engineers, managers and production engineers need to be involved in order to understand and implement the changes in manufacturing that will produce substantial business improvement.

Computer-integrated manufacturing (CIM) aspects are being examined to determine their impact on businesses strategies and objectives. Some of these aspects include computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided process planning (CAPP), Robotics, direct numerical control (DNC), flexible manufacturing system (FMS), computer-aided production management (CAPM), and computer-aided engineering (CAE). CIM has been applied in many different companies and the main goals achieved are [108]:

- Major reduction in lead times, inventory, and production area
- Help to construct priorities
- Relationships improved
- Improved production scheduling
- Improvements to production systems
- Reduced work-in-progress (WIP)
- Improved communication between sales and marketing, and between engineering and manufacture
- Simplification of shop-floor system
- Elimination of storage
- Just in Time (JIT) production
- Reduction in critical manufacturing lead times

1.2 SIMULTANEOUS/CONCURRENT ENGINEERING

Simultaneous or Concurrent Engineering can be defined as "the design of a product together with its manufacturing process" [85].

O'Grady [81] says that it "involves the simultaneous consideration in the design phase of life-cycle factors such as product, function, design, materials, manufacturing processes, testability, serviceability, quality, and reliability". Its importance relies in the fact that it is in the design phase where many of the product's costs are determined. It is difficult and sometimes more expensive to try to improve a design after the product has already been designed. The cost cannot be reduced effectively once we get a product into production.

The problem is that until now, there was a sequential procedure related to the design and process planning, since the manufacturing or process engineers were not involved in the design of a product during the design process. As a consequence, there was a high increase in the period of time between the product conception and its release in the market. This results in bad products and delayed releases to the market. It is important to "be aware of the importance of teamwork between every function in the business cycle to achieve continuous improvements to our competitiveness" [70].

Concurrent engineering is one of the most effective methods used to reduce costs in today's competitive economies. Its effectiveness relies on the ability to integrate product and process design in order to achieve concurrency. Some restructuring and improvement could be done to the process planning in order to accomplish this.

The concurrent product and process planning activities for small and medium size batches can be achieved in two stages [102]:

Stage 1
Manufacture in cells to achieve the 'lowest possible production cost'. Group Technology has many useful applications in this regard.

Stage 2
Ensure that the designed or redesigned product could be manufactured within the resources available. In this way, the 'total product development cost' will be minimized. Designers can use an Artificial Intelligence design environment to help developing 'manufactured product designs'.

In order to achieve this and have a 'useful manufacturability knowledge base', it is necessary to integrate (and not just combine or interface) the CAD system and the CAPP system, but this will imply some modifications in the actual activities related to the design and process planning activities.

1.2.1 Planning for Manufacturing

Low-cost manufacturing does not just happen. There is a close relationship between the design of a product and the selection of processes and equipment required for producing the design. Each of these steps must be carefully considered, planned, and coordinated before manufacturing starts.

The steps involved in getting one product from the original idea stage to manufacturing are closely related to each other. For example, the design of the tooling is conditioned by the design of the parts to be produced. It is often possible to simplify the tooling if certain changes are made in the design of the parts or the design of the manufacturing system. Similarly, the material selection will affect the design of the tooling or the processes selected. Close coordination of all the various phases of manufacture is essential. All mistakes and "bugs" should be eliminated during the preliminary phases because changes become more and more costly as work progresses.

With the advent of computers and computer-controlled machines, the integration of the design function and the manufacturing function through the computer is a reality. This is usually called CAD/CAM. The key is a common database from which detailed drawings can be made for use by both the designer and the manufacturing engineer and from which programs can be generated to make all the tooling.

In order to help the designer, O'Grady [81] recommends the use of constraint networks, defined in the next section, which will give advice on possible design improvements. Some advantages include enough flexibility to approach the 'design problem' from a variety of ways, design with incomplete information, and ability to work with all life-cycle information.

Actually, the constraint networks are not usually recommended, especially because of the volume, variety and separation of life-cycle information and functions. One way of implementing this system is by defining a design team, but then one encounters problems like group decision-making and dissimilar knowledge, which is not up-to-date as well. In order to solve this, some 'emulated design team' strategies have been developed and they can be categorized as follows:

1) Design Rating

It is used to evaluate the ease of manufacture or assembly by assigning a numerical value to each design. The whole design is evaluated and the acceptance rating is given. In this way, poor or no feedback is given to the designer for improvements. The evaluation is done for the whole finished design instead of doing it during the design process. Another disadvantage is that 'the domain considered is usually fairly narrow'.

2) **Structured Approach**

It is eminently done for manufacturing and corresponds to a review done after the design is finished by using checklists or procedures. The results obtained could be unrealistic because of its inflexible structure. Accurate cost information is needed and this may be difficult to obtain. The results may be viewed with greater accuracy than is actually warranted. The strict structuring may be unrealistic, resulting in suboptimization.

3) **Reference Approach**

Here the designer uses reference books, databases, handbooks, standards and design guides, and incorporates this with the design in order to improve it. The designer is responsible for the consideration and integration of this information into design decisions. With this method the volume and variety of information managed by the designer is very high. Hence, it is usually very difficult to achieve optimal solutions.

4) **Automatic Design**

In this method both, the life-cycle requirements and the design, are fulfilled and generated automatically. It involves examining the requirements for the design and producing automatically a design that satisfies the life-cycle requirements specified. Not too much work has been done in this area. Because of the great amount of information and computation that has to be managed in the knowledge base, it is difficult to carry out with any degree of success.

5) **Design Advice**

After looking at the design and its requirements, some advice is given to the designer. Not too much information is needed, because it is supposed that the designer could access his own related information. The final decision of the designer is kept in a log, allowing an audit trail to be developed, in order to be able to redesign in a relatively efficient way. This is the area in which this project belongs, and is more specifically related to route and design generation.

O'Grady [81] thinks that the main requirements for a design advice system are:

- Enough flexibility allowing the possibility of considering various options
- Design regardless of incomplete information
- Handle large diversity of life-cycle information
- Interface with all other related systems (databases, CAD systems)
- User-friendly
- Enable 'design audits'

1.2.2 Constraint Networks

Every design tries to satisfy certain constraints. "A constraint network is a collection of constraints which are interconnected by virtue of sharing variables" [81]. These variables can be selected and tested either by computers, humans, or a combination of both. In the first case, the problems will be similar as those found in the Automatic Design method mentioned above. In the second one, the time and effort related even with small networks makes it impractical. Whereas the combination of these two is a very practical solution, and is known as constraint monitoring approach. SPARK [81] is an example of a constraint network language for concurrent engineering and it was developed by obtaining information from interviews with company personnel in functions related to the problem (design and manufacture) and by reviewing standards.

1.2.3 Design for Manufacture (DFM)

DFM is defined by Subramanyam [102] as "addressing the manufacturing-related concerns of individual piece parts". It is directly related to designing for cost and according to Pugh [85], its principal objectives are:

- Minimize component and assembly costs
- Minimize development cycles
- Enable higher-quality products to be made

Its basic elements are:

1) Design for assembly (DFA)
2) Design for piece-part producibility (DFP)

Work has been done by Cutkosky and Tenenbaum [23], in which "the designer specifies the design he is creating by specifying a sequence of processing steps". For example, a machined part would be defined as a blank that is shaped with operations such as holes or pockets. The methodology for achieving the DFM concept involves the "designer working in 'manufacturing' modes". In order to generate processing requirements and check for violation of constraints related to manufacturing, knowledge-based systems and solid-modelling systems are used.

1.2.3.1 Design for Assembly (DFA)

This is one of the major sub-areas of concurrent engineering, in which a lot of work has been done in recent years. It has been studied basically in two areas:

1) Selection of assembly method
2) Design for manual assembly, high speed automatic assembly, or robot assembly

DFA is based in the efficiency and cost of assembly. The user can calculate this by the use of charts and a set of rules.

The aim is to design 'good assembly practices' into a product instead of planning them into a production line. There are some approaches that enable the designer to cut down the number of parts and, therefore, make the assembly process easier. Some work has been done in relation to this. Lai [63] has presented a function description language (FDL) in which the functions of the components in an assembly are defined and then redundant ones are eliminated. Ishii [54] talks about design compatibility analysis (DCA), which tries to quantify "the degree of compatibility between design requirements (specifications) and the proposed design". Rehg [89] uses a CAD system to integrate design and assembly.

Finger [34] gives a way of performing mechanical designs that include life-cycle requirements. According to Subramanyam [102], one of the deficiencies of this method is that it is more related with the assembly level and not with the manufacture of the components. Dewhurst and Boothroyd [28] try to solve this drawback by dividing the problem into two levels. The first one is related with the principles needed to have a design with the fewest parts. The second one tries to satisfy the manufacturability constraints.

1.2.3.2 Design for Piece-Part Producibility (DFP)

This is more complex and takes into account more parameters because of the variety of possible production processes in order to manufacture a piece-part, since the information required for each one must be accessed each time. Even though some standardized information already exists, more knowledge-based systems are needed in this area to help the design team.

1.2.4 Taguichi Approach

This is a model for design process and it consists of three phases:

Phase 1 - System Design
Technology and experience are used to get the most favourable design alternative.

Phase 2 - Parameter Design
Optimal values of parameters of the design alternative obtained in the previous phase are determined.

Phase 3 - Tolerance Design
Permitted tolerances are selected for the design parameters according to the loss function of quality control.

According to Subramanyam [102], this approach is applicable for high volume production of parts on dedicated systems (e.g. transfer lines). An expert team will be formed and they will determine the product and process parameters. In this method it is necessary to know in advance the manufacturing processes needed to manufacture the part.

1.2.5 An AI-Based Design Environment

Subramanyam [102] presents a computer-based design environment for small and medium batch-sizes. With this environment, the designer can know if it is possible to manufacture the part according to the design specifications and the 'machining-related concerns'. A *model-based reasoning system* is used.

"Model-based reasoning is the knowledge-based system approach to problem solving that involves building, analysing and reasoning from an explicit computational model of the structure, principle, function, and behaviour of an underlying system. Separation of the structured/functional model of a problem domain from the problem-solving knowledge is the basis of any model-based reasoning system" [61,79]. This system is used to model the product and the manufacturing resources.

A reasoning system is based on the multiple cooperative knowledge sources (MCKS) paradigm and it involves three areas [32,49,66]:

- A database accessed by everyone
- A group of 'knowledge sources'
- A manager or controller

A computer-based knowledge source is used for each relevant task of the refinement process, such as facility selection, fixture selection, machine selection, operation selection, etc. The manager is in charge of controlling the concurrent activities between the product and the process knowledge sources.

1.3 INFORMATION SYSTEMS FOR INTEGRATED MANUFACTURING

Although intensive research in product and process design, production planning, and scheduling has been done, the full information flow between these modules has not yet been reached. This could be achieved by linking the relevant manufacturing systems (i.e. CAD, CAPP, MPC, and SFC) according to the common data between them. This common data can be classified into two groups [47]:

<u>Static Data</u>

- product data
- resource data
- process data

Dynamic Data

- planning data

In Figure 2 the flow of common data between the systems is shown.

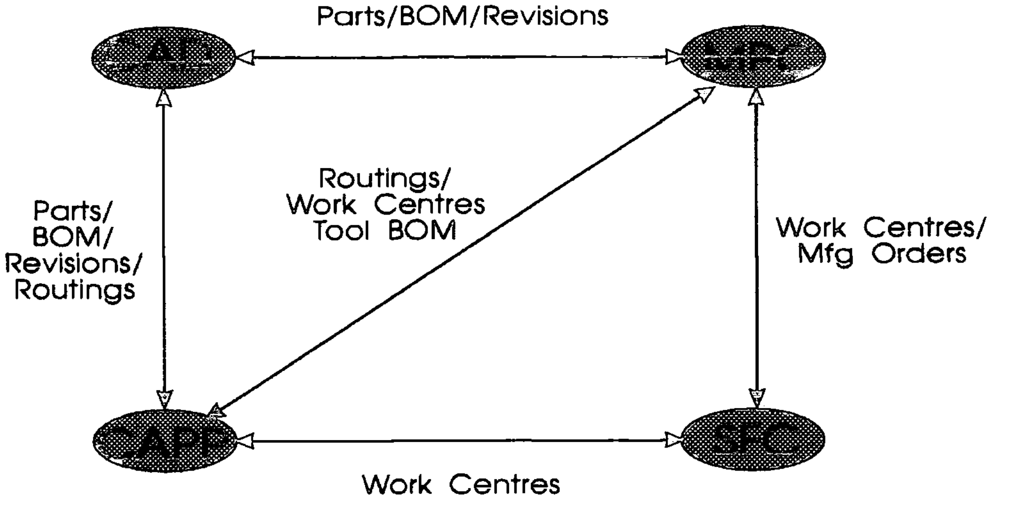


Figure 2. Common Data Flow between CAD, CAPP, MPC, and SFC

The way to reach the full flow of information proposed by Harhalakis [47] is to design "a knowledge-based system (KBS) to control the functional relationships and information flow within the elements of the integrated system". This is achieved by using Petri Nets, a tool for graphical modelling. A description of each one of the systems is given in the next paragraphs.

Computer-Aided Design (CAD)

The CAD system is in charge of the product design. By means of this application system, the design alternatives can be evaluated, new parts can be created, and existing ones can be modified. The Bill of Materials (BOM) starts here. A CAD system enables the user to design a component, product, tool, or fixture. The implementation of the CAD system results in significant improvement in the quality and efficiency of the design function [44].

Computer-Aided Process Planning (CAPP)

The CAPP system, defined by Harhalakis [47] as "the originator of process plans", has to work in an integrated way with CAD in order to decrease the 'product development cycle', as will be shown in the next section. The manufacturing process plans are generated here, specifying the operations, work centres, tools, jigs, fixtures, setup and run times. BOMs for the tools, jigs, and fixtures are generated here.

Manufacturing Planning and Control (MPC)

Plans the acquisition of raw materials and coordinates the manufacture of parts. Records the process plans provided by CAPP and the product structures of assemblies to present them later to the SFC system. Keeps information related to the work centres. (See Section 1.5).

Shop Floor Control (SFC)

"A system which directly controls the transformation of planned manufacturing orders into a set of jobs, for the transformation of raw materials into products" [47]. Its basic functions are:

- Capacity planning and resource allocation based on inputs from MPC.
- Short-term capacity adjustment by using alternative routings, planning overtime, and altering priorities.
- Feedback for reporting machine performance and status, job completion stage, and actual labour and material usage.

CAPP will provide the detailed route information that will be used by SFC together with the information produced by MPC in order to generate the job schedules and monitor them. More details about this subject are described in Section 1.5.

1.3.1 Overall CIM Information Flow Architecture

Computer-integrated manufacturing (CIM) systems have emerged as a result of the developments in manufacturing and computer technology [62].

Harhalakis [47] suggests that all the modules presented in the last section can be integrated through a "general distributed database management system (DDBMS)" driven by the KBS to "control the information flow, following procedural rules constraints and other procedures derived from the company policies", as shown in Figure 3. The DDBMS is in charge of the integration, while the KBS will manage and control the information flow.

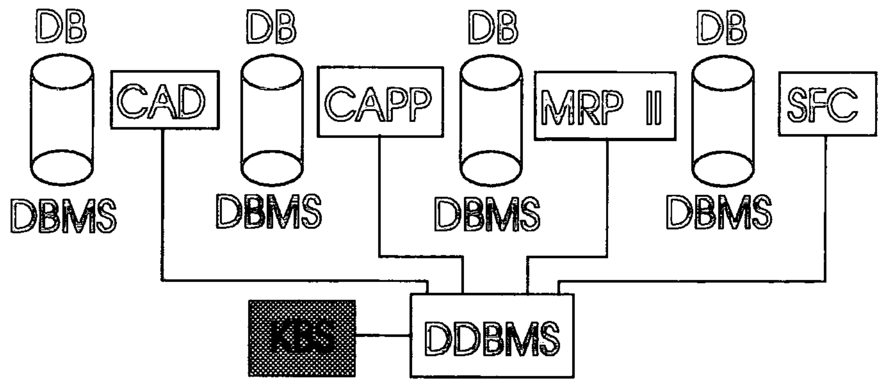


Figure 3. Overall CIM Information Flow Architecture

CIM is a new concept adopted by a number of companies in order to remain competitive. Some of the benefits of implementing a CIM system are:

- Decrease of manufacturing cost
- Decrease in number of personnel
- Decrease in processing time
- Decrease in work-in-progress inventory
- Increase in machine utilisation
- Better decision making
- Increased performance to customers

Additionally to this, other functional areas should be integrated within a CIM system. Some of these are described in the next paragraphs.

Production Planning

Production planning involves establishing production levels for a known length of time [44]. This forms the basis for the following two functions:

- Material requirement planning (MRP)
- Machine loading and scheduling

MRP II is a system in which the master scheduling, material requirement planning, and other functions are integrated with the company's business plan.

In order to perform scheduling in computer-integrated manufacturing (CIM) systems, interaction among various databases is necessary.

Computer-Aided Manufacturing System (CAM)

CAM involves programming of NC machines and material handling carriers. It is based on the part design produced by the CAD system and the process plan produced by the CAPP system.

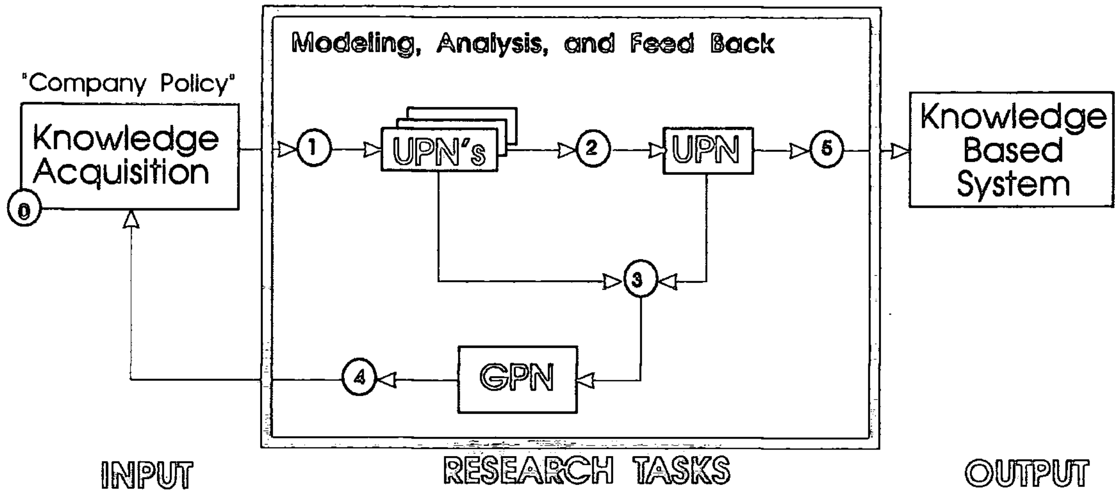
Computer-Aided Quality Control System

In the past, the quality control function (experimental design, inspection, and testing of the manufactured parts and products) has been performed manually . As in the case of process planning, the use of computers, robots and other automated equipment has greatly reduced the human involvement in quality control. For example, robots equipped with vision systems have, in some cases, eliminated human involvement. At the same time, they perform inspection more efficiently. Computer-controlled coordinate measuring machines and laser beam devices are also used for inspection in manufacturing systems.

1.3.2 Knowledge Base Design Methodology

A methodology is proposed by Harhalakis [47] in which the first step is to define rule specifications related to a specific company policy, and then model them with Updated Petri Nets (UPN) (a special set of Coloured Petri Nets (CPN)), and a "hierarchical modelling methodology". This terms are defined in the next paragraphs.

The UPN model is then converted into General Petri Nets (GPN) in order to validate it in case of conflicting company rules or errors from the modelling phase. After validation, the UPN model is translated by a parser into a "rule specification language". At the end, an Artificial Intelligence (AI) production system is produced, which controls operations, access, and modification of data involved in the processes corresponding to the manufacturing applications integrated. This process is depicted in Figure 4.



0. Expression of company policy for the integration of specific application systems (CAD/CAPP/MPC/SFC).
1. Modeling of the knowledge base using a formal language, Updated Petri Nets (UPN), a sub set of Coloured Petri Nets.
2. Synthesis Rules to combine modeled scenarios of the company policy into an integrated system.
3. Transform the UPN into Generalized Petri Nets (GPN) for Knowledge Base Verification.
4. Analysis, discovery of inconsistencies and incompleteness, and feedback.
5. Translation from UPN to the knowledge Based System.

Figure 4. Knowledge Base Design Methodology

1.3.2.1 Petri Nets

Petri Nets help representing not only sequential but concurrent activities in a graphical way and are very helpful when modelling and analyzing "complex dynamic relationships of interacting systems" [47]. Coloured Petri Nets are generalized Petri Nets with aggregated information in tokens, places, and arcs. They are applied at different abstract levels. Harhalakis [47] employs them for modelling the rule base and the "database changes which ensure consistency in representing the database status in the CIM system".

Updated Petri Nets are defined as a "directed graph with three types of nodes: places which represent facts or predicates, primitive transitions which represent rules or implications, and compound transitions which represent meta-rules (sub-nets)" [47]. The components of UPN are: data, facts, rules, and meta-rules.

Petri Nets are used because of their ability to validate the KBS in a mathematical and systematic way. The validation consists mainly in the completeness, consistency and conflicts [80,65].

1.4 ALLOCATION OF RESOURCES

In order to assure that the most appropriate resources are assigned for producing a given product, reliable information is a prerequisite. There are many methods that can be used for this purpose [91], some of which are described in the next paragraphs.

1.4.1 Linear Programming

This method is used when allocating scarce resources. It is useful when the problem variables are 'linearly related to each other'. It is especially applicable in production systems studies and, according to Riggs [91], it can be profitable in the three evaluation stages: planning, analysis, and control.

<u>Applicable Problems</u>

- Planning the location of supply facilities to minimize transportation costs
- Analyse operations and methods to improve profits
- Control machine loading to achieve maximum utilisation

1.4.2 Assignment Method

In this method the Hungarian algorithm is employed. The format of the variables <u>must</u> constitute a square matrix. A dummy variable with zero costs in each cell is added to make the number of rows equal to the number of columns.

<u>Applicable Problems</u>

- Matching situation where:
  (a) some type of rating can be given to the performance of each pairing
  (b) number of applicants equal number of positions open

1.4.3 Graphical Method

This is another variant of Linear Programming and is suitable for the selection of an optimal mix, i.e. determine the proportion to produce when the resources are limited, in order to maximize profit. For accomplishing this, some prerequisites must be fulfilled [91]:

1) The objective must be stated explicity.
2) Alternate courses of action must be available.
3) Resource limitations must be known.
4) Relationship of variables must be known.

1.4.4 Transportation or Distribution Method

It is used to determine preferred routes for the distribution of supplies from a number of origins to different destinations [91]. This method has also been used to help identify the distribution pattern for any resource which seems to be the more profitable or the one with the lowest cost.

<u>Other Applicable Problems</u>
- Products to make or buy
- Plant layout
- Product marketing

The problem must be represented in a matrix with no limit to the number of origins or destinations. This matrix defines:

1) Amount and location of supply and demand.
2) Cost or profit of supplying one unit from each origin to each destination.

The optimal distribution route is obtained by first finding the initial solution and then making sequential tests and revisions of improved solutions "until no further improvements are available" [91]. This procedure could let several equal cost-distribution patterns, i.e. alternative routes.

1.4.5 Vogel's Approximation Method

The first step is to find an initial solution that will match supply and demand [91]. This method is based on the fact that if the lowest cost route is not allocated, a penalty must be charged. Other similar method is the assignment by inspection or Northwest Corner Rule, where the rim conditions are met progressively by starting the assignment at the Northwest corner of the matrix.

1.4.6 Optimal Solution by the Stepping-Stone Method

This method helps to determine whether a change is appropriate, where should it be made, and how much is saved by making it. A saving (negative transfer cost) is a positive opportunity cost because it "represents a cost not incurred by not selecting the best possible alternative" [91]. On the other hand, a negative opportunity cost is an extra cost.

1.5 MANUFACTURING PLANNING AND CONTROL SYSTEM

There are many techniques implemented for manufacturing control, such as manufacturing resource planning (MRP), Just in Time (JIT), total quality control, etc. These controls are necessary because nowadays the customers expect high quality products and very fast turn around on orders.

1.5.1 Organization and Information Processing in Manufacturing

Groover [44] has designed a model of manufacturing including the physical and information-processing activities. The first group of activities is concerned with automation, while the second one is concerned with CIM (Figure 5).

In the information-processing cycle in a factory (Figure 6) [44], the manufacturing planning process is divided into four areas:

<u>**Process Planning**</u>

In this area, the manufacturing or industrial engineer is in charge of producing the route sheet necessary to establish the "sequence of individual processing and assembly operations needed to produce the part" [44]. This will be analysed in more detail in Chapter 4.

Master Schedule

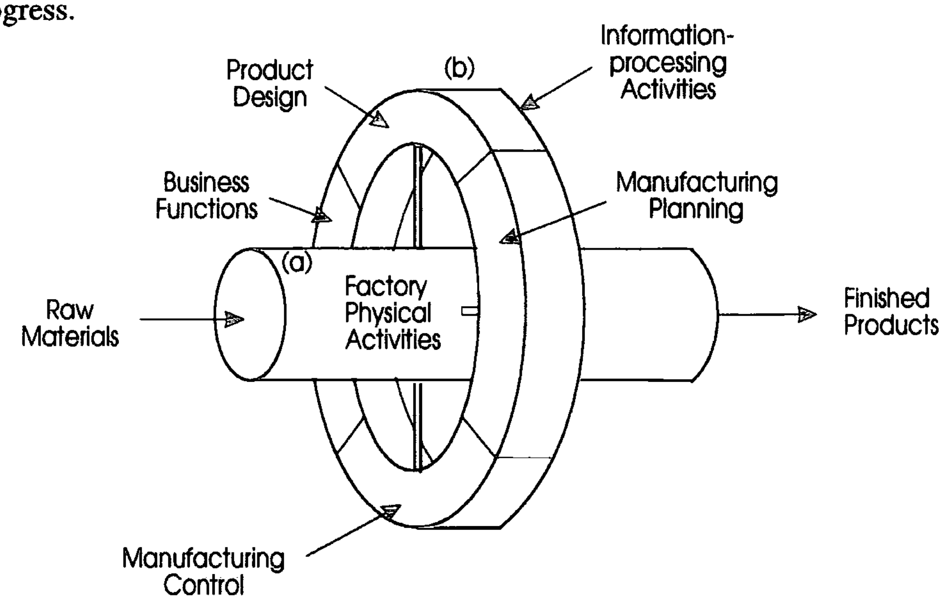
This is a list of products to be made, in what quantity, and when to deliver them.

Requirement Planning

Here, orders of raw materials and purchased parts from suppliers for individual components and subassemblies are planified.

Capacity Planning

In this area, the activities related to manpower and machine resources plannning are under progress.



(a) the factory as a processing pipeline where the physical manufacturing activities are performed, and

(b) the information-processing activities that support manufacturing as a ring that surrounds the factory.

Figure 5. Model of Manufacturing

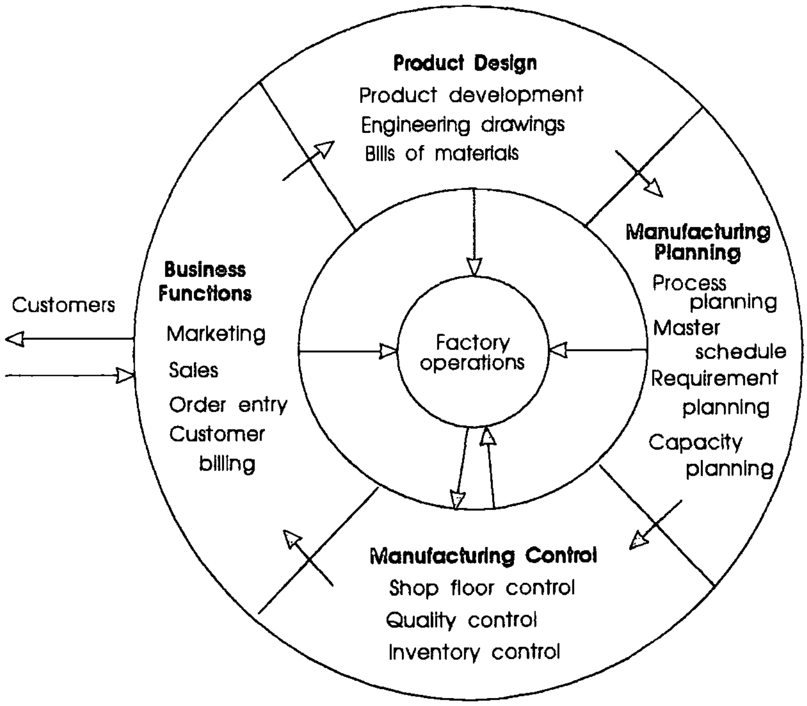


Figure 6. Information-processing cycle in a typical manufacturing firm

1.5.2 JIT

Is an approach to manufacturing which concentrates mainly on producing the required items meeting the required quality in the required quantities and in the required time. Its goal is to pursuit "excellence in all phases of manufacturing systems design and operation".

For the implementation of JIT in a SFC system, a Kanban system is used. The Kanban system controls the initiation of production and flow of material in order to get the exact quantity of items (components, sub-assemblies, purchased parts) in exactly the right place at exactly the right time. JIT supports manufacturing in three basic aspects [8]:

1) It functions as an intelligent match of product design with market demand.

2) It encourages the definition of product families, in which a common design and manufacturing attributes are shared and as a result, the products can be manufactured

in product oriented cells. The cells can be used to "aid the design process and reduce unnecessary duplication in product design." [8] A manufacturing cell generates flow patterns of materials in a plant and allows a group of operators and its supervisor to be responsible for a component or group of components.

3) Establishes a close relationship with suppliers in order to achieve raw material and purchased components deliveries on time.

1.5.3 Improved Manufacturing Performance Based on Reduced Lead Time

According to Bauer [8], there are five basic approaches:

1) Product design for ease of manufacture and assembly, achieved by modular design and design for simplification.

2) Manufacturing planning techniques, achieved by production smoothing, which means that single lines can produce many varieties of a product each day as a result of the market demand. Basically, this technique utilises short production lead times to influence the market demand in order to match the 'capability of the production process'.

3) Techniques to facilitate the reduction in queuing production and setup times as a consequence of product based plant layouts. This is achieved by using U-shaped layouts that allow unit production and transport, since the machines are close together and may be connected with chutes or conveyors, leading to synchronization.

Reduction in Queuing Times

Each unit produced in each cycle is sent to the next process at the end of the cycle. This implies moving away from batch based production systems to flow based systems.

Reduction in Operation Times

Since the plant layout is product oriented, operation times are reduced.

Reduction in Transport Times

U-shaped layouts minimize transport needs for a component or assembly.

Reduction of Setup Times

One should separate internal and external setup times. Internal setup refers to the setup process which requires the machine to be inoperative in order to undertake it. The aim is to convert as much as possible of the internal setup to external setup, eliminating any adjustment process where possible.

4) An approach to the use of manufacturing resources, leading to multiskilled and multifunction operators, and hiring of temporary operators when needed. This decreases overtime, releases temporary operators and increases the number of machines handled by one operator.

5) Quality control and quality assurance procedures causing total quality control to be carried out by inspection in order to prevent defects rather than detect them. The automatic control of defects includes a mechanism to detect abnormalities or defects as they occur and the capacity to stop production when a defect or abnormality occurs.

1.5.4 MPC AND MRP

The Manufacturing Planning and Control System (MPC) provides the required information for the efficient management of the materials flow, utilization of people and equipment, coordination of internal activities involving suppliers, and communication with customers about market requirements. The system provides the managers with the support to make intelligent decisions of manage operations [107].

The Manufacturing Resource Planning (MRP) determines the time-phased plans for all component parts and raw materials required to produce all the products in the Master Production Scheduling (MPS). This material plan can afterwards be utilized in the detailed capacity planning systems (Rough Cut Capacity Planning (RCCP) and Capacity Requirements Planning (CRP)) to calculate labour or machine centre capacity needed to manufacture all the parts [107,8]. (See Figure 7).

The managerial objective of MRP is to provide "the right part at the right time" to meet the schedules for completed products. In order to achieve this, "MRP provides *formal* plans for each part, whether raw material, component, or finished product" [107].

It is also important to accomplish these plans without excess inventory, overtime, labour, or other resources. Bauer [8] structures the MRP system as in Figure 8.

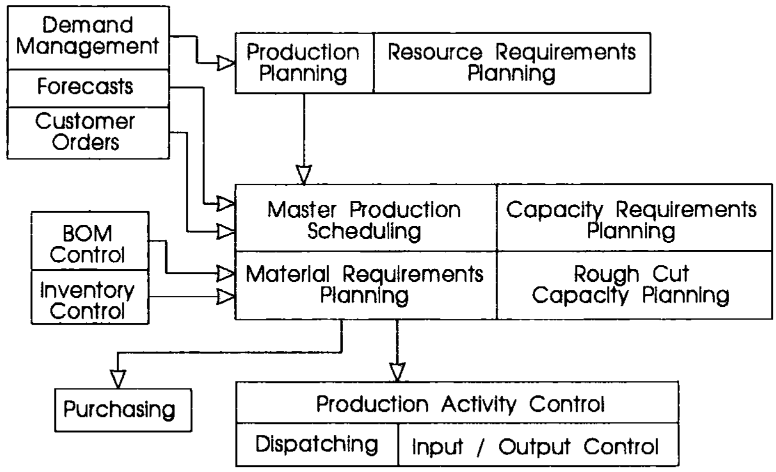


Figure 7. Manufacturing Planning and Control System

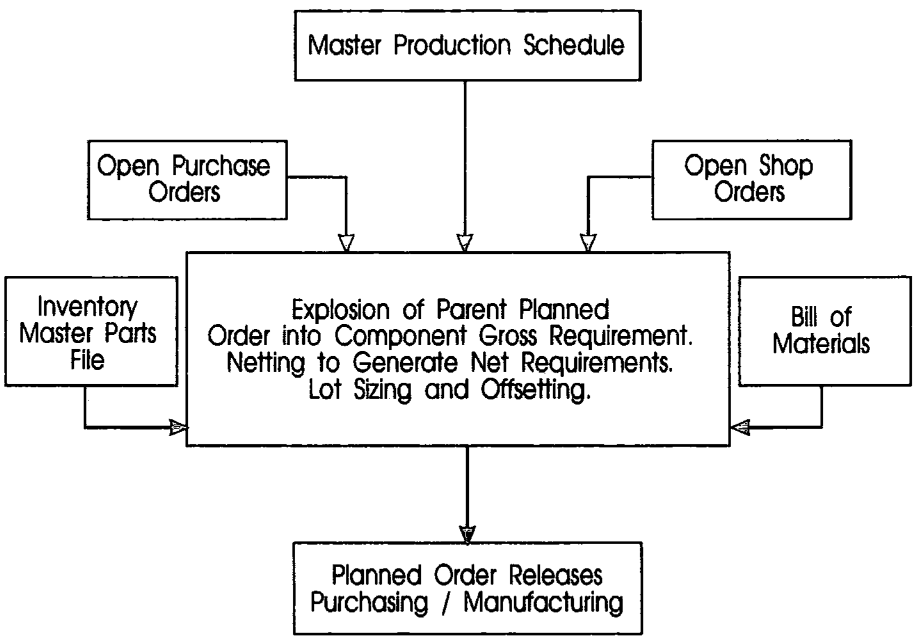


Figure 8. Basic Structure of an MRP System

The general MPC framework depicted in Figure 9 shows that detailed requirements planning is characterized by the use of time-phased requirement records. The front end of the MPC system produces the Master Production Schedule (MPS). The back end, or execution system, deals with shop-floor scheduling of the factory and with managing materials coming from suppliers.

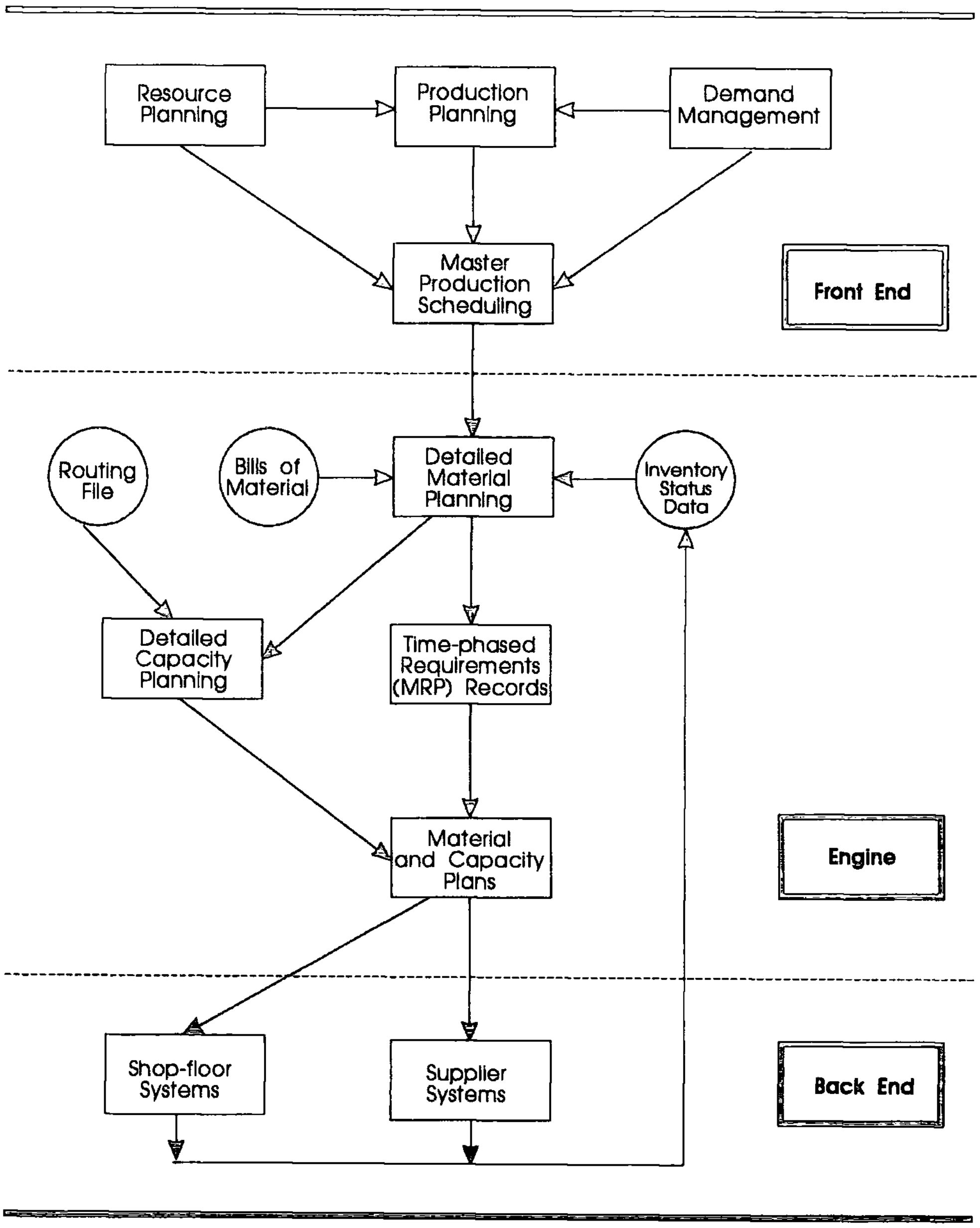


Figure 9. Detailed Manufacturing Planning and Control System Framework

The MRP represents a central system in the engine portion of Figure 9. This means taking a time-phased set of MPS requirements and producing a resultant time-phased set of parts and raw material requirements. Additionally, MRP requires two other basic inputs. A bill of material (BOM) showing, for each product, what other parts are required as direct components. The second basic input is inventory status.

The BOM is a document that specifies the subordinate components required to physically make each part or assembly. A **single-level BOM** comprises only the immediately required subordinate components, not the components *of* the components. An **indented BOM** is a list of components, from the final product all the way down to the raw materials [107].

An MRP system serves a central role in MPC. It translates the overall plans for production into the detailed individual steps necessary to accomplish those plans. It provides information for developing capacity plans, and it links the systems that actually get the production accomplished.

Effective use of an MRP system allows development of a forward-looking (planning) approach to managing material flows. It provides a coordinated set of linked product relationships, thereby permitting decentralised decision making on individual components.

1.6 PROCESS PLANNING

The process planning for a mechanical part involves the preparation of a plan that outlines the production routes, manufacturing operations, machine tools, fixtures, and tools required to produce the part [62]. Based on the design specifications provided by the design engineer, the process planner determines a process plan for the part that minimizes production cost, manufacturing time, and ensures the quality of the part. It is a tedious and demanding task that requires good knowledge of production processes and machine capabilities.

1.6.1 Computer-Aided Process Planning System

Since process planning is a complex task, there has been a trend to automate it, by providing decision support in order to increase production efficiency and produce parts more economically. As a result, a number of CAPP systems have been developed. Examples are GENPLAN, MIPLAN, and CPPP [62].

There are two basic approaches to automated process planning:

- Variant approach
- Generative approach

In the variant approach, each part is classified based on a number of attributes and coded using a classification and coding system. The code and the process plan for each part are stored in a data base. When it is required to generate a process plan for a new part, the part is coded and a process plan for a part similar to the new part is retrieved from the data base. The retrieved process plan is modified if necessary. The variant approach is useful when there is a great deal of similarity between parts.

In the generative approach, according to Kusiak [62], there are no process plans stored in the data base. Instead, the data base contains information about parts, machines, and tooling and the process planning system creates the required process plan. Existing generative process planning systems can generate process plans for parts that have rather simple geometry. In fact, most of the existing systems are not trully generative because they require human interaction.

The generative process planning approach is suitable for the application of knowledge-based systems. A knowledge-based system for process planning must be capable of generating process plans for complex parts. It is also desirable to have a knowledge-based system that provides alternative process plans.

Using an artificial intelligence (AI) framework, the process planning problem has been formulated as a sequence of actions (operations) and resources (machines, tools, etc.) that enable the goal state (producing a finished part) to be reached given the initial state (raw material). On the basis of the preceding formulation, a number of intelligent process-planning systems have been developed. Some of the expert process planning systems developed to date, their characteristics, and references are presented in Table 3. It should be stressed that each system presented represents a research methodology rather than a software ready for industrial implementation.

Expert System	Knowledge Representation	Inference Strategy	Programming Language
TOM	Rules	Backward chaining	LISP
PROPLAN	Rules	Forward and Backward chaining	LISP
GARI	Rules	Forward chaining	MACLISP
EXCAP	Rules	Backward chaining	PASCAL
CUTTECH	Rules	Backward chaining	n/a
AGFPO	Rules	Forward chaining	PROLOG
SIPP	Frames	Brand-and bound	PROLOG
Hi-Mapp	Rules	Backward chaining	INTERLISP
SAPT	Rules	n/a	LISP
CIMS	Rules	n/a	n/a

Note: n/a - information not available.

Table 3. Expert Systems for Process Planning

Due to the diversity of the process planning task, it is difficult to apply a uniform approach for its automation. As shown in Table 4 the process planning task can be decomposed into seven phases.

Phase Number	Phase Name	Solution Approach
1	Volume decomposition	KB
2	Selection of alternative machines, tools and fixtures	KB
3	Machining optimization	OPT/KB
4	Decomposition of machinable volumes	KB
5	Selection of machinable volumes	OPT/KB
6	Generation of precedence constraints	KB
7	Sequencing of machinable volumes	OPT/KB

KB: Knowledge-based approach
OPT/KB: optimization and knowledge-based approach

Table 4. Phases of Process Planning

1.6.2 Selection of Alternative Machines, Tools, and Fixtures

The process of selection of machines, tools, and fixtures is based on part features and it is typically performed in two stages. In the first stage one selects a process, such as drilling or milling, and in the second stage, machines, tools, and fixtures. Since the process of selection of machines, tools and fixtures is highly qualitative, a knowledge-based approach is very suitable.

CHAPTER 2
INFORMATION TECHNOLOGY AND MANUFACTURING SYSTEMS

2.1 THE ROLE OF ENGINEERS IN MANUFACTURING

Many engineers have as their function the designing of products. The products are brought into reality through the processing or fabrication of materials. "A *design engineer*, better than any other person, should know what the design is to accomplish, what assumptions can be made about service loads and requirements, what service environment the product must withstand, and what appearance the final product is to have" [26]. In order to meet these requirements, the material(s) to be used must be selected and specified. In most cases, in order to utilize the material and to enable the product to have the desired form, the designer knows that certain *manufacturing processes* will have to be employed. In many instances, the selection of a specific material may dictate what processing is used. On the other hand, when certain processes must be used, the design may have to be modified in order for the process to be utilized effectively and economically. Certain dimensional characteristics can dictate the processing, and some processes require certain sizes of the parts. In converting the design into reality, many decisions must be made. In most instances, they can be made most effectively at the design stage. It is thus apparent that design engineers are a vital factor in the manufacturing process, and it is of great importance to the company if they can *design for manufacturing*.

Manufacturing engineers select and coordinate specific processes and equipment to be used, or supervise and manage their use. Some design special tooling that is used so that standard machines can be utilized in producing specific products. These engineers must have a broad knowledge of manufacturing processes and of material behavior so that desired operations can be done effectively and efficiently without overloading or damaging machines and without adversely affecting the materials being processed. "Although it is not obvious, the most hostile environment a material may ever encounter in its lifetime is the processing environment" [26].

The machines and equipment used in manufacturing and their arrangement in the factory also comprise a design task. *Industrial* or *manufacturing engineers* who design (or lay out) factories have the same concerns of the interrelationship of design, the properties of the materials that the machines are going to process, and the interface of the materials and the machines.

2.2 MANUFACTURING SYSTEMS

The *manufacturing processes* are collected together to form a *manufacturing system (MS)*. The manufacturing system takes inputs and produces products for the customer. The production system includes the manufacturing system and services to it, and it refers to the total company. Different machines do different operations, and some machines do operations better than others. The arrangement of machines (often called the plant layout) defines the design of the manufacturing system. The plant layout influences the way products are scheduled through the shop floor and depends upon the volume and variety of production.

The production system therefore includes the manufacturing system plus all the other functional areas of the plant for information, design, analysis, and control. These subsystems are somehow connected to each other to produce either goods or services or both (See Figure 10). Goods refer to material things. Services are nonmaterial things that we buy to satisfy our wants, our needs, our desires. A description of production terms for manufacturing systems (MPSs) can be found in Appendix 1.

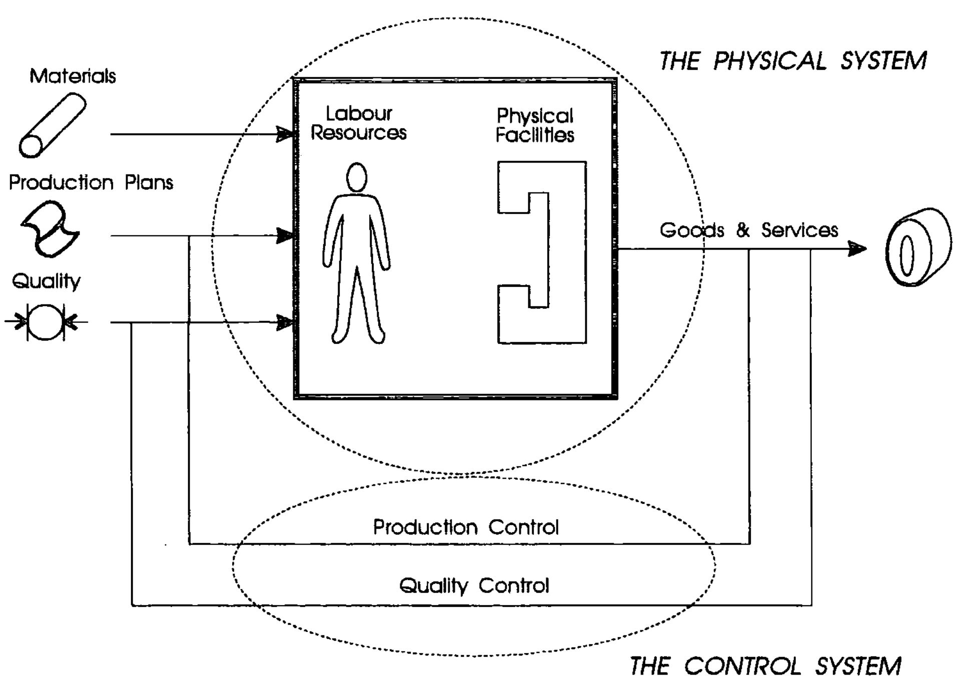


Figure 10. The Elements of a Production System

Control of a system applies to overall control of the whole, not merely of the individual processes or equipment. The entire manufacturing system must be controlled in order to control inventory levels, product quality, and output rates. The organisation of the system begins with planning for production. Batch production or automation, robotics, cellular or flow layout of equipment, and special sequencing of the batches are typical plans that may be undertaken.

Five manufacturing system designs can be identified: the *job shop*, the *flow shop*, the *"linked-cell" shop*, the *project shop*, and the *continuous process*. The latter system primarily deals with liquids, gases (such as oil refinery) rather than solids or discrete parts.

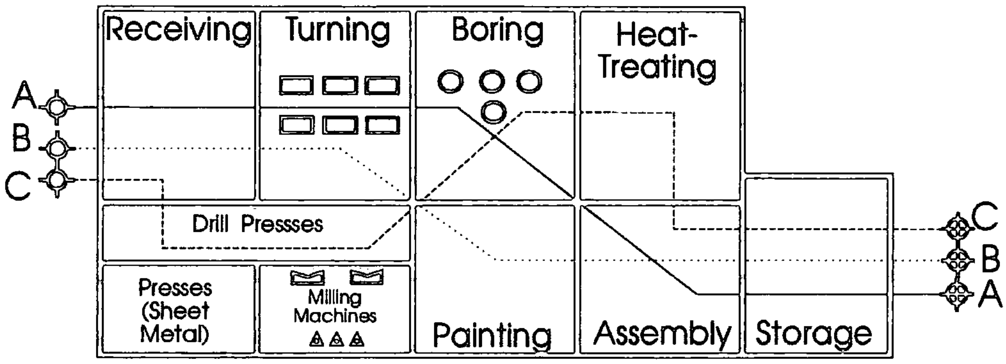
The *job shop* is characterized by large varieties of components, general-purpose machines, and a functional layout (Figure 11). This means that machines are collected by function (all lathes together, all milling machines together) and the parts are routed around the shop in small batches to the various machines.

Flow shops are characterized by larger batches, special-purpose machines, less variety, and more mechanization. Flow shop layouts are typically either continuous or interrupted. If *continuous*, they basically run one large-volume complex item in great quantity and nothing else. If *interrupted*, the line manufactures large batches but is periodically "changed over" to run a similar but different component.

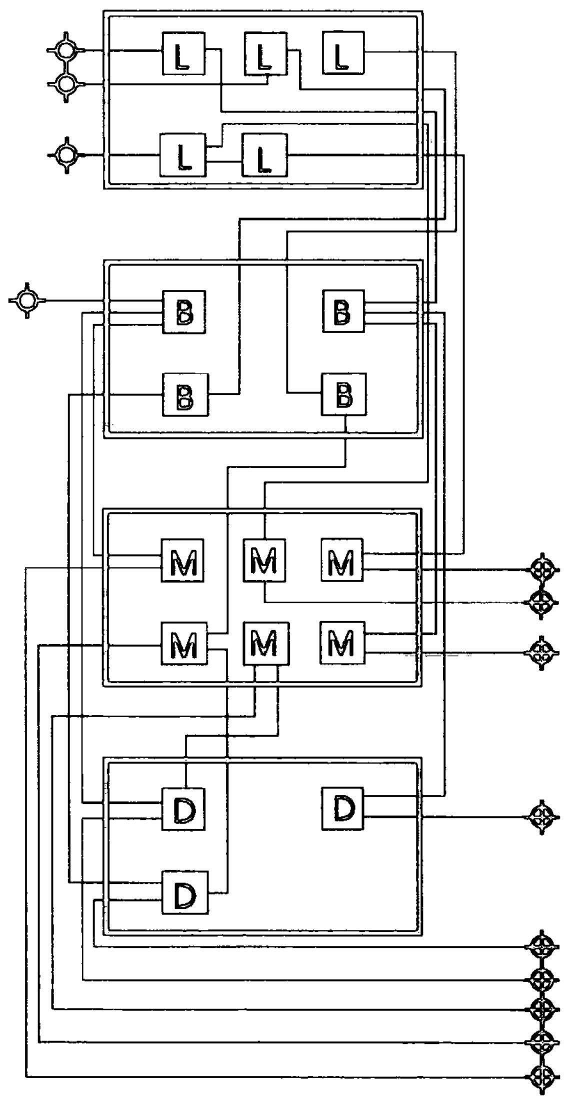
The *"linked-cell"* manufacturing system is composed of manufacturing cells connected together (linked) using sometimes a unique form of inventory and information control (Kanban).

The *project shop* is characterized by the immobility of the item being manufactured. It is necessary that the men, machines, and materials come to the site. The number of end items is not very large. Thus the job shop usually supplies parts and subassemblies to the project shop in small lots.

Naturally, there are many hybrid forms of these manufacturing systems, but the job shop is the most common system. Because of its design, the job shop has been shown to be the least cost-efficient of all the systems. Component parts in a typical job shop spend only 5% of their time in machines and the rest of the time waiting or being moved from



(a) Job Shop – Functional or Process Layout



(b) Production Job Shop – Functional Layout

Figure 11. Functional Layouts

one functional area to the next. Once the part is on the machine, it is actually being processed (that is, having value added to it by changing its shape) only about 30%-40% of the time. The rest of the time it is being loaded, unloaded, inspected, and so on. The advent of numerical control machines increased the percentage of time that the machine is in cycle because tool movements are programmed and the machines can automatically change tools or load and unload parts. This type of machines will be explained in more detail later in this chapter. However, there are a number of trends that are forcing manufacturing management to consider means by which the job shop system itself can be redesigned to improve its overall efficiency. These trends have forced manufacturing companies to convert their batch-oriented job shops into "linked-cells". One of the ways to form a cell is through the use of *group technology* (See Section 2.6.2).

2.3 CHARACTERISTICS OF PRODUCTION SYSTEMS

Production systems can be divided into six categories according to DeGarmo [26]:

1) Workstation

Individual bench, machine, or discrete process; craft work, single stations, or NC machine tools working independently; the most primitive production system.

2) Cell

Simplest organized production effort; may or may not be computer controlled or robot assisted; composed of two or more workstations.

3) Flexible workstations

Volume of production has less effect, and use of the computer is characteristic; examples include low quantities of engine blocks.

4) Mechanization

Dedicated to production of large quantities of one product, with little model variation; examples include high-volume and automobile parts. Computers and robots do not have a significant role, although tools and pneumatic, electric, and electronic controls are important.

5) Automation

Examples include transfer lines, which may or may not be computer controlled. More recent automation has included robots, which are used for arc welding and parts handling, for example.

6) Continuous-flow processes

Examples include production of bulk product, such as chemical plants and oil refineries. Features are: flow process from beginning to end, sensor technology available to measure important process variables, use of sophisticated control and optimization strategies, and full computer control.

2.4 THE MACHINE SHOP AND METAL PROCESSING

2.4.1 Metal Cutting

In manufacturing products it is important that the processes employed should be efficient and capable of producing parts of acceptable quality. Metal cutting processes include turning, planing, milling, and drilling operations as well as other processes performed by machine tools. Parts are produced by removing metal in the form of small chips. The selection of machine tools and cutting tools is a very important activity.

2.4.2 Types of Machine Tools

A large variety of machining work is performed in jobbing shops, where the number of machine tools is limited. Among the machine tools in use in such shops are NC, CNC and manual engine lathes, milling machines, drill presses, shapers, planers, boring mills, and grinders. These are equipped with various fixtures and adapters in order that a wide range of work may be performed. Work in the jobbing shop usually consists of producing small quantities of a each part. The operator performs different operations on the machines assigned to him.

When production reaches a moderate volume, the jobbing shop becomes a batch production environment. The machine tools and equipment of the jobbing shop are also used in the batch production environment, since these machines answer the requirements of limited production; in addition, however, other machine tools, such as machining centres and grinders designed for large production, will be found [26]. The recent trend in this area is a reduction in batch size that puts pressure on setup times. Multi-tool and multi-spindle machine tools are common particularly in Flexible Manufacturing Systems (FMS).

In mass production environments, many parts are produced at low cost while ensuring a high degree of dimensional accuracy to provide interchangeability. Some machines previously discussed also form part of this environment. However, the predominating machine tools in plants operating on large production volumes include automatic and semiautomatic machines of special design and rugged construction that perform specialized operations. Among these machines are the following: complex turret lathes, automatic screw machines, automatic lathes, multi-spindle drilling machines, centerless grinders, broaches and other types of grinding machines, fully automatic machines (such as crankshaft turning machines), and cylinder block facing machines. Many of these are single-purpose machines built at high cost, but their ability to perform operations at low cost per unit warrants their purchase.

2.4.3 Turning, Drilling, Boring, and Milling Machine Tools

The oldest and most common machine tool is the lathe, which removes material by rotating the workpiece against a single-point cutter. Parts can be held between centres, attached to a face plate, supported in a jaw chuck, or held in a draw-in chuck or collet. Although this machine is particularly adapted to cylindrical work, it may also be used for other operations. Plane surfaces can be obtained by supporting the work in a face plate or chuck. Normal operations performed on a lathe include longitudinal turning, facing, profiling, threading, grooving, and parting-off.

One of the simplest machine tools used in production and toolroom work is the drill press. *Drilling* produces a hole in an object by forcing a rotating drill against it. The same can be accomplished by holding the drill stationary and rotating the work, such as drilling on a lathe with the work held and rotated by a chuck. Although the drill press is essentially a single-purpose machine, a number of dissimilar operations, such as drilling, reaming and threading, are possible with other cutting tools on this machine tool.

Boring is enlarging a hole that has already been formed. Principally, it is an operation of truing a hole that has been drilled previously with a single-point lathe-type tool.

A *milling machine* removes metal when the work is fed against a rotating cutter. Except for rotation, the circular cutter moves vertically along the (z) axis. The milling cutter has a series of cutting edges on its circumference, each acting as an individual cutter in the cycle of rotation. The work is held on a table that controls the feed against the cutter. In most machines there are three possible table movements - longitudinal, crosswise, and vertical - but in some the table may also possess a swivel or rotational movement.

The milling machine is considered the most versatile of all machine tools. Flat or formed surfaces may be machined with excellent finish and accuracy. Angles, slots, gear teeth, and recess cuts can be made with various cutters. Drills and reamers can be held in the arbor socket. Because table movements have micrometer adjustments, holes and other cuts can be dimensioned accurately. Most operations performed on shapers, drill presses, gear-cutting machines, and broaching machines can be done on the milling machine. Heavy cuts can be taken with little appreciable sacrifice in finish or accuracy. Cutters are efficient in their action and the life of modern tools is great. These advantages plus the availability of a variety of cutters make the milling machine indispensable in any machine shop and toolroom.

2.4.4 Numerical Control Machine Tools

NC is the operation of machine tools and other processing machines by a series of coded instructions. Perhaps the most important instruction is the relative positioning of the tool to the workpiece. An *organized list of commands* constitutes an *NC program.* "NC is not a machining method; it is a means for machine control" [26]. NC is considered as one of the most productive developments in manufacturing in this century.

NC should be considered whenever there is similar raw material and work parts are produced in various sizes and complex geometries. Applications are in low-to medium-quantity batches, and similar processing sequences are required on each workpiece. Those production shops having frequent changeovers will benefit.

Development of the ***machining centre*** with ***tool storage*** resulted from NC. Each tool can be selected and used as programmed. These machining centres can do almost all types of machining such as milling, drilling, boring, and facing Such machining operations can be programmed to occur simultaneously. The NC program selects and returns cutting tools to and from the storage magazine, if equipped, and also inserts them into a spindle. Parts can be loaded and moved between pallets, manipulated by rotation, and inspected after the work is finished. Robotic operation is possible, also being accomplished by NC.

Systems having a computer controlling more than one machine tool are known as *direct numerical control* (DNC). One or more NC machine tools is connected to a common computer memory to receive "on-demand" or real-time distribution of data. In this system there is no punched tape. It allows storage of extremely long programs that will not fit into the memory of a computer NC machine.

Computer numerical control (CNC) systems use a dedicated stored-program minicomputer to perform NC functions in accordance with control programs stored in computer memory. It provides basic computing capacity and data buffering as a part of the control unit.

2.5 MANUFACTURING LAYOUTS

Plant layout is the physical arrangement of all facilities within the factory. It depends on product design and specifications, production volume, manufacturing operations for the product, and assembly sequence for the product. The best layout will attempt to use the least space consistent with safety, comfort, and product manufacture. It will consider operations, inspections, delays, transportation (material handling), and storage. The type employed depends on many factors, and the existing shape of the building is a prominent one.

2.5.1 Flexible Manufacturing Systems (FMS)

The basic structure of machine tools has changed little since the early days of metal cutting, but automation has altered machine tools into several distinct types designed for specialized processes. Recently, however, the trend has been away from dedicated special machines and toward highly adaptable self-contained systems.

Flexible machine tool systems may have several power units, each of which can drive any number of multiple-spindle machining heads. These special-purpose heads can be set up ahead of time and changed quickly. Workpieces are transported automatically between workstations, and the entire head-changing and workpiece transport operation is under the control of a central process computer (See Figure 12).

Machining centres not only allow different ways to make parts but a different way to do business. The modular construction of the system makes it possible to expand when necessary. Design changes and prototypes are easily accommodated because of the low setup cost, and inventory can be precisely controlled. In general, the flexibility of the system permits changes in the production schedule, design specifications, and even the product, all at a much lower cost than with conventional systems.

FMS are arrangements of individual work stations, cells, machining cells, and robots under the control of a computer. Sometimes FMS means flexible *machining* systems. Workpieces are mounted on pallets that move through the system transferred by towlines, conveyors, or drag chains. FMS is closely related to cellular systems.

Equipment and manufacturing cells are located along the material transfer highway. Different parts move on the conveyor and generally the quantity is small. The process begins with a robot or operator loading or unloading a CNC machine in FMS. After processing in FMS the robot will return the semifinished or finished part to the conveyor.

Pallet transfer to and from the machines is by automatically guided vehicles (AGVs). These carriers are often rated by the tonnage capacity they are able to move. Automatic loading palletizers can be used to mount and unmount the part on the vehicle.

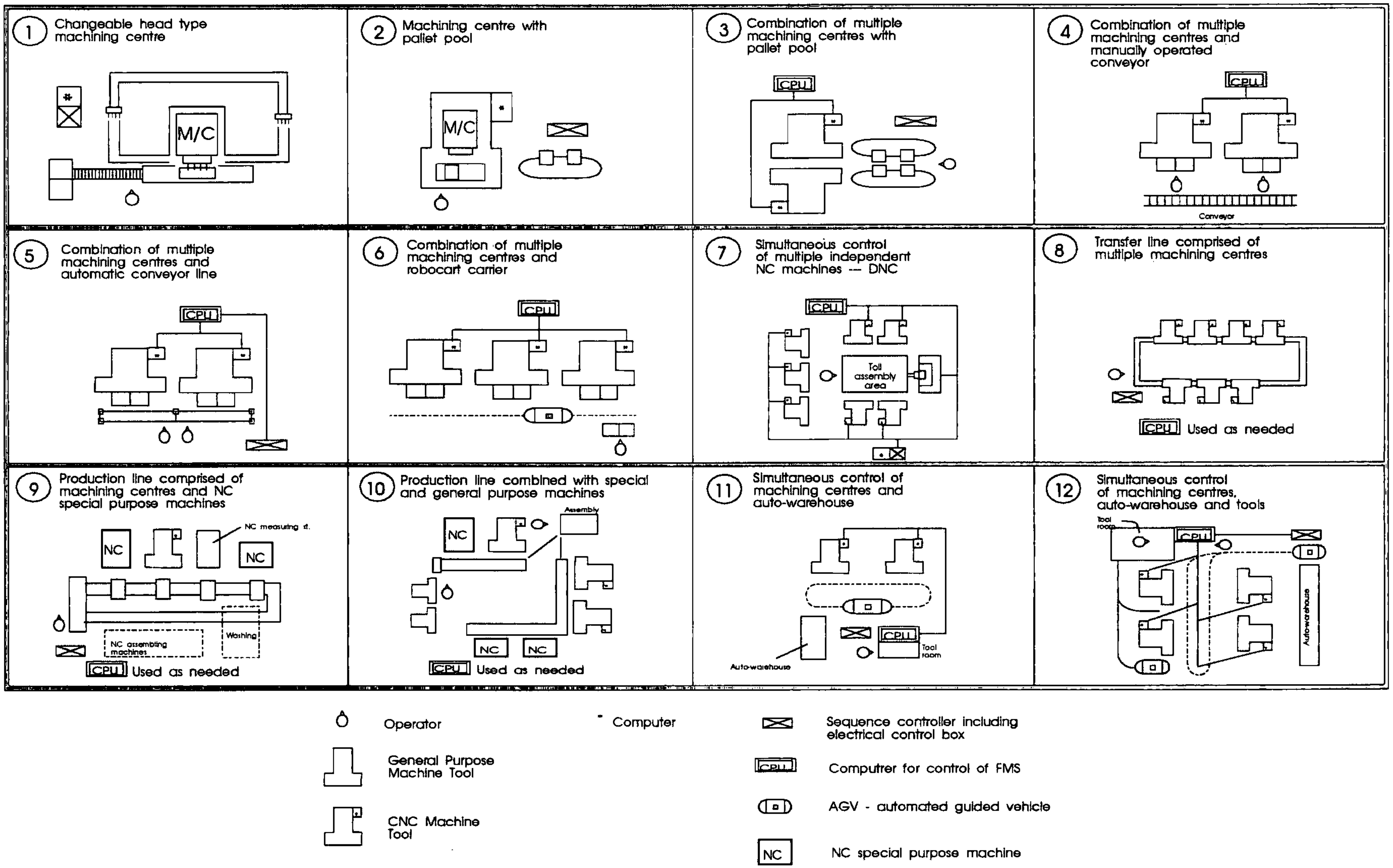


Figure 12. FMS Layouts

Not only are parts moved, but tools are moved between the stations if a part requires tooling that is not available on a specific machine. The robots mount the tool into the carriage where it is available for the part at the first time needed. The robot arms are able to reach the tool and extend it the required distance.

A flexible machining system (FMS) is one of the forms of implementing computer-aided manufacturing. FMSs possess a number of distinct features:

1) The degree of automation of machines and material handling systems in a FMS is much higher than in an equivalent classical machining system. This observation follows from the definition of a FMS.

   A FMS can be defined as a set of machines linked by a flexible material handling system (e.g., robot, automated guided vehicle), all controlled by a computer system.

2) A FMS consists of fewer machines than an equivalent classical machining system.

3) The layout of machines in a FMS is determined by the type of material handling equipment used.

4) The number of setups in a process plan designed for a FMS is significantly smaller than in an equivalent classical process plan.

5) In a FMS, the processing time per machine load is much longer than it would be in an equivalent classical machining system.

6) The volume and flow of information in a FMS are much higher than in an equivalent classical machining system.

7) In a FMS, batch sizes result from other sizes, the capacity of fixtures, and the limited life of tools rather than being determined by optimization procedures similar to those used in classical manufacturing systems.

8) The design of a FMS has an impact on its operation.

2.5.2 Cell Layout

Cell production may involve several machines connected by a conveyor system. If it is a specialized cell, it will make only certain classes of parts. In some situations cell design may approach the efficiency of an automated transfer line.

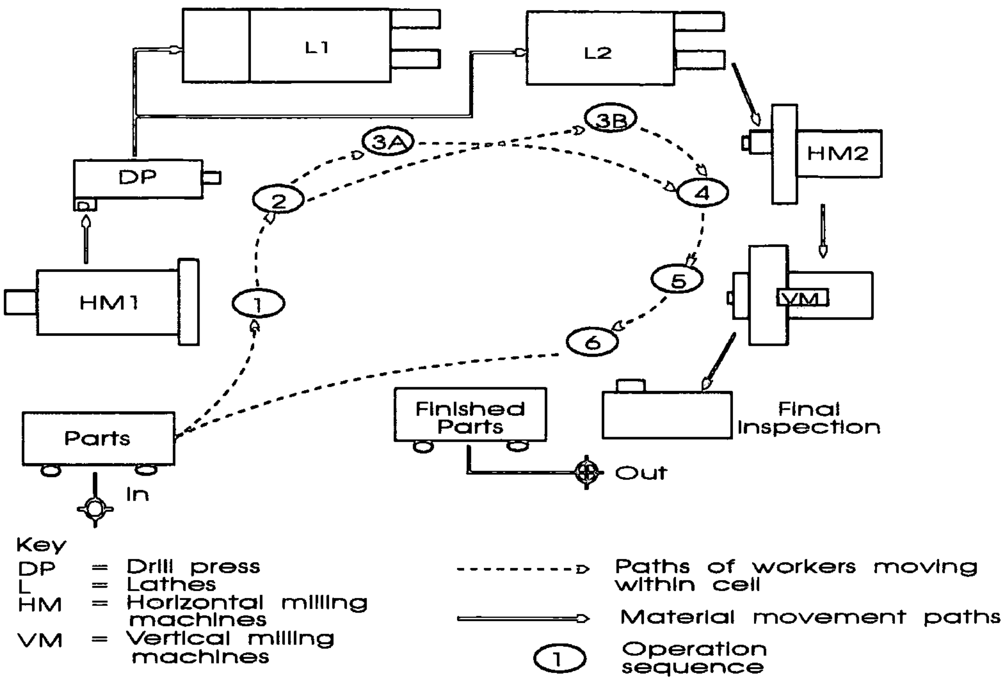
Cell production encourages the following benefits: for simple product design fewer and more straightforward tooling and setups, shorter material-handling distances, and less complicated production and inventory control. Improved process planning procedures are possible.

The cells may be stationed along an in-line material transfer system such as a conveyor. Raw and intermediate-finished parts move along the conveyor. A "ready for workpiece" signal from the control unit of the first machine in a manufacturing cell instructs the robot to look for the required workpiece on the conveyor. The robot picks up the workpiece, loads it onto the machine, and sends a signal to the machine control to begin its operations on the workpiece. A "part-finished" signal from the last machine tool to the robot requests that the completed part be unloaded and transferred to the outgoing conveyor. The cycle would then be repeated (See Figures 13 (a,b), 13 (c)).

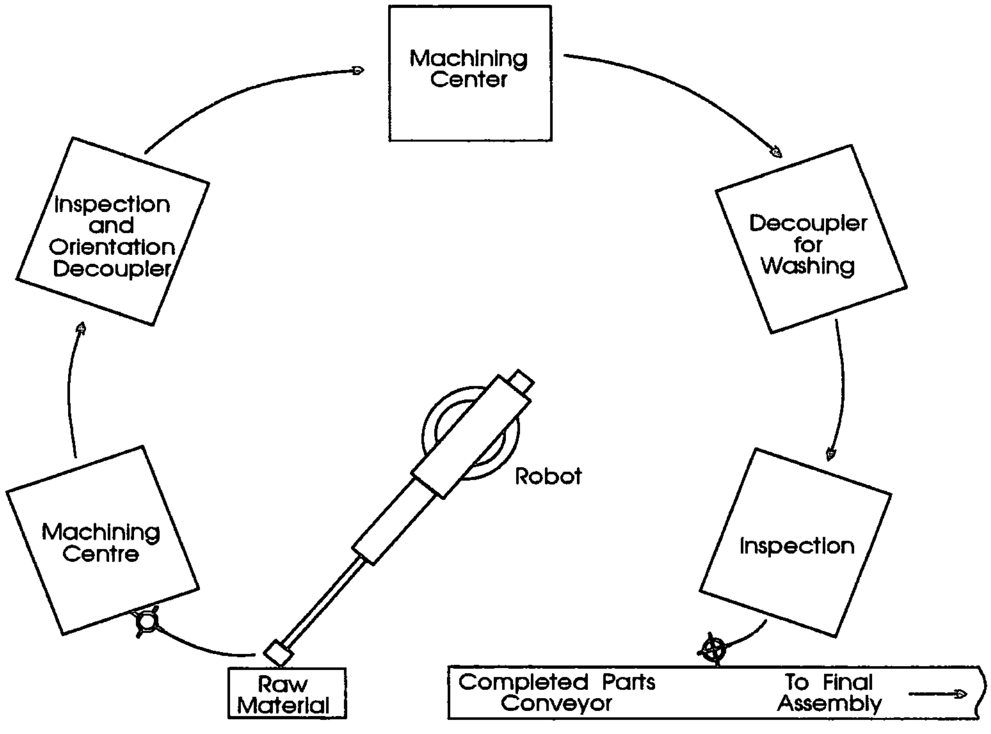
2.5.3 Group Technology Layout

Group technology (GT) is a concept whereby similar parts are grouped together into part families. Parts of similar size and shape can often be processed through a *similar set of processes*. A part family based on manufacturing would have the same set or sequences of manufacturing processes. The set of processes is called a cell. Thus, with GT, job shops can be restructured into cells, each cell specializing in a particular family of parts (See Figure 14). The parts are handled less, machine setup time is shorter, in-process inventory is lower, and the time needed for parts to get through the manufacturing system is greatly reduced.

One variation of group technology (GT) includes the concept of GT machine cells, groups of machines arranged to produce similar part families. A cellular arrangement of production equipment achieves an efficient work flow within the cell. Labour and machine specialization for the particular part families produced by the cell are possible, raising the total productivity of the cell.

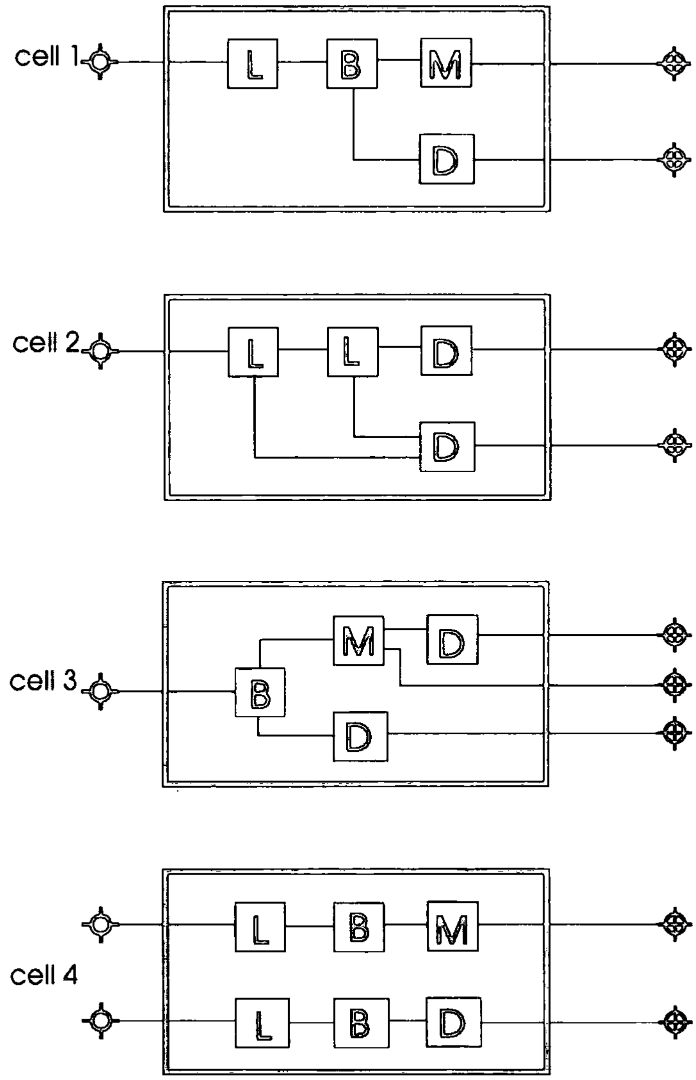


(a) Manned Manufacturing Cell
(with six machines and one multifunctional worker)
(The lathe operation is duplicated)



(b) Robotic Cell
(Decoupler checks part,reorients part
for next machine, and controls inventory
in the cell)

Figure 13 (a,b). Cellular Layouts



(c) CMS

The job shop can be converted into manufacturing cells by applying group technology which finds compatible families of parts. Cells can be designed to process families of parts.

CMSs elimininate functionality on the factory floor. Integration of production systems functions -- inventory, quality control and machine maintenance -- is then possible.

Cells can be linked to operate synchronously with subassemblies and final assembly lines.

Figure 13 (c). Cellular Layouts

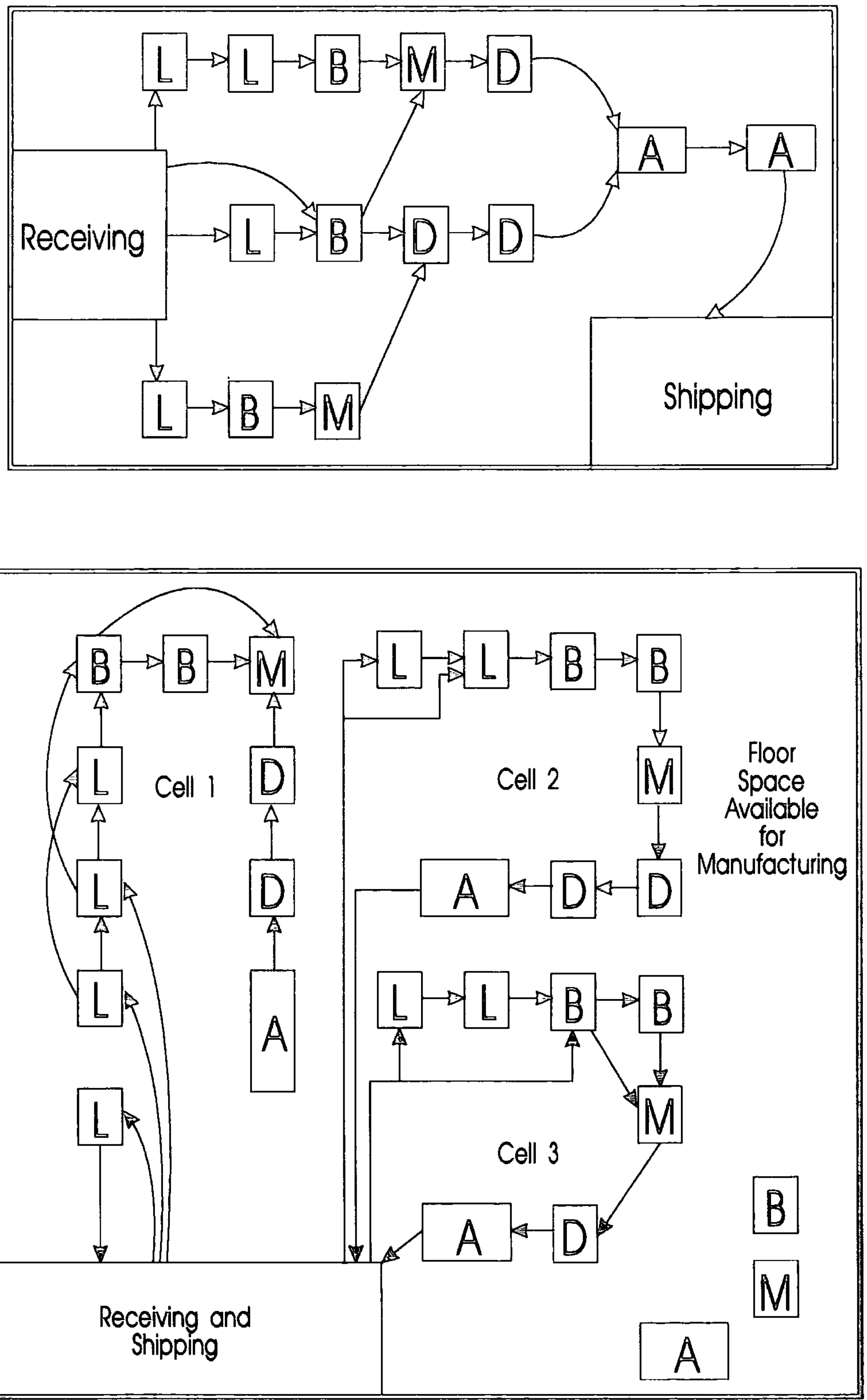


Figure 14. Group Technology Layouts
(grouping processes into cells
to process family parts)

One limitation of the *flow line layout* requires that all parts in the family be processed through the machines in the same sequence. While some processing steps can be ignored, it is necessary that the flow of work through the system be unidirectional. Reversal of work flow is accommodated in the more flexible group machine layout, but not conveniently in the flow line configuration.

Group technology (GT) is a management philosophy based on the recognition that similarities exist in design and manufacture of discrete parts. In "family of parts manufacturing", GT achieves advantages on the basis of these similarities. Similar parts are arranged into part families. Each family posseses similar design and manufacturing characteristics. Efficiencies result from reduced setup times, lower in-process inventories, better scheduling, streamlined material flow, improved quality, improved tool control, and the use of standarized process plans. In some plants where GT has been implemented, the production equipment is arranged into machine groups or cells to facilitate work flow and parts handling. In product design there are also advantages obtained by grouping parts into families. A parts classification and coding system is required in a design retrieval system. GT is a prerequisite for computer-integrated manufacturing.

Parts classification and coding are concerned with identifying the similarities among parts and relating these similarities to a coding or a number system. Part similarities are of two types: *design attributes* (such as geometric shape and size) and *manufacturing attributes* (the sequence of processing steps required to make the part). It should be noted that GT is not a science with precise formulas, but rather is a tool to be developed in each plant.

Coding can be used in computer-aided process planning (CAPP). CAPP involves the computer-generation of an operations sheet or route sheet to manufacture the part.

2.5.4 Transfer Lines

This layout is used mostly when a part or product is highly standardized and will be manufactured in large quantities. An automated transfer machine will produce the parts with a minimum of skilled labour. Between each section there is a provison for banking parts. This layout, although highly efficient, can be utilized only to make products in very large volume, and desired changes of design in the products must be avoided or delayed because it would be too costly.

2.6 METHODS OF WORK-HANDLING

For small quantities the customary method of handling a workpiece is manual if the mass is less than 30 to 50 lb (10-25 kg) or by crane or conveyor if heavier. The Occupational Safety and Health Act (OSHA) and management practice encourage operator safety and welfare, which provides for robots, automatic equipment, and other handling devices if the quantity is large or the weight is prohibitive.

If the quantity of production is sufficient, mechanical loaders have an economic advantage over manual loading. A variety of mechanisms is available to load, position, control the cycle, and unload the workpiece. Systems are available that can completely process and assemble the item.

2.6.1 Mechanization

A variety of design configurations is possible. The movement of the workpiece may be circular around the machine or linear along the machine if one machine is used. Circular movement uses less floor area. Straight-line type machines allow addition and subtraction of stations, thus facilitating interchangeability and continuous chip or waste removal. Indexing is most suited for drilling, and turning operations. In constant-travel mechanization the workpiece is advanced with indexing in either a circular or straight-line path, and locating and clamping the workpiece is required only once. Constant-travel mechanization is preferred for milling, broaching, and grinding operations.

2.6.2 Automation

Involves automatic handling between machines and continuous automatic processing at the machines. The elements *continuous* and *automatic* are necessary to separate automation from mechanization. Automation exists only when a group of related operations are tied together mechanically or electronically or with the assistance of computers or with robots. Computers and robots are not necessary to have automation.

2.6.2.1 Automation in Mass Production

Handling and moving the part was solved first for mass production. The part is moved from station to station by mechanical means, and the only manual movement remaining is that of loading a new length or batch of raw materials.

2.6.2.2 Transfer Equipment

Mechanical loading and transfer devices are used to move components of varied geometry from machine to machine. Special jaws grip the part, life, move, and turn it on arms, and place it into the new work position. Travel distance, direction, sequence, and speed are controlled mechanically, electromechanically, or with fluidic controls. Robots anc computer control are used. Dead stops, *mechanical arms* , or *iron hands* can be reprogrammed, but not very readily. But robotic manipulators overcome the inflexibility of mechanical manipulators.

2.6.2.3 Assembly Lines and Materials Moving

Materials handling is achieved by many methods. Installing automatic or semiautomatic handling equipment between machines already on line is successful and permits easy introduction of automation into existing production systems.

2.6.2.4 Towline or Wire Guidance

Workpieces are attached to pallet fixtures or platforms that are carried on carts towed by a chain located beneath the floor. The pallet fixture is designed so that it may be conveniently moved and clamped at successive machines in manufacturing cells. The advantage of this methos is that the part is accurately located in the pallet, and it is correctly positioned for each machining or assembly operation.

With the ***wire guidance*** system, carts can move along a path determined by wire embedded in the floor. A cart picks up a finished palletized workpiece from the machining centre and delivers it to an unload station elsewhere in the system.

2.6.2.5 Roller Conveyor

A conveyor consisting of rotating rollers may be used throughout the factory. The conveyor can transport palletized workpieces or parts that are moving at constant speed between the manufacturing cells. When a workpiece approaches the required cell, it can be picked up by the robot or routed to the cell via a cross-roller conveyor. The rollers can be powered either by a chain drive or by a moving belt that provides for the rotation of the rollers by friction.

2.6.2.6 Belt Conveyor

In this materials-moving system, either a steel belt or a chain driven by pulleys transports the parts. This system can operate by three different methods. In *continuous transfer* the workpieces are moving continuosly and either the processing is performed during the motion or the cell's robot picks up the workpiece when it approaches the cell.

Synchronous transfer is mainly used in automatic assembly lines. The assembly stations are located with the same distance between them, and the parts to be assembled are positioned at equal distance along the conveyor. In each station a few parts are assembled by a robot or automatic device with fixed motions. The conveyor is of an indexing type; namely, it moves a short distance and stops when the product is in the station, and subsequently the assembly takes place simultaneously in all stations. This method can be applied where station cycle times are almost equal.

Power and free material handling allows each workpiece to move independently to the next manufacturing cell for processing.

2.6.2.7 Robots

The Robot Institute of America defines *industrial robots* as "a reprogrammable multifunctional manipulator designed to move materials, parts, tools, or other specialized devices through variable programmed motions for the performance of a variety of tasks".

CHAPTER 3
PHILOSOPHY OF THE INTELLIGENT ROUTE GENERATOR

3.1 OVERALL STRUCTURE

Production engineering is a critical activity and the applications of the corresponding considerations in the early stage of the design process will help to recognize likely problems related with machine tool and material usage, manufacturing tolerances, process planning, and production scheduling. The aim of this research work is the integration of design and process planning in order to optimize the design according to resource selection and route generation considerations. In order to accomplish this goal, the basic steps for constructing an Intelligent Route Generator (IRG) are presented. IRG has two main functions (See Figure 15). First, the routing data are calculated at the design stage and stored in a knowledge-based system (KBS). Then, by means of the concurrent engineering team acting as the core communication element between CAD and CAPP, the optimal route will be generated and stored in the KBS. (This process will be explained in more detail in the following paragraphs.)

This information will serve as the input to the production control process, which will give rise to the material and capacity plans (i.e., the detailed production plans). This production plans from the production process module and the process plans from the process planning module will supply the required information to the manufacturing module.

As shown in Figure 16, the designer, through the CAD system, creates the component's drawing and sends it to the CAPP system in order to generate the list of operations required to manufacture the component. This list will include all the options available in relation to the order of the operations, since sometimes it is not compulsory to execute all the operations in a certain order. Any flexibility in the order of operations could affect in a considerable way the lead times, utilisation of machines, and bottlenecks in the shop floor. This order of operations will be specified by expert process planning.

Taking into account this flexibility, an algorithm implemented using an expert system builder (Crystal), will calculate all the possible routes and lead times for each of the possible sequences of operations. From this, the best route will be selected and stored in the KBS, as depicted in Figure 17. The combination of operations

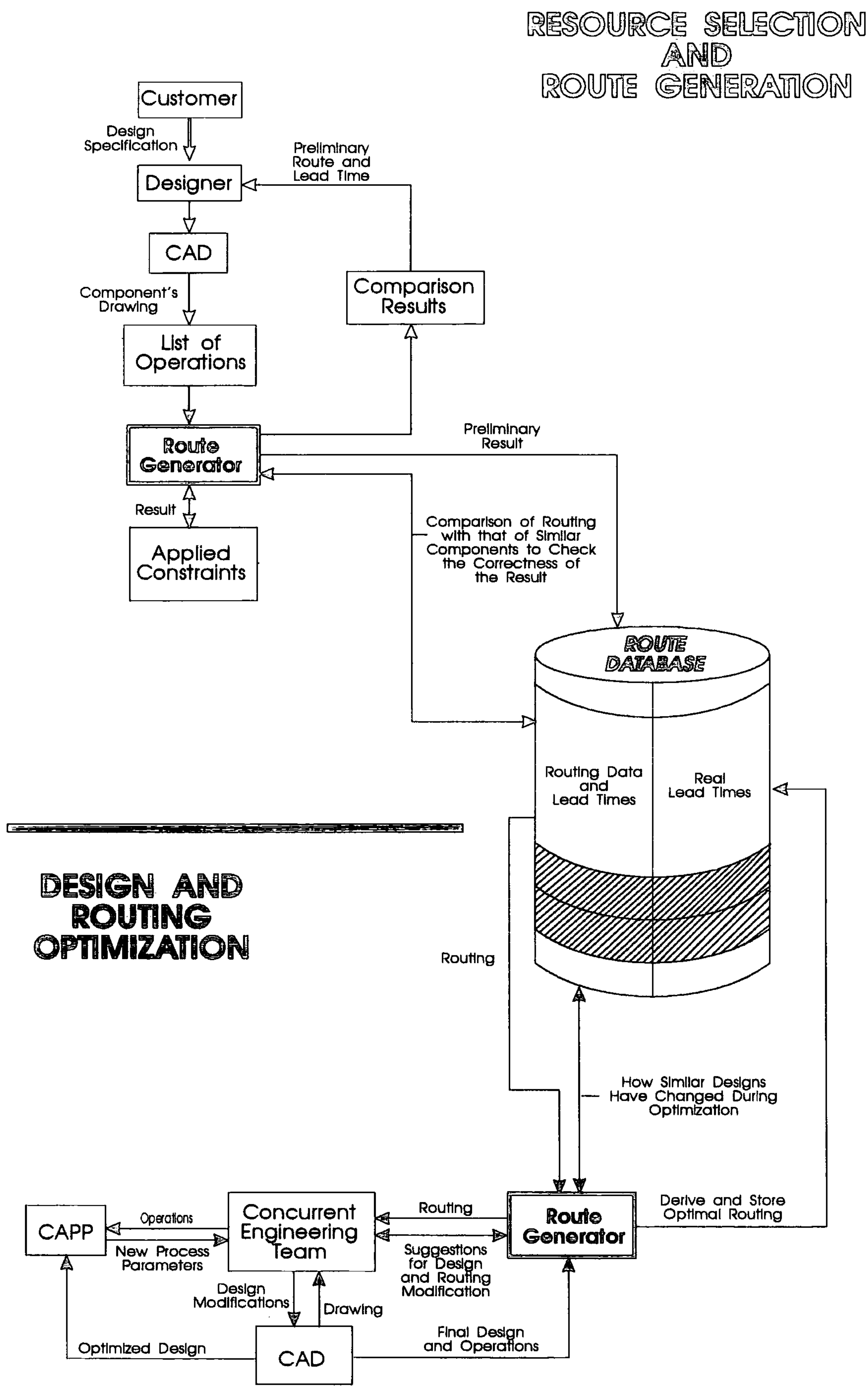


Figure 15. IRG Knowledge Base Interface

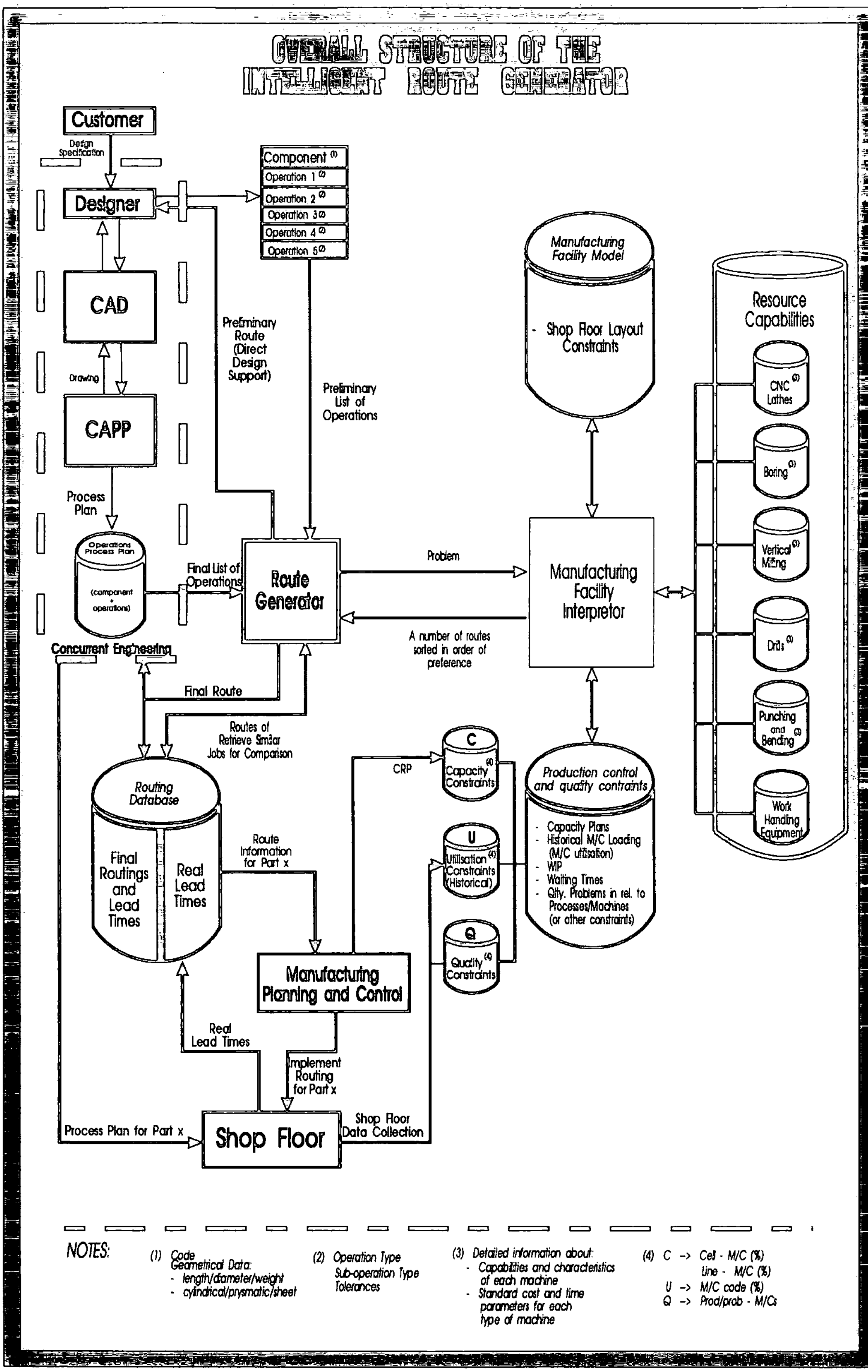


Figure 16. Overall Structure of the IRG

and machines that can perform these operations will be obtained and variables such as lead time, cost, actual and past machine utilisation, factory layout, capacity, and work handling will be the main aspects on which to base the selection. These will be standard parameters and will be used for the rough-cut route generation (See Figure 18). It is important to determine how the machines selected will affect the total capacity planning. Historical data will be used and a projection will be made on how many hours of machining are available and how many are required to do the task.

By means of Crystal, the correctness of the result obtained in this process will be checked by comparing it with previous routes of similar components already stored in the KBS. The results of this comparison will then be sent to the designer in order to give him feedback about the route selected and its corresponding lead time (See Figures 15, 17). With this information in hand, the designer could try to modify the actual design and add some improvements to it in order to reduce the total production cost. This can be done both at the design level and in a concurrent engineering environment.

The Intelligent Route Generator works as a communication platform between CAD and CAPP. IRG is an integrating tool/concept used by both design and process planning. The system provides the designer with feedback related to manufacturability and performs aggregate process planning tasks (i.e., selection of resources and routes). Addtionally, the IRG system calculates costs and times using 'standard' parameters in order to have cost and lead time indications. Hence, IRG does 'job estimating' functions.

It is expected that the time and cost estimates will be updated and optimised as part of the detailed process planning. Feedback cycles should be implemented from optimised plans and shop floor data. This feedback information should be stored in a knowledge base in order to compare new IRG routes to historical ones. This closed loop system is future work.

Suggestions for further work based on this project are presented in the lower part of Figure 15. The second phase of the project will consist on the optimization of both the design and the routing. In this optimization process, the information about the component's drawing (provided by the CAD system), the route stored in the KBS (calculated by Crystal and calculated in the first phase of the project), the suggestions for design route modification (provided by Crystal and obtained by means of analysing how

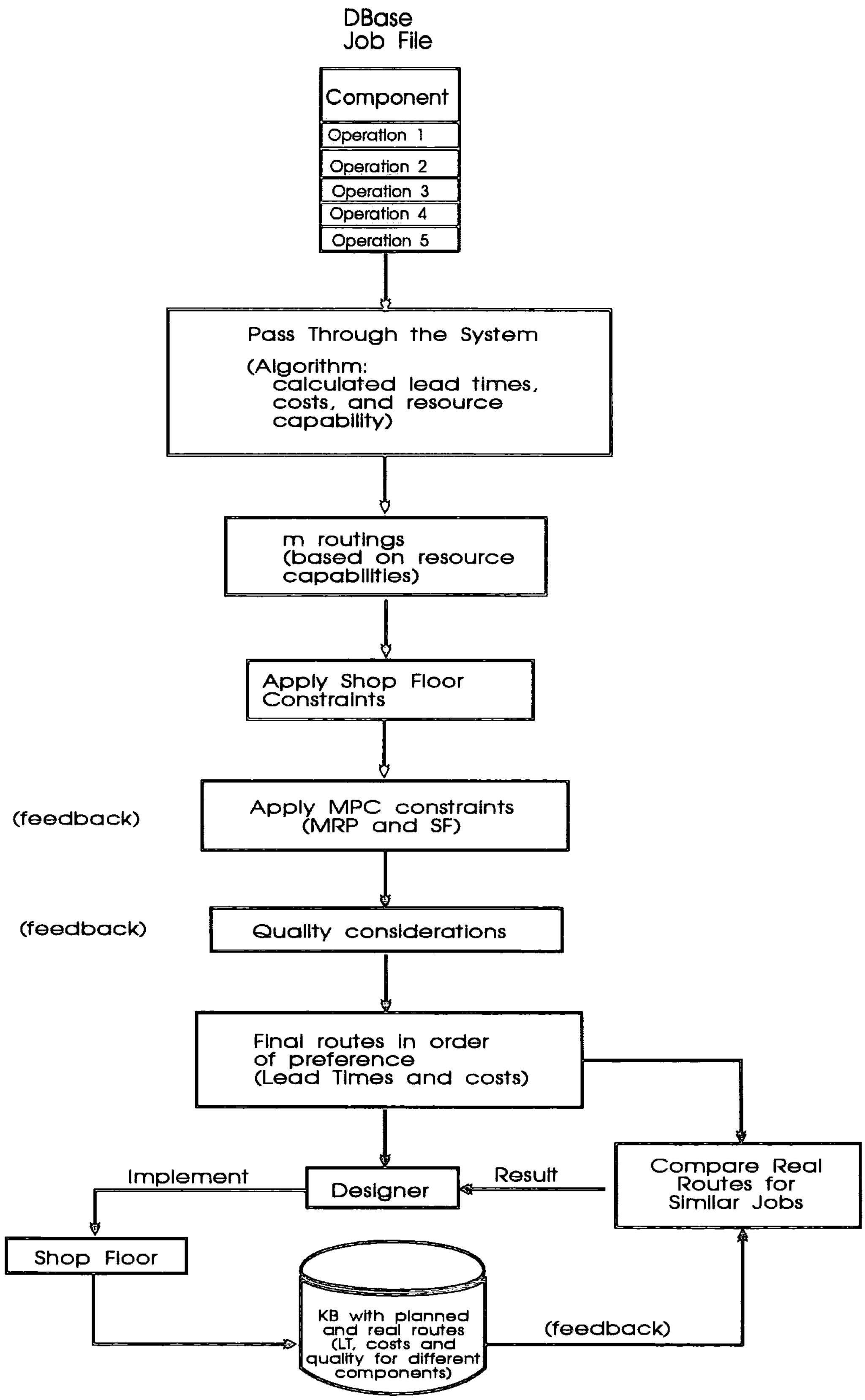


Figure 17. Overall Process

similar designs have changed during the optimization process), and the new more accurate process parameters (provided by the CAPP system) will be analysed in concurrent engineering procedures. The suggestions for design and route modification will be stored in the KBS for future analysis of components with similar routes. New design modifications will be generated and the optimized design will be sent back to the CAD system. The resource and route selection algorithm (used in the first phase) will process this information and will give as a result an optimal route, which will be sent for further analysis to Crystal in order to be sure that it fulfils the constraints specified in the system according to each company policies. After this verification process, the optimal route will be stored in the KBS.

In the theory of deterministic machine routing, a set of parts is to be processed on a set of machines (processors) in order to minimize (maximize) a certain performance measure. A job (part or component) may require of a number of operations. All machining parameters are assumed to be known in advance. Each operation is to be performed by one machine at a time.

In this project, as described in the last paragraphs, an algorithm has been developed to calculate and estimate cost of manufacturing a component and optimal route according to its route and lead time. It works within a Crystal environment making full use of an interface with DBase III Plus. A benefit is that the program acts as an advisor producing automatic decision support. An advantage of having this implemented is that you can evaluate *"what if"* situations in order to make comparative evaluations. It is important to give the most accurate values to the parameters, preferably by experts.

The technique can be used to specify if a component should be made in house or not, if by means of the optimal route it seems not to be cost-effective. One important aspect is that it has to be used in the early stages of the design process in order to gain the most of it. The model is based on manufacturing considerations. The processing cost is based on the cost of producing an ideal design and the relative cost coefficients of each component.

The resources under consideration are production machines used for metal removal operations. *Resource selection* is interpreted in this work as consisting of two parts: the selection of the most suitable machines to perform specific operations and the analysis of machine sequences used to manufacture a particular product.

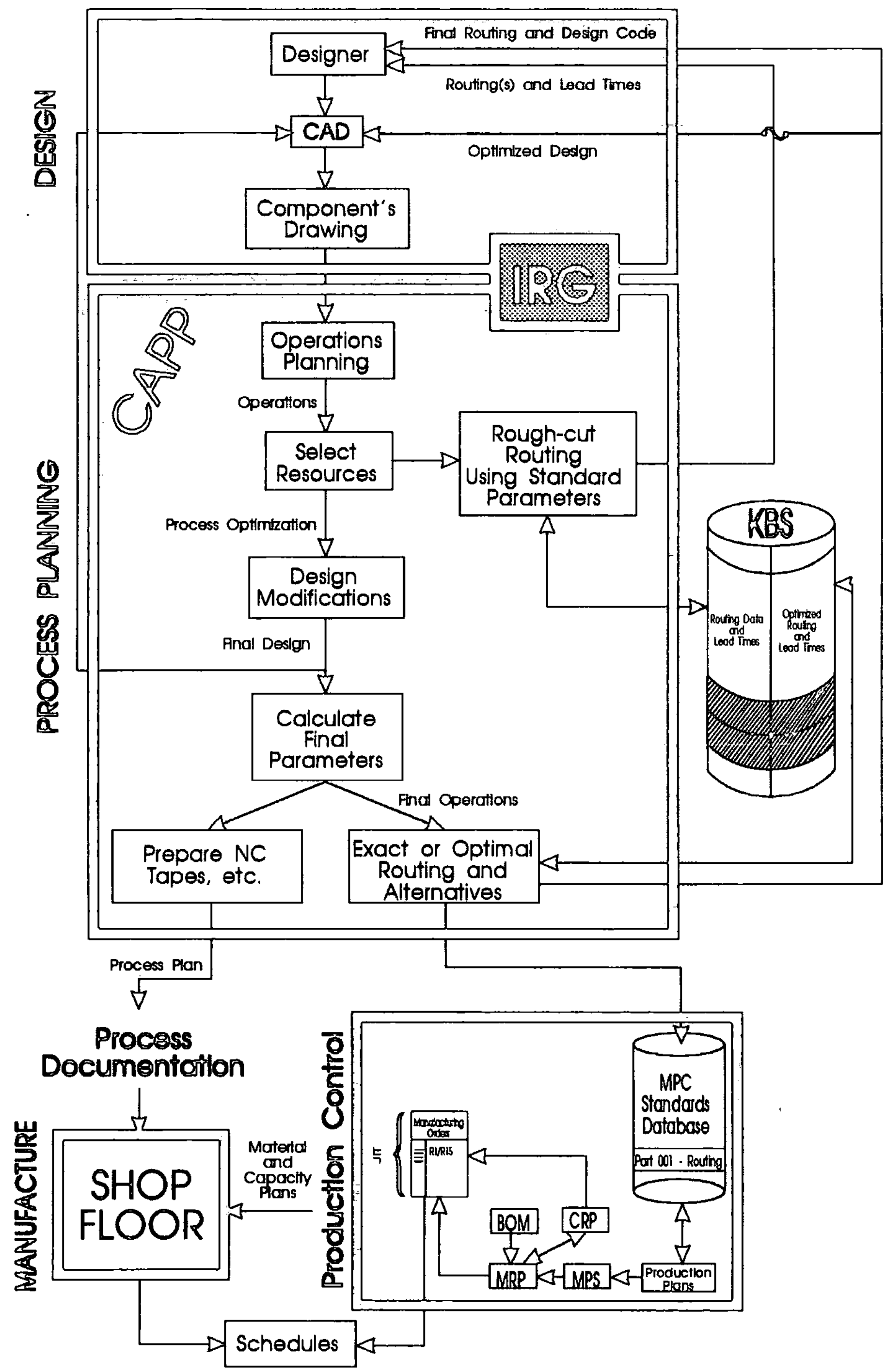


Figure 18. Overview of the Process Planning Interfaces

The machines selected for manufacture must be those which can perform the required task at the lowest cost, and with the highest possible efficiency. The introduction of NC machines has resulted in increased capacity of available resources. Each machine is often capable of many different operations, and thus the selection of resources is becoming more demanding. As the number of potential machines available for a particular operation increases, the distinction between them becomes increasingly important if costs are to be minimised and the machines potential to be fully exploited.

Resource selection is an ideal area for expert system implementation, as it is governed by many specific rules and heuristics, and is also an area which involves the consideration of a large volume of information. The aim of this project was to develop a methodology for resource selection and to implement this by constructing an expert system which will assist designers and process planners in machine tool selection.

3.2 RESOURCE SELECTION AND ROUTE GENERATION

Input to the resource selection function is usually in the form of a list of operations required for the production of a component. This information is used in the machine selection stage.

The machine selection function considers each operation in the list, and assesses the suitability of all available machines for that operation. If a machine does not have the capability to perform the operation specified, it is rejected. A list of suitable machines is therefore produced for each operation.

The suitable machines are then evaluated using other criteria, according to the preferences of the process planner. A list of machines can therefore be produced for each operation, ranked by level of performance. Ideally, the highest ranking machine should be selected, but consideration may be given to using a machine of lower rank which is capable of performing many operations in the sequence, thereby reducing setup and material handling time. This leads on to the second function, the determination of a machine sequence and routing, explained below.

More than one sequence of operations may be produced, because the provisional sequence of operations is often flexible, as operations may sometimes be performed in different order without affecting the finished product. For each sequence of operations there is a number of machines that can do each sequence. All the possible sequences can be considered, and different routes proposed and assessed, the objective being to select the most efficient route.

The final choice of a sequence of machines to produce a specific component will therefore depend upon the capabilities and desirability of the machines in that sequence, and also the performance of the sequence itself in terms of time, cost and efficiency.

3.3 SHOP FLOOR CAPACITY

The aim is to obtain the most efficient utilisation of the company's current resources. Allocation of production machinery to operations must be achieved in such a way as to minimise the cost of the component and may include other considerations such as the number of different machines involved, material handling, lead time, and cost.

The number of machines on the shop floor which are considered may be reduced for particular layouts. For a funcitonal layout, all the machines on the shop floor are considered, but the number may be reduced if the layout is cellular. When machines are arranged according to Group Technology principles, groups of machines are placed together in cells according to the type of product they manufacture. This results in many benefits, including reductions in material handling and setup times, higher machine utilisation and more efficient use of shop floor space.

If a new product is similar to the family of products that is being manufactured in a particular cell, only that cell need to be considered in the provision of resources. This is because the machines have been grouped to provide the most efficient production of that family type, and so the best machines for the new product will be contained in the family cell. This will significantly reduce the amount of information processed by the expert system, and a solution will be found more quickly.

The expert system needs to know to which GT cell does the product correspond, and that cell is specified as a stand-alone layout in order to make the best selection of resources.

3.4 METAL REMOVAL OPERATIONS

The range of production processes available is large, and subsequently there is a large variety of machine types which may be used to manufacture a particular product. Different types of machines may need to be defined in a different manner, and so, the project considered a restricted range of machines.

3.4.1 Types of Metal Removal Operations and Machinery

Metal removal operations may be classed in one of two categories: those which apply to cylindrical components and those which apply to prismatic components. Some types of operation may be applied to both categories, but may require different types of machines to perform the operation. Appendix 2 shows the common types of metal removal machines.

Table 3 shows the various types of metal removal processes or operations commonly performed on cylindrical and prismatic components. As there is a wide range of operations and machine types available, resource selection may be simplified by the association of particular machine types with particular operations, as depicted in Table 4.

3.5 SELECTION OF MACHINES FOR METAL REMOVAL OPERATIONS

This section details the relevant parameters in the assessment of metal removal operations. The most important parameters are those which need to be fulfilled so that the machine will be capable of performing a particular operation. These parameters will now be described.

Workpiece Geometry
Indicates whether the workpiece is cylindrical or prismatic in shape.

Operation Type
The resource under consideration must be capable of performing the exact operation required. (See Table 4).

Component Description	Machine Classification	Area	Operation Type	Code
Cylindrical	CNC/NC Lathe	Area 1	Turning (Longitudinal) Facing Boring (Internal Turning)	TU FC BO
		Area 2	Parting Off Grooving	PA GR
		Area 3	Threading	TC
		Area 4	Drilling Reaming	DC RC
Cylindrical and Prismatic	CNC Vertical Boring Machine	Area 1	Vertical Boring	BO
Prismatic	CNC Vertical Milling Machines, Machining Centres	Area 1	Facing Shouldering (Square, Radius, Angle) Chamfering	FP SH CH
		Area 2	Contouring Pocket Milling (Pocketing) Copy Milling	CO PM CM
		Area 3	Vertical Slotting Horizontal Slotting T-Slotting	VS HS TS
		Area 4	Threading	TP
		Area 5	Drilling Reaming	DP RP
Prismatic	Drilling Centres	Area 1	Drilling Reaming	DP RP
		Area 2	Threading	TP

Note: *Every group or area must have standard roughing and finishing times for an ideal component.*

Table 3. Parametric Model for Calculating Times and Costs

Component Description	Operation Type	Machine Type
Cylindrical	TU	CNC Turning Centre
	FC	CNC Turning Centre Vertical Boring Machine
	BO	CNC Turning Centre Vertical Boring Machine
	TC	CNC Turning Centre
	GR	CNC Turning Centre
	PA	CNC Turning Centre
	DC	CNC Turning Centre
	RC	CNC Turning Centre
Prismatic	FP	CNC Vertical Milling Centre / (Multispindle) Horizontal Milling Centre / (Multipallet)
	DP	CNC Vertical Milling Centre / (Multispindle) Horizontal Milling Centre / (Multipallet) Drilling Centre
	CH	CNC Vertical Milling Centre / (Multispindle) Horizontal Milling Centre / (Multipallet)
	SH	CNC Vertical Milling Centre / (Multispindle) Horizontal Milling Centre / (Multipallet)
	TP	CNC Vertical Milling Centre / (Multispindle) Horizontal Milling Centre / (Multipallet) Drilling Centre
	TS	CNC Vertical Milling Centre / (Multispindle) Horizontal Milling Centre / (Multipallet)
	SL	CNC Vertical Milling Centre / (Multispindle) Horizontal Milling Centre / (Multipallet)
	CO	CNC Vertical Milling Centre / (Multispindle) Horizontal Milling Centre / (Multipallet)
	PM	CNC Vertical Milling Centre / (Multispindle) Horizontal Milling Centre / (Multipallet)
	RP	CNC Vertical Milling Centre / (Multispindle) Horizontal Milling Centre / (Multipallet) Drilling Centre

Table 4. Association of Operation and Machine Types

Workpiece Dimensions

The dimensions of the workpiece must be less than the equivalent dimensions of the available 'working area' of the resource. Cylindrical components are defined by their diameter and length. Prismatic components are defined by their length, width, and height.

Tolerance (Accuracy)

If a component is to be made to a particular tolerance, then the resource used must be capable of this tolerance or better.

Other parameters may not be so critical to the actual capability of the machine to perform a specific operation but could show how cost-effective and easy it would be to produce a component.

Speed Range and Feed Range

These parameters determine machining time and cost. Hence a specific machine may be economical than another one based on these parameters.

Cost per Operation

The cost for a particular operation per component may be calculated for each machine. This is obviously an important consideration as costs should be minimised where possible.

Times

Setup, change over and tool changing times are important parameters on which to select a resource. A machine which requires long setup, change over, or tool changing times will be of lower productivity. Longer times will lead to higher costs, and all the above times should be minimised where possible.

Additional Parameters

Parameters such as skill level and number of operators, auxiliary equipment, environmental problems, ease of maintenance, utilisation and reliability, should also be considered. In this project, no consideration has been given to them, but their implementation can easily be done by having a database assigning specific weighting for each parameter.

3.6 SELECTION OF MACHINE SEQUENCES

Some of the parameters that have been analysed in order to evaluate the possible routes are described in this section.

3.6.1 Material Handling

The transportation of materials in different stages in the production process should be minimised as much as possible. Material handling is costly and yet adds no value to the product. Wherever possible, production flow on the shop floor should be designed to minimise this.

Hence, once individual machines have been selected, the machine sequences considered satisfactory should be tested according to the aim of material handling minimisation. Consideration should also be given to material handling equipment available. Many types of equipment and methods of material handling may be available on the shop floor. Some popular methods are: overhead cranes, conveyors, A.G.V.s, forklift trucks, and manual transportation. There may also be set paths on the shop floor for material handling (particularlly with A.G.V.s), and these must be considered when evaluating the distance from one machine to the next. Points to be considered when assessing the material handling for a sequence may also include:

a) The time taken and cost of the material handling methods.

b) The sequence should be constructed to fit in with, and utilise, existing material handling paths.

c) The material handling method should be suitable for the workpiece at all times.

The aim is to minimise material handling time and cost, and to ensure that the machines selected are served by the quickest, cheapest, and most suitable material handling equipment.

3.6.2 Cost per Component

The cost per component is obviously of critical importance when considering which machines to use to manufacture a component. It can be simply expressed in this case as the direct manufacturing costs plus the stockholding cost. The manufacturing costs can be calculated as the sum of the costs for machining and setting for each machine in the sequence. The calculation can be seen in Chapter 4.

The cost per component differs between one sequence and another if one or more machine(s) are easier to set or complete the machining required in a shorter period of time.

3.6.3 Manufacturing Lead Time (MLT)

It is defined as the total time taken for the component to be produced, i.e. the total time required to manufacture an item [8], and it consists of:

1) Order preparation time
2) Queue time
3) Setup time
4) Run time (process time)
5) Transportation time
6) Inspection time
7) Put away time

In a batch production system, the lead time is made up of four components, as illustrated in Figure 19. The interest of the company is to minimise MLT, thus reducing costs and increasing efficiency. For each sequence, the MLT is calculated.

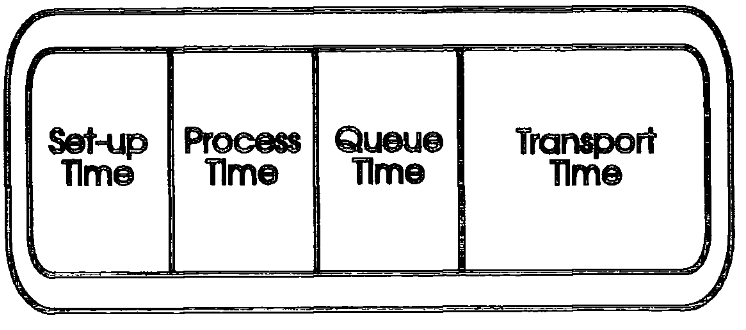


Figure 19. Breakdown of the Lead Time in a Batch Production System

3.7 EXPERT SYSTEM FUNCTIONS

3.7.1 Source of Information for the Machine Selection

The aim is to produce ranked lists of machines for each operation specified by the user. Information is required from the user regarding each operation, and machines capable of the operation are then identified. These machines are then ranked. The shop floor capacity resources may be further divided into distinct cells if the layout is cellular. If a new product is similar to an existing product, made in a particular cell, only those machines in the cell will be considered.

3.7.2 Number of Operations and Setups

The number of different operations required to produce a component is used as a counter to allow the system to loop the required number of times to identify machines for each operation. These operations are grouped according to the setups needed for the machines.

3.7.3 Machines Capable of Performing the Operation

The next stage is the application of all information collected so far, i.e. the evaluation of the parameters described in the last section for the machines available. If a machine fails on a single criterion, it is immediately rejected.

3.7.4 Sequence Determination

This function considers the time and costs associated with the use of different machine sequences. The sequences can then be judged, scored and ranked. Three main parameters may be considered. These are: the material handling, the manufacturing lead time, and the cost per component. The total scores for all the machines in a particular sequence is also considered to assess which is the optimal sequence.

From the different possible operation sequences, and the lists of machines to be used for each operation, the combinations of machines which may be used to produce a component is found.

3.7.5 Material Handling

Distance

The total distance travelled in material handling between the machines in the sequence. All reasonable material handling routes are considered, and the total distance is calculated for each one.

Material Handling Equipment

The items of material handling equipment available for each part of the proposed material handling routes are evaluated.

Use of Existing Material Handling Routes

The routes under consideration should be compared with existing ones in order to identify the areas over which existing material handling is available. The sequences may therefore be scored by the least costly and/or least utilised material handling equipment, and by the use of existing material handling routes, depending on what the user considers to be important.

3.7.6 Cost per Component

The value of this parameter is calculated for each machine sequence considered, using the equation in Chapter 4 of this report.

3.7.7 Lead Time

The lead time is calculated as shown in Chapter 4 of this report.

3.8 TESTING OF THE SYSTEM

A demonstration expert system, developed using the *Crystal* expert system building package, is supplied with this report. The management of data is done using *DBase III Plus*. It is intended to illustrate the potential of expert systems in the resource selection area, and follows many of the themes described in this report. A brief example of the methodology which has been outlined in this section of the report is given in Chapter 6.

CHAPTER 4
PRODUCTION CONCEPTS AND MATHEMATICAL MODELS

There are a great variety of methods to calculate and compute the different manufacturing factors that affect production performance. A recopilation of the mathematical models most commonly employed in the production environment is presented in this chapter. The formulas employed for the routing and costing algorithm are presented in the following section, mainly divided in two areas: timing and costing.

4.1 MATERIAL FOR THE ROUTING AND COSTING ALGORITHM

4.1.1 Processing/Machining Times

Machining time is the time that the tool is actually in the feed mode or cutting and removing chips.

4.1.1.1 Lathe Machines (Turning Type Operations) (Turning, Boring, Facing) [96]

Single Pass

$$t_2 = \frac{\pi * D_c * L_c}{v * s} \quad (min) \qquad [4\text{-}1]$$

Note: For threading use the pitch (p) instead of the feed rate (s).

Multipass

$$t_2 = t_{2_C} + t_{2_R} \quad (min) \qquad [4\text{-}2]$$

$$t_{2_C} = \frac{\pi * D_c * L_c}{v * s} \qquad [4\text{-}3]$$

$$t_{2_R} = \frac{L_c}{s_{Rapid}} \qquad [4\text{-}4]$$

$$t_{2_{Final}} = n_p * t_2 \qquad [4\text{-}5]$$

where, n_p=number of passes

$$t_{2_C} = t_{2_{Cutting}}$$ [4-6]

$$t_{2_R} = t_{2_{Retrieve\ Tool\ (Retrack)}}$$ [4-7]

$$\text{Cutting Speed } v = \frac{\pi * D * n}{1000} \quad (m/min)$$ [4-8]

4.1.1.2 Milling Machines [96]

$$t_2 \cong \frac{cutting\ length}{table\ feed} \quad (min)$$ [4-9]

$$t_2 = \frac{L_c}{u} + \frac{L_c}{s_{Rapid}}$$ [4-10]

$$t_{2_{Final}} = n_p * t_2$$ [4-7]

where, n_p=number of passes

$$\text{Spindle Rotation } n = \frac{v * 1000}{\pi * D} \quad (rpm)$$ [4-11]

$$\text{Table Feed } u = n * z * s_z \quad (mm/min)$$ [4-12]

4.1.1.3 Drilling Machines (Drill and Threading Operations) [96]

$$t_2 = \frac{L}{s} + \frac{L}{s_{Rapid}} \quad (min)$$ [4-13]

$$t_{2_{Final}} = n_p * t_2$$ [4-7]

where, n_p=number of passes

$L=5*D$ (D is the value for the maximum cutter diameter) [4-14]

$$\text{Feed Rate } s = n * s_n \quad (mm/min)$$ [4-15]

4.1.2 Costing

4.1.2.1 Cost per Part per Machine

$$C_{P_i} = x * t_1 + \sum_{k=1}^{m}\left(x * t_{2,k} + x * t_3 * \frac{t_{2,k}}{T} \right) \quad [4\text{-}16]$$

where, i = number of machine
k = number of operations
$T \approx 22.5$ (tool life)
m = number of machines required

4.1.2.2 Cost per Batch per Machine

$$C_{B_i} = Q * C_{P_i} + x * t_0 \quad [4\text{-}17]$$

4.1.2.3 Cost per Batch for Processing

$$C_{B_P} = \sum_{i=1}^{m} C_{B_i} \;\; ; \;\; C_{B_1} + C_{B_2} + \ldots + C_{B_m} \quad [4\text{-}18]$$

where, m machines are required.

4.1.2.4 Transportation Cost for Batch

$$C_{T_{x,y}} = t_{x,y} * x_T \quad [4\text{-}19]$$

$$t_{x,y} = \frac{L_{x,y}}{(s_{TR} * 0.75)} \quad [4\text{-}20]$$

$$C_{B_T} = C_{T_{Entry,1}} + \sum_{i=1}^{m-1} C_{T_{i,j+1}} + C_{T_{m,Exit}} \quad [4\text{-}21]$$

where, x_T = cost rate of transportation equipment
m machines are required

4.1.2.5 Material Cost per Batch

$$C_{B_M} = Q * MC_C \quad [4\text{-}22]$$

where, m is the material cost per component from the component database.

4.1.2.6 Total Cost per Batch

$$C_B = C_{B_P} + C_{B_T} + C_{B_M} \quad [4\text{-}23]$$

4.2 RELATED MATHEMATICAL MODELS

4.2.1 Manufacturing Lead Time [45]

$$MLT = \sum_{i=1}^{N_m} (T_{sui} + QT_{oi} + T_{noi}) + \sum_{i=1}^{N_m - 1} T_{ti,i+1} + T_{ts,1} + T_{t_{N_m,E}} \quad [4\text{-}24]$$

where, T_{sui} --> setup time for machine i (includes arranging the workplace and installing the tooling and fixturing required for the component)

T_{oi} --> time per operation at machine i

T_{noi} --> non-operation time associated with machine i

$T_{ti,i+1}$ --> travel time between machines i and $i+1$

$T_{ts,1}$ --> travel time between entry point and machine 1

$T_{tN_m,E}$ --> travel time between exit point and machine N_m

Q --> batch size (i.e. the number of units in the batch)

N_m --> number of operations (or machines) through which the component must be routed in order to be completely processed

4.2.2 Machining Times

Machining time is the time that the tool is actually in the feed mode or cutting and removing chips.

4.2.2.1 Lathe Machines (Turning-Type Operations) (Turning, Boring and Facing)

$$t_2 = \frac{L}{sN} = \frac{L\pi D}{V_c s} \quad [3,94] \qquad [4\text{-}25]$$

where, t_2 --> machining time
L --> length of cut for metal cutting (length of shaft)
s --> feed rate of spindle and shaft
N --> lathe spindle speed (rotary cutting speed), $V_c/\pi D$
D --> diameter being cut
V_c --> peripheral velocity of surface
(Values must be inserted in consistent units.)

The feed rate, also expressed in inches per minute, can be found as:

$$s_m = sN \qquad [4\text{-}26]$$

4.2.2.2 Milling Machines

a) $$t_2 = \frac{L + A + O}{s} \quad [94] \qquad [4\text{-}27]$$

where, t_2 --> actual milling time *(min)*
L --> length of cut *(in)*
A --> approach of cutter *(in)*
O --> overtravel of cutter *(in)*
s --> feed rate *(in/min)*

The approach of the cutter (*A*) is the distance the table must move the work into the cutter to reach full cutting depth or width.

The overtravel of the cutter (*O*) is the distance the table must travel in power feed minus the total length of cut. It is a safety factor that allows for variation in the length of workpieces, and clamping.

The feed (s) is the most important factor, but there are wide variations in feed depending upon the cutter, the material, and the method of holding the work.

b) $t_2 = \frac{L\pi D_c}{V_c n_t s_t}$ [3] [4-28]

where, t_2 --> machining time
L --> length of cut
D_c --> diameter being cut
V_c --> peripheral velocity of surface
n_t --> number of teeth on cutter
s_t --> feed per revolution per tooth
(Values must be inserted in consistent units.)

4.2.2.3 Drilling Machines (Drill and Threading Operations)

a) $t_2 = \frac{H + 0.3d}{sN}$ (for blind hole) [94] [4-29]

$t_2 = \frac{H + 0.5d}{sN}$ (for through hole) [94] [4-30]

where, t_2 --> machining time *(min)*
d --> diameter of drill *(in)*
H --> depth of hole to be drilled *(in)*
s --> feed in inches per revolution of spindle
N --> drill spindle speed *(rpm)*

b) $t_2 = Ls_{dt}$ [3] [4-31]

where, t_2 --> machining time *(min)*
L --> length of cut for metal cutting (length of shaft) *(in-mm)*
s_{dt} --> drilling or tapping feed rate in minutes per inch

4.2.3 Handling Time [3]

Handling time is the time required to load and unload the workpiece from the machine. It can also include the occasional dimensional inspection of the part. It is independent of cutting speed and is a constant for a specified design and machine.

4.2.4 Batch Time Rate [45]

$$\frac{\text{BatchTime}}{\text{Machine}} = T_{su} + QT_o \qquad [4\text{-}32]$$

where, T_{su} --> set up time for machine (includes arranging the workplace and installing the tooling and fixturing required for the product)

T_o --> time per operation at machine

If there is scrap rate:

$$\frac{\text{BatchTime}}{\text{Machine}} = T_{su} + \frac{QT_o}{(1-q)} \qquad [4\text{-}33]$$

where, q --> scrap rate

4.2.5 Production Time [45]

$$T_p = \frac{\text{BatchTime}/\text{Machine}}{Q} \qquad [4\text{-}34]$$

where, T_p --> average production time per unit of product for the given machine

Q --> batch size

If Q=1 (i.e. for a job shop):

$$T_p = T_{su} + T_o \qquad [4\text{-}35]$$

where, T_{su} --> set up time for machine (includes arranging the workplace and installing the tooling and fixturing required for the product)

T_O --> time per operation at machine

4.2.6 Production Rate [45]

$$R_p = \frac{1}{T_p} \qquad [4\text{-}36]$$

where, R_p --> average production rate for the machine

T_p --> average production time per unit of product for the given machine

4.2.7 Metal Removal Rate

$$R = 250 * v * s_n * D \quad (mm^3 / min) \qquad [4\text{-}37]$$

where, D is the value for the maximum cutter diameter.

4.2.8 Operation Time [45]

$$T_o = T_m + T_h + T_{th} \qquad [4\text{-}38]$$

where, T_O --> operation time

T_m --> actual machining time

T_h --> workpiece handling time

T_{th} --> tool handling time per workpiece (represents all the time spent in changing tools when they wear out, changing from one tool to the next for successive operations performed on one machine) (is the average time per workpiece for any and all of these tool handling activities)

4.2.9 Production Capacity [45]

$$PC = WS_w HR_p \qquad [4\text{-}39]$$

where, PC --> production capacity (measured as the number of good units produced per week)

S_w --> number of shifts per week

H --> hours per shift

R_p --> production rate

W --> number of work centres under consideration, capable of producing at a rate R_p units per hour, operating H hours per shift
(a work centre is defined as the production system in the plant typically consisting of:

- 1 worker and 1 machine
- 1 automated machine and no worker
- several workers acting together on a production line)

4.2.10 Utilisation [45]

$$U = \frac{\text{Output}}{\text{Capacity}} \qquad [4\text{-}40]$$

where, U --> proportion of time that the facility is operating relative to the time available under the definition of capacity, usually expressed as a percentage (refers to the amount of output of a production facility relative to its capacity)

4.2.11 Availability [45]

Typically expressed as a percentage. Used as a measure of reliability for equipment. Especially related with automated production equipment.

$$\text{Availability} = \frac{\text{MTBF} - \text{MTTR}}{\text{MTBF}} \qquad [4\text{-}41]$$

where, MTBF --> mean time between failures (average length of time between breakdowns of the piece of equipment)

MTTR --> mean time to repair (average time required to service the equipment and place it back into operation when a breakdown does occur)

4.2.12 Work in Progress [45]

Amount of product currently located in the factory that is either being processed or is between processing operations. It is inventory that is in the state of being transformed from raw material to finished product.

$$\mathrm{WIP} = \frac{\mathrm{PC} \times \mathrm{U}}{\mathrm{S_w H}} (\mathrm{MLT}) \qquad [4\text{-}42]$$

where, PC --> production capacity
U --> utilisation
S_W --> number of shifts per week
H --> hours per shift
MLT --> manufacturing lead time

4.2.13 Costing

4.2.13.1 Cost per Operation

a) $C_{operation} = C_1 t + C_2 \frac{h}{b}$ [60] [4-43]

where, C_1 --> hourly machine rate (£/hour)
t --> time to machine one part
C_2 --> hourly setting rate (£/hour)
h --> time to set up for a batch
b --> batch size

b) *Operation unit cost* is composed of handling, machining, tool changing, and the tool cost. [3]

4.2.13.2 Cost per component [60]

$$C_{component} = m + \sum \left(C_1 t + C_2 \frac{h}{b} \right) \qquad [4\text{-}44]$$

where, m --> material cost per part *(£)*
C_1 --> hourly machine rate *(£/hour)*
t --> time to machine one part
C_2 --> hourly setting rate
h --> time to set up for a batch
b --> batch size

4.2.13.3 Cost per Batch

$$C_{batch} = b\left(m + C_1 t + C_2 \frac{h}{b}\right) \qquad [4\text{-}45]$$

where, m --> material cost per part (£)
C_1 --> hourly machine rate (£/hour)
t --> time to machine one part
C_2 --> hourly setting rate
h --> time to set up for a batch
b --> batch size

4.2.13.4 Handling Cost per Operation [3]

$$HandlingCost = C_o t_h \qquad [4\text{-}46]$$

where, C_o --> direct labour wage, does not include overhead costs *(£/min)*
t_h --> time for handling *(min)*

4.2.13.5 Manufacturing Cost (Machining Cost)

a) $Mc = C_o T$ [3] [4-47]

C_o --> productive hour cost for the machine and operator (£/min)
T --> machining time *(min)*

b) Mc = VCm + RcPc [2] [4-48]

V --> volume of material required in order to produce the component

Cm --> cost of the material per unit volume in the required form

Pc --> basic processing cost for an ideal design component by a specific process

Rc --> relative cost coefficient assigned to a component design (taking account of shape complexity, suitability of material for processing, selection dimensions, tolerances and surface finish)

To allow secondary processing: (i.e. more than one operation)

$$Mc = VCm + (Rc_1Pc_1 + Rc_2Pc_2 + ... + Rc_nPc_n) \qquad [4\text{-}49]$$

$$Mc = VCm + \sum_{i=1}^{n} Rc_i Pc_i \qquad [4\text{-}50]$$

n --> number of operations required to achieve the finished component

1) Basic Processing Cost (Pc)

To represent it for a particular process first identify the factors on which it is dependent:

- Equipment costs including installation
- Operating costs: labour, number of shifts worked, supervision and overheads
- Processing times
- Tooling costs
- Component demand

$$Pc = \alpha T + \frac{\beta}{N} \qquad [4\text{-}51]$$

α --> cost of setting up and operating a specific process, including plant, labour, supervision and overheads per second

β --> process specific total tooling cost for an ideal design

T --> process time in seconds for processing an ideal design of component by a specific process

N --> total component demand

Values for α and β are based on expertise from companies specializing in producing components in specific technological areas.

2) **Relative Cost Coefficient (Rc):**

This coefficient will determine how much more expensive it will be to produce a component with more demanding features than the "ideal" design.

$$Rc = \phi(Cmp, Cc, Cs, Ct, Cf) \quad [4\text{-}52]$$

where, Cmp --> relative cost associated with material-process suitability

Cc --> relative cost associated with producing different geometries by various processes

Cs --> relative cost associated with achieving component section reductions/thickness

Ct --> relative cost associated with obtaining a specified tolerance

Cf --> relative cost associated with obtaining a specified surface finish

If $Rc = Cmp^a Cc^b Cs^c Ct^d Cf^e$ [4-53]

and a, b, c, d, e --> are weight components assigned the value of unity

Then $Rc = CmpCcCsCft$ [4-54]

where, Cft is the higher of Cf and Ct, but not both, because when a fine surface finish is being produced, fine tolerances could be attained at the same time and thus it would be incorrect to compound both relative cost coefficients.

For the ideal design Cmp...Cf are unity, but as the component design moves away from this state then one or more of the coefficients may increase in magnitude, thus changing Mc.

4.2.13.6 Tool Changing Cost per Operation [3]

$$ToolChangingCost = \frac{C_o t_c t_m}{T} \qquad [4\text{-}55]$$

where, t_c --> tool changing time *(min)*

The tool changing time t_c is the time to remove a worn-out tool, replace or index the tool, reset it for dimension and tolerance, and adjust for cutting. The time depends on whether the tool being changed is a disposable insert or a regrindable tool for which the tool must be removed and a new one reset. In lathe turning and milling there is the option of an indexable or regrindable tool. The drill is only reground.

4.2.13.7 Tool Cost per Operation [3]

$$ToolCostperOperation = \frac{C_t t_m}{T} \qquad [4\text{-}56]$$

where, C_t --> tool cost, £

4.2.14 Additional Notes [3]

4.2.14.1 Tool Cost

Tool cost C_t depends on the tool being disposable tungsten carbide insert or a regrindable tool for turning. For insert tooling, tool cost is a function of the insert price, and the number of cutting edges per insert. For regrindable tooling the tool cost is a function of original price, and total number of cutting edges. As the speed increases the cost for the tool increases. (See Table 5).

Operations	Times and Costs
Time to index a turning type of carbide tool	2 min
Time to set a high-speed tool	4 min
Large milling tool replacement	10 min
Remove drill, regrind, and replace	3 min
Cost per tool cutting corner for turning, carbide	$3
Cost for hig-speed steel tool point	$5
Cost per milling cutter, 6-in. carbide	$1500
Drill cost	$3

Table 5. Tool Changing or Indexing Times and Costs

The total cost per operation is composed of these four items. Machining cost is observed to decrease with increasing cutting speed while tool and tool changing costs increase. Handling costs are independent of cutting speed. Thus we can say that unit cost C_u is given as

$$C_u = \sum \left[C_o t_h + \frac{t_m}{T}(C_t + C_o t_c) + C_o t_m \right] \qquad [4\text{-}57]$$

Upon substitution of t_m and T and after taking the derivative of this equation with respect to velocity and equating the derivative to zero, the minimum cost may be found as

$$V_{min} = \frac{K}{\left[\left(\frac{1}{n} - 1\right)\left(\frac{C_o t_c + C_t}{C_o}\right) \right]^n} \qquad [4\text{-}58]$$

which gives the velocity for the unit cost of a rough-turning operation. In this development, we give no recognition to revenues that are produced by the machine. Consequently, V_{min} identifies the minimum velocity without revenue considerations.

Ocasionally to avoid ***bottleneck situations*** there is a need to accelerate production at cutting speed greater than that recommended for minimum cost. In these expedited operations, we assume the tool cost to be negligible, or $C_t = 0$. If the costs in the basic model are not considered, the model gives the time to produce a workpiece, and we develop

$$T_u = t_h + t_m + \frac{t_c t_m}{T} \qquad [4\text{-}59]$$

where, T_u --> minutes per unit

The production rate (unit per minute) is the reciprocal of T_u. The equation that gives the cutting speed that corresponds to maximum production rate is

$$V_{max} = \frac{K}{\left[\left(\frac{1}{n} - 1\right) t_c\right]^n} \qquad [4\text{-}60]$$

The tool life that corresponds to maximum production rate is given by

$$T_{max} = \left[\left(\frac{1}{n} - 1\right) t_c\right] \qquad [4\text{-}61]$$

4.2.14.2 Setup and Cycle

Setup includes work to prepare the machine, process or bench for producing the parts. Starting with the machine in a neutral condition, setup includes punch in and out, paperwork, obtaining tools, positioning unprocessed materials nearby, adjusting, and inspecting. It also includes return tooling, cleanup, and teardown of the machine ready for the next job. The setup does not include the time to make parts or perform the repetitive cycle. Setup estimating is necessary for job shops and companies whose parts or products have small- to moderate-quantity production. As production quantity increases, the effect of the setup value lessens its unit importance, although its absolute value remains unchanged. Setup is measured in hours.

Cycle time or *run time* is the work needed to complete one unit after the setup work is concluded. It does not include any element involved in setup. Besides finding a value for the setup, the planner finds a unit estimate for the work from the listed elements, which have the dimension of minutes. These times include *allowances* in addition to the work time that take into account *personal* requirements, *fatigue* where work effort may be excessive because of job conditions and environment, and legitimate *delays* for operation-related interruptions. Because the allowances are included in the time for the described elements, and several or many operations, the allowed time is *fair*. The concept of fairness implies that a worker can perform the work throughout the day.

The operation is broken down or detailed into elements that are described in estimating tables. These elements may be listed on a standardized company form, or marginal jottings on the operations sheet may suffice, or even scratch pad calculations may be followed. Computer-based estimating is possible. The purpose of the formal or informal elemental breakdown is identical: a *listing of elements* that will do the work is visualizes and this listing is coordinated with the company data or manual.

$$T_u = \sum \text{OperationElementsFromTables} \quad [4\text{-}62]$$

where, T_u --> minutes per cycle

The engineer will select the appropriate elements for the job from the tables. Inasmuch as the cycle elements are expressed in minutes, pieces per hour are found using

$$\text{PiecesPerHour} = \frac{60}{T_u} \quad [4\text{-}63]$$

The operations sheet requires cycle hours per 100 units. This is found using

$$H_s = T_u \times \frac{100}{60} \quad [4\text{-}64]$$

where, H_s --> cycle hours per 100 units

The unit estimate is computation made by using the setup, cycle hours per 100 units, and the lot quantity. This unit quantity varies and is an important fact found on the operations sheet.

$$UnitEstimate = \left({SU}/{N} + {H_s}/{unit} \right) \qquad [4\text{-}65]$$

where, SU --> setup hours for operation as recorded from data tables
N --> lot number
H_s --> for the purposes of this equation is per unit

The unit estimate includes a prorated share of the lot number.

4.2.14.3 Cost and Price from the Operations Sheet

The "cost for labor and overhead" is found by multiplying the unit estimate by the "labor and rate", in dollars per hour, by the "labor plus overhead rate" for each operation. Overhead is a cost item that considers depreciation of machines, tool cost, space, power, heat, and other indirect costs. After multiplying by the labour and overhead rate, we then have the *machine hour cost* for that operation. When unit material cost is added along with machine hour costs for the operations, the full cost is found.

CHAPTER 5

A KNOWLEDGE-BASED SYSTEM FOR PRODUCTION ROUTE GENERATION IN DISCRETE MANUFACTURING

In recent years manufacturing industry has had significant developments, which can be seen by the increase in the number of automated systems employed. The success of these systems in increasing productivity depends a lot on the effective use and proper selection of available resources such as machines, tools, fixtures, and material handling systems. Therefore, in order to improve the design and management functions in automated manufacturing systems, knowledge-based systems are used as decision support tools.

5.1 COMPONENTS OF A KNOWLEDGE-BASED SYSTEM

The basic components in a knowledge-based system includes the following (See Figure 20):

- Knowledge base
- Working memory
- Inference engine
- Knowledge acquisition module
- User interface module

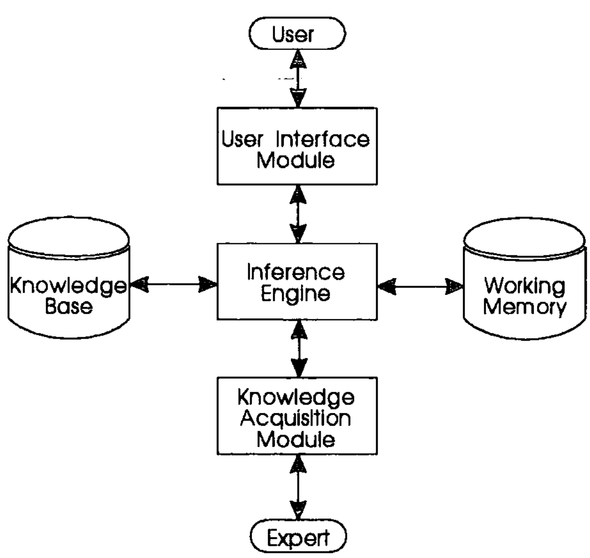


Figure 20. The Basic Components of a Knowledge-Based System

In knowledge-based systems, the effective representation of knowledge is one of the most critical issues. Andrew Kusiak [62] describes the domain knowledge as having many forms, including detailed definitions of domain-specific terms, descriptions of individual objects, classes of objects and their interrelationships, and criteria for making decisions.

5.1.1 Inference Engine

A knowledge base system should have a good inference mechanism that will enable it to use the knowledge of the domain. There are different types of inference engines, depending on the type of inference knowledge representation scheme adopted. According to Kusiak [62], in a rule-based system the inference engine or rule interpreter examines facts and executes rules contained in the knowledge base according to the inference and control procedures selected. The application of inference rules to a knowledge base enables goals or conclusions to be proved or disproved, or new facts and rules to be created.

5.1.2 Problem Solving Mechanisms

There are two basic problem solving mechanisms. In top-down problem solving the problem solving mechanism reasons backward from the conclusion, repeatedly reducing goals to subgoals, until eventually all subgoals are solved directly by the original assertions. In bottom-up problem solving, the problem solving mechanism reasons forward from the hypotheses, repeatedly deriving new assertions from old ones, until eventually the original goal is solved directly by derived assertions. This project uses a combination of both mechanisms, by reducing rules to subrules and at the same time deriving new assertions for the next rules according to the derived assertions.

5.1.3 Production Rules

Production rules are defined as a "subset of predicate calculus with an added prescriptive component indicating how the information in the rules is to be used during the reasoning" [62].

5.1.4 Structured Production Rules

Production rules have been most frequently used to represent knowledge in knowledge-based systems. However, the unstructured production systems have some disadvantages. One of them is the inefficiency of program execution due to the necessity of scanning a large number of production rules. In order to increase the efficiency of a production system, production rules can be structured. This type of a production system is called a structured production system.

5.1.5 Knowledge Acquisition

One of the traditional methods of knowledge acquisition is protocol analysis [57]. Verbal protocol analysis can be used for the development of knowledge-based systems in manufacturing. Protocol analysis can be used in conjunction with many other data gathering techniques to extract knowledge from an expert. The protocols typically provide the initial ideas and inspirations, and the additional methods, such as building a computer model and having the expert to evalulate the results, can be used to test and refine the ideas produced by protocol analysis.

5.1.5.1 Protocol Definition

A protocol is a record of information and protocol analysis is the process by which a detailed record of an action is taken and the behavior through the analysis of that record is studied.

A protocol defines the expert's thought process behind the problem solving. It shows the ways that were explored and the alternatives that were considered. "Protocol analysis is the study of these mental footprints and the attempt to construct models of thinking from the paths that were taken during problem solving" [62].

Sometimes the best method of solving a problem is the method used by most people. For example, people can still do the design of parts or the recognition of objects much more quickly than any existing computer program. The idea is simply to borrow their methods and code them into programs. Is in cases like this where the use of protocol analysis to obtain problem solving methods can save the researcher much time spent in trial and error experimenting with different approaches.

5.2 STRUCTURE OF THE KNOWLEDGE-BASED INTELLIGENT ROUTE GENERATION SYSTEM (IRG)

In the IRG system the routing problem is defined in a prescribed format, which is the system input. The system processes the input and initially decides main aspects of the pre-defined algorithm, such as component characteristics, and factory layout. The basic components of the IRG are shown in Figure 21.

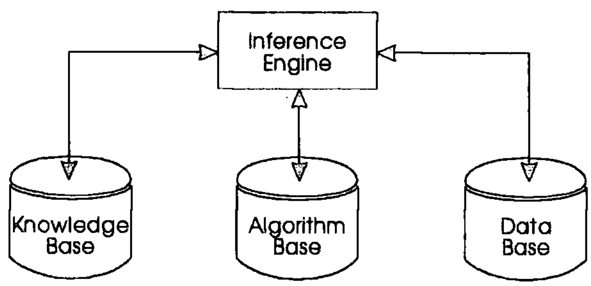


Figure 21. Structure of the IRG

5.2.1 Knowledge Base

The knowledge in IRG has to be acquired from routing experts (process planners) as well as routing literature. The knowledge has to be derived using a protocol analysis, as described above. Models are used to represent the knowledge related to the description of routing problems, parts, operations, and the routes generated.

The procedural-knowledge of IRG is in the form of production rules. In order to handle different problems the production rules are divided into three classifications:

1) Selection of an appropriate path through the algorithm to solve the problem, determined by the given component information.

2) Control of the procedure of applying the sequence of the priority rules in the heuristic algorithm.

3) Evaluation of the routes obtained and selection of the optimal route.

5.2.2 Algorithm Base

In the algorithm base the algorithm selected for the generation of the optimal route is stored. It can be modified or appended at any time, and new algorithms can be incorporated in the algorithm base if needed when the solutions diverse depending on the hypotheses and goals selected.

5.2.3 Data Base

The data base contains parameters of the routing models as well as working space used by the algorithm. New models can be added when needed.

5.2.4 Inference Engine

The inference engine in IRG controls the activation of rules in the knowledge base and the procedure of route generation of the algorithm. The inference engine uses what is known as a forward chaining control strategy. This means that in a given class of rules it attempts to activate all the rules that are related to the case considered. If a rule is activated, i.e., the conditions are true, then the actions of the rule are carried out, including all the subrules related to it. When it is needed, some rules stop the search of the inference engine and switch the control process to the algorithm. This is done when the action does not depend any more on inference results, but on a procedure that is pre-established by the algorithm. During the execution of the IRG, the inference engine maintains a list of the rules which have been activated, in order to keep track and re-evaluate some of them if necessary depending on the results obtained.

5.2.5 The Heuristic Algorithm

A process plan specifies the operations which are required on a specific component, their corresponding processing times, and the resources required such as machines and work handling equipment. In many manufacturing systems, a basic process plan and one or more alternative process plans are associated with each component. A basic process plan will be defined as the optimal process plan while, in most cases, an alternative process plan will be a suboptimal one. The resources specified by an alternative process plan will at least be partially different from the resources of the basic process plan.

The overall objective of the project is to generate a number of routes according to an aggregate process plan (i.e., list of generic manufacturing operations). The optimal route is then determined by making full use of the concurrent engineering characteristics, and a number of alternative routes are evaluated.

In the process of route generation, an operation might not be processed according to the basic process plan due to the unavailability or high utilisation of the resources specified in the basic process plan. A number of priority rules will be tested. The following five priority routing rules have been incorporated into the heuristic algorithm:

Rule 1: Selection of machine types according to the list of operations given in the component process plan specification. Additionally, the selection of machine types depends upon the operations grouped in one setup. A setup includes the work needed to prepare a machine for a job. A machine can execute more than one operation per setup. This information will be provided in the process plan specification.

Rule 2: Selection of machines according to shop floor capabilities. Firstly, this is based on the selection of the layout to be used, and then the selection of machines that will match the machine types specified in each setup group.

Rule 3: Selection of machines according to the geometrical component specifications.

Rule 4: Selection of machines according to tolerance values.

Rule 5: Selection of machines according to total cost per batch. This includes processing costs and transportation costs.

The priority rules are used in various stages of the algorithm in the sequence shown here. In order for a route to be applicable, it has to fulfil all these rules.

5.2.5.1 Routing Algorithm

The algorithm used for the IRG system is presented here. The names in brackets specify the corresponding knowledge-based file names in the Crystal environment.

Step 1.

User inputs component information *(IRG08.KB)*:

a) Component code and description
   (i.e., component description: "C" - cylindrical, "P" - prismatic --> *1 character*
   component code: "0001" --> *4 characters*)

b) Material type
   (i.e., "MS" - mild steel, "AS" - alloy steel, "SS" - stainless steel, "CS" - cast steel, "CI" - cast iron, "NF" - non ferrous material) *(2 characters).*

c) Batch size *(Q --> 4 digits).*

d) <u>Case A</u>
   If first character of component code and description is "C" then ask user to input:
   (i) Solid or hollow (S/H) *(1 character).*
   (ii) Length *(Lc --> 5.2 digits).*
   (iii) General maximum outside diameter *(Dc --> 5.2 digits).*
   (iv) Calculate Lc/Dc ratio with information from (ii) and (iii) *(5.2 digits).*
   (v) Calculate the component weight *(Wc --> 5.2 digits).*

[5.1]

where, V_c corresponds to the component volume and is calculated according to the formula described below; and ρ is the material density obtained from averaging the values of the materials [74] used in this project (the average value is 7500 kg/m³).

$$V_c = \frac{\pi}{4} * D_c^2 * L_c \qquad [5.2]$$

   (vi) Calculate material cost per component *(MC_c [£] --> 4.2 digits).*

$$MC_c = W_c * MC_W \qquad [5\text{-}3]$$

where, MC_W corresponds to the material cost per unit weight and is calculated according to information obtained from the Durham's University Manufacturing Workshop and depicted in the following formulas. (The approximate cost of £600 is applied to a material piece of 7m length and 0.1m diameter.)

$$V_w = \frac{\pi}{4} * D_w^2 * L_w = \frac{\pi}{4} * (0.1m)^2 * (7m) = 0.055m^3 \quad [5\text{-}4]$$

$$W_w = V_w * \rho = 0.55m^3 * 7500 \, {}^{kg}/_{m^3} = 412.5kg \quad [5\text{-}5]$$

$$MC_w = \frac{£600}{412.5kg} = 1.45 \, {}^{£}/_{kg} \quad [5\text{-}6]$$

Case B

If first character of component code and description is "P" then ask user to input:

(i) Solid or hollow (S/H) *(1 character).*

(ii) Length *(Lc --> 5.2 digits).*

(iii) Width *(WDc --> 5.2 digits).*

(iv) Height *(Hc --> 5.2 digits).*

(v) Calculate the component weight *(Wc --> 5.2 digits).*

$$W_c = V_c * \rho \quad [5\text{-}1]$$

where, V_c corresponds to the component volume and is calculated according to the formula described below; and ρ is the material density obtained from averaging the values of the materials [74] used in this project (the average value is 7500 kg/m³).

$$V_c = L_c * WD_c * H_c \quad [5\text{-}7]$$

(vi) Material cost per component *(MC_c [£] --> 4.2 digits)*, calculated as in Case A.

e) Ask user how many setups are needed, the maximum number of setups is 3.

f) Ask user to input operations for each setup and show user a list of operation codes and descriptions according to component description:

(i.e., if cylindrical component then operation list will be:

TU	-->	Turning (Longitudinal)	user choose R/F (roughing or finishing)
FC	-->	Facing	user choose R/F (roughing or finishing)
BO	-->	Boring (Internal Turning)	user choose R/F (roughing or finishing)
TC	-->	Threading	assign automatically R

GR	-->	Grooving	assign automatically R
PA	-->	Parting Off	assign automatically R
DC	-->	Drilling	assign automatically R
RC	-->	Reaming;	assign automatically R

if prismatic component then operation list will be:

FP	-->	Facing	user choose R/F (roughing or finishing)
DP	-->	Drilling	assign automatically R
CH	-->	Chamfering	user choose R/F (roughing or finishing)
SH	-->	Shouldering	user choose R/F (roughing or finishing)
TP	-->	Threading	assign automatically R
TS	-->	T-slots	user choose R/F (roughing or finishing)
SL	-->	Slotting	user choose R/F (roughing or finishing)
CO	-->	Contouring	user choose R/F (roughing or finishing)
PM	-->	Pocket Milling	user choose R/F (roughing or finishing)
RP	-->	Reaming	assign automatically R)

(i) If operation selected is threading, then ask for pitch *(3 digits)* and number of passes *(2 characters)*.
Show table and let the user choose the values (See Appendix 1).

(ii) If operation selected is not threading, ask for tolerance value *(Tc --> 3 digits)* and number of passes *(2 characters)*.

(iii) Assign the machine identification number:

<u>Setup 1</u>

In both cases (C/P), the second character of the setup description will be "1" (i.e., all operations in this setup will be done in the first machine) *(a=1)*.

<u>Setup 2</u>

Ask users if the same machine is going to be used in this setup:

(1.1) If "yes" then the second character of the setup description will be "1" *(b=a)*.

(1.2) If "no" then it will be "2" *(b=a+1)*.

Setup 3

Ask user if the operations in this setup will be done in:

(1.1) Same machine as setup 1, then second character of the setup description will be "1" *(c=a)*.

(1.2) Same machine as setup 2, then assign value of machine description in setup 2 *(c=b)*.

(1.3) If none of the above, then the second character of the setup description will be *(c=b+1)*.

Step 2.

First selection of machines according to list of operations (selection of machine types) *(IRG08.KB)*:

a) According to the component description and operation code, select possible types of machines from Machine/Operation database and store the types of machines in an array (the maximum number of arrays for machine types will be 5; i.e., one for each operation code).

b) For each setup, compare the available types of machines. If all the operations included in a setup cannot be done on a single machine type, reject this type of machine. Keep one array of machine types per setup (i.e., maximum three arrays in total, one for each setup).

c) If more than one setup is going to be done in the same machine, compare the machine types within these setups, and just keep, in the corresponding arrays, the machines that are the same.

Step 3.

Second selection of machines according to shop floor capabilities *(IRG15.KB)*:

a) Ask the user the layout to be used.

b) Access the corresponding Machine/Work Handling/Location database according to the layout selected, and obtain the list of machine codes (machine numbers) for each setup (i.e., comparing the machine types of the arrays from Step 2 with the machine types included in the layout).

Step 4.

Third selection of machines according to component size and weight *(IRG25.KB)*:

a) For all of the machines selected in Step 3 select the information in the Machine database and check if:

(i) Component description = "C" then:
L_C *(component length)* $\leq$ *Z Axis Travel*
D_C *(component general maximum outside diameter)* $\leq$ *X Axis Travel*

(ii) Component description = "P" then:
L_C *(component length)* $\leq$ *First Part of Table Size Overall*
WD_C *(component width)* $\leq$ *Second Part of Table Size Overall*
H_C *(component height)* $\leq$ *Spindle Nose to Table*

(iii) Both cases:
W_C *(component weight)* $\leq$ *Table Load Capacity / Weight (TC)*

(iv) Select only those machines that satisfy these restrictions.

(v) Obtain the machine cost rate *(x)*, change over time (t_0), setup time/component changing time (t_1), tool changing time (t_3) and tolerance from the Machine database and store it in the Output database.

Step 5.

For all the operations in each setup, calculate the processing/machining/operation/cutting times *(IRG37.KB)*:

a) Obtain feed rates *(s)* and velocities *(v)* for each operation according to the component material type. (This information is obtained from the Material/Operation database and the velocity values have to be converted from *m/min* to *mm/min*).

(i) If the operation is threading, obtain the velocity from this database and the pitch given by the user in Step 1 will be used as feed rate *(s=p)*.

b) If Multipass = "01" and component description = "C" and operation code ≠ "DC" or "RC", then:

(i) Calculate processing time:

$$t_2 = \frac{\pi * D_C * L_C}{v * s} \quad (min) \qquad [4\text{-}3]$$

(ii) Calculate final processing/machining time:

$$t_{2_{Final}} = n_p * t_2 \quad (min) \qquad [4\text{-}5]$$

where, n_p (number of passes) is obtained from the information given by the user in Step 1.

c) If Multipass ≠ "01" and component description = "C" and operation code ≠ "DC" or "RC", then:

(i) Calculate cutting time:

$$t_{2_C} = \frac{\pi * D_C * L_C}{v * s} \quad (min) \qquad [4\text{-}3]$$

(ii) Calculate retrieve tool/retrack time:

$$t_{2_R} = \frac{L_C}{(s_{Rapid})} \quad (min) \qquad [4\text{-}4]$$

where, S_{Rapid} will have a standard value of *9875.00 mm/min*, which was obtained from averaging the valules for Rapid Traverse in XY and Z of all the machines in the Machine database used for this project.

(iii) Calculate processing/machining time:

$$t_2 = t_{2_C} + t_{2_R} \quad (min) \qquad [4\text{-}2]$$

(iv) Calculate final processing/machining time:

$$t_{2_{Final}} = n_p * t_2 \quad (min) \qquad [4\text{-}5]$$

where, n_p (number of passes) is obtained from the information given by the user in Step 1.

d) If component description = "P" and operation code ≠ "DP" or "RP" then:

(i) Calculate spindle rotation:

$$n = \frac{v}{\pi * D} \quad (rpm) \qquad [5\text{-}8]$$

where, D is the value for the maximum cutter diameter (obtained from the Material/Operation database).

(ii) Calculate table feed:

$$u = n * z * s_z \quad (mm / min) \qquad [4\text{-}12]$$

where, z is the number of teeth.

(iii) Calculate processing time:

$$t_2 = \frac{L_C}{u} + \frac{L_C}{s_{Rapid}} \quad (min) \qquad [4\text{-}10]$$

where, S_{Rapid} will have a standard value of *9875.00 mm/min*, which was obtained from averaging the valules for Rapid Traverse in XY and Z of all the machines in the Machine database used for this project.

(iv) Calculate final processing time:

$$t_{2_{Final}} = n_p * t_2 \ (min) \qquad [4\text{-}5]$$

where, n_p (number of passes) is obtained from the information given by the user in Step 1.

e) If operation code = "DP" or "RP" or "DC" or "RC" then:

(i) Calculate spindle rotation:

(1.1) For cylindrical components:

$$n = \frac{v}{\pi * D_C} \ (rpm) \qquad [5\text{-}9]$$

where, D_c is the value for the general maximum outside diameter (obtained from the Component database).

(1.2) For prismatic components:

$$n = \frac{v}{\pi * D} \ (rpm) \qquad [5\text{-}8]$$

where, D is the value for the maximum cutter diameter (obtained from the Material/Operation database).

(ii) Calculate feed rate:

$$s = n * s_n \ (mm/min) \qquad [4\text{-}15]$$

where, s_n is the same as s_R in the Material/Operation database.

(iii) Calculate processing time:

$$t_2 = \frac{L}{s} + \frac{L}{s_{Rapid}} \quad (min) \qquad [4\text{-}13]$$

where, $L=5*D$, having D as the value for the maximum cutter diameter, and S_{Rapid} will have a standard value of *9875.00 mm/min*, which was obtained from averaging the values for Rapid Traverse in XY and Z of all the machines in the Machine database used for this project.

(iv) Calculate final processing time:

$$t_{2_{Final}} = n_p * t_2 \quad (min) \qquad [4\text{-}7]$$

where, n_p (number of passes) is obtained from the information given by the user in Step 1.

Step 6.
Separate the output file into three setup files *(IRG37.KB)*.

Step 7.
For all the machines in each setup, compare the tolerance and calculate the processing costs *(IRG46.KB)*:

a) Compare the component tolerance (in each operation) versus the machine tolerance (except for threading operations):

$$T_C \text{ (operation tolerance)} \leq T_M \text{ (machine tolerance)}$$

b) Calculate cost per part per machine:

$$C_{P_i} = x*t_1 + \sum_{k=1}^{m}\left(x*t_{2,k} + x*t_3*\frac{t_{2,k}}{T} \right) \qquad [4\text{-}16]$$

where, i = number of machine

k = number of operations

$T \approx 22.5\ min$

m=number of machines required

c) Calculate cost per batch per machine:

$$C_{B_i} = Q * C_{P_i} + x * t_0 \qquad [4\text{-}17]$$

where, Q *(batch size)* is retrieved from the Component database, and x *(machine cost rate)* and t_0 *(change over time)* are retrieved from the Machine database.

Step 8.

Compare all the machines in the 1/2/3 setups to form an array with all possible routings *(IRG59-5.KB)*:

a) For each machine in setup 1 (in the machine types array) compare its value of setup description with each one in the machine types array of setup 2, according to the cases explained below:

(i) If the set up descriptions are different (i.e., a ≠ b; see Step 1.h.v, 1.h.vi, 1.h.vii), then compare values and form routings with all the machine types in setup 2 that are different from the ones in setup 1.

(ii) If number of setups > 1 and the setup descriptions are the same (i.e., a=b) then select the same machine as in setup 1.

(iii) If component description = "P" and number of setups = 3, then:

(1.1) If c=a then select the same machine as the one selected for setup 1.

(1.2) If c=b then select the same machine as the one selected for setup 2.

(1.3) If c>b then compare values and form routings with all machine types in setup 3 that are different from the ones selected for setup 1 and setup 2.

Step 9.

Calculate the cost per batch for processing for all the routings generated in Step 8 *(IRG59-5.KB)*:

$$C_{B_P} = \sum_{i=1}^{m} C_{B_i} \quad ; \quad C_{B_1} + C_{B_2} + \ldots + C_{B_m} \qquad [4\text{-}18]$$

where, *n* machines are required.

Step 10.

Calculate the transportation cost for batch *(IRG67.KB)*:

a) From the Shop Floor Layout database retrieve the specific material entry and exit coordinates according to the layout selected. (All the coordinates are expressed in layout units, where 0.5 layout units *(u)* correspond to 2 metres.)

b) For each route calculate the distance between the entry point and the first machine:

$$a1 = (X - Entry\ Coordinate) \ - \ (X\text{ - }Initial\ Coordinate)_1 \qquad [5\text{-}10]$$

$$b1 = (Y - Entry\ Coordinate) \ - \ (Y\text{ - }Initial\ Coordinate)_1 \qquad [5\text{-}11]$$

$$L_{Entry,\ 1} = \sqrt{a1^2 + b1^2} \ \ (u) \qquad [5\text{-}12]$$

c) Calculate the distance between all consecutive points according to the routing selected for all machines in the route, except the last one:

$$a2 = (X - Final\ Coordinate)_x \ - \ (X\text{ - }Initial\ Coordinate)_y \qquad [5\text{-}13]$$

$$b2 = (Y - Final\ Coordinate)_x \ - \ (Y\text{ - }Initial\ Coordinate)_y \qquad [5\text{-}14]$$

$$L_{x,y} = \sqrt{a2^2 + b2^2} \ \ (u) \qquad [5\text{-}15]$$

h) Calculate $t_{n,Exit}$

$$t_{f,Exit} = \frac{L_{n,Exit}}{(s_{TR} * 0.75)} \ (\min) \qquad [5\text{-}20]$$

where, S_{TR} is the velocity of transportation equipment and depends on the work handling equipment that will be used (i.e., forklift trucks --> 100 m/min, conveyor belts --> 10 m/min, cranes --> 5 m/min); and *0.75* is the work handling equipment stopping factor.

i) Calculate the loading and unloading times per batch (i.e., for each loading and unloading: forklift trucks --> 3 min assuming that all the batch will be shifted at once, conveyor belts --> 5 seconds per part, cranes --> 2 min per part assuming one at a time).

(i) Calculate $t_{L/U_{Entry,1}}$

(1.1) If work handling equipment = forklift truck, then

$$t_{L/U_{Entry,1}} = LoadingTime + UnloadingTime \ \ (min) \qquad [5\text{-}21]$$

(1.2) If work handling equipment = conveyor belt or crane, then

$$t_{L/U_{Entry,1}} = (LoadingTime + UnloadingTime) * Q \ \ (min) \qquad [5\text{-}22]$$

where, Q is the batch size retrieved from the Component database.

(ii) Calculate $t_{L/U_{x,y}}$

(1.1) If work handling equipment = forklift truck, then

$$t_{L/U_{x,y}} = LoadingTime + UnloadingTime \ \ (min) \qquad [5\text{-}23]$$

(1.2) If work handling equipment = conveyor belt or crane, then

$$t_{L/U_{x,y}} = (LoadingTime + UnloadingTime) * Q \quad (min) \qquad [5\text{-}24]$$

where, Q is the batch size retrieved from the Component database.

(iii) Calculate $t_{L/U_{f,Exit}}$

(1.1) If work handling equipment = forklift truck, then

$$t_{L/U_{n,Exit}} = LoadingTime + UnloadingTime \quad (min) \qquad [5\text{-}25]$$

(1.2) If work handling equipment = conveyor belt or crane, then

$$t_{L/U_{n,Exit}} = (LoadingTime + UnloadingTime) * Q \quad (min) \qquad [5\text{-}26]$$

where, Q is the batch size retrieved from the Component database.

j) Calculate the total transportation time t_T:

$$t_{Tran_{Entry,1}} = t_{Entry,1} + t_{L/U_{Entry,1}} \quad (min) \qquad [5\text{-}27]$$

$$t_{Tran_{x,y}} = t_{x,y} + t_{L/U_{x,y}} \quad (min) \qquad [5\text{-}28]$$

$$t_{Tran_{n,Exit}} = t_{n,Exit} + t_{L/U_{n,Exit}} \quad (min) \qquad [5\text{-}29]$$

$$t_T = t_{Tran_{Entry,1}} + \sum_{i=1}^{n-1} t_{Tran_{i,i+1}} + t_{Tran_{n,Exit}} \quad (min) \qquad [5\text{-}30]$$

k) Obtain the x_T *(cost rate of transportation equipment)* from the Work Handling Equipment database (for the purposes of this work it will have the standard value of 5£/hr=0.083£/min).

l) Calculate the transportation cost for batch:

$$C_{B_T} = t_T * x_T \quad (£)$$ [5-31]

m)Calculate the material cost per batch:

$$C_{B_M} = Q * MC_c \quad (£)$$ [4-22]

where, Q and MC_c are retrieved from the Component database.

n) Calculate the total cost per batch:

$$C_B = C_{B_P} + C_{B_T} + C_{B_M} \quad (£)$$ [4-23]

Step 11.

From all the values of total cost per batch for each route, choose the lowest one and select its corresponding route in the routing array as the optimal route *(IRG67.KB)*.

Step 12.

Store this route in the Routing database *(IRG67.KB)*.

5.3 DATABASE APPROACH

5.3.1 Definition of a Database

"A database is a well organised collection of data. One should be able to process, update, and make additions to the contents of a database in a simple and flexible way. It should also be easy to make different kinds of unplanned as well as planned retrievals from the database." [100]

The contents of a database should be classified in a meaningful manner. A computerised database system that can carry out all the tasks of maintaining and accessing a database is known as a Database Management System (DBMS).

The program chosen for use in this project was Ashton-Tate's DBase III Plus. The program has all the necessary inbuilt database management functions, such as file creation and manipulation and searching of the database. It is also sufficiently fast for the job, and is the proven international database standard.

DBase III Plus was chosen to be used in this project because of all its inbuilt database management functions, such as file creation, and manipulation and searching of the database. Its functions as a programming language where not totally used, since the files defined within it where accessed from Crystal through its interface module and corresponding commands.

5.3.2 IRG Database Structure Definition

5.3.2.1 Subassembly / Fabrication Database Structure

(for reference only, not to be used by the route generator)

1. Subassembly code
2. Description
3. Number of components
4. Codes of components

5.3.2.2 Component Database Structure

1. Component code and component description (i.e. "C" - cylindrical, "P" - prismatic, "S" - sheet)
2. Material type
3. Material cost per component
4. Discrete Component geometry:
   a) *Cylindrical:*
      (i) Solid or hollow
      (ii) Length
      (iii) General maximum outside diameter
      (iv) L/D ratio
   b) *Prismatic:*
      (i) Solid or hollow
      (ii) Length

(iii) Width

(iv) Height

c) *Sheet:*

(i) Length

(ii) Width

(iii) Thickness

5. Weight

6. Batch size (Q)

7. Operations required: (5 fields of 10 characters)

a) Operation code (2 characters)

b) Roughing/Finishing (1 character)

If finishing, then number of passes must always be 1.

c) Set up number (2 characters --> 1 for set up number; 1 for machine identification)

d) Tolerance or pitch if it is threading (0 if no tolerance; to be compared with the machine tolerance) (3 characters divided by 1000 if tolerance or divided by 100 if pitch)

e) Multipass (2 characters) (01...24)

f) Operation number (this is specified by the position of the field)

5.3.2.3 Operation Database Structure

(18 files, one for each operation type)

(definition for TU, FC, BO operation types only)

(for reference only, not to be used by the route generator)

1. Description:

a) Component code

b) Machine code

c) Sub-operation type (codes for the direction of machining)

d) Roughing or finishing

e) Tolerance mor surface finish

2. Geometrical data:

a) Maximum approach angle of the profile

b) Maximum trailing angle of the profile

c) Total depth of cut (i.e., stock)

d) Total length of cut

e) Component diameter before cut

f) If hollow: the maximum internal diameter (dint) is required

3. Tool data:

a) ISO code for holder / boring bar

b) ISO code for insert

c) Insert grade (manufacturer's code)

4. Approved cutting conditions:

a) Velocity (% variance from ITS value)

b) Feed rate (% variance from ITS value)

c) Depth of cut (% variance from ITS value)

d) Specific tool life (% variance from ITS value)

5. Workholding method (i.e. "CH" - chuck,"CT" - chuck + tailstock, "CO" - collet)

5.3.2.4 Machine Database Structure

1. Machine code
2. Machine type
3. Machine number
4. Working area geometry:

a) *Lathes, vertical boring:*

(i) Maximum workpiece length (mm)

(ii) Maximum workpiece diameter (mm)

b) *Mills, vertical drills:*

(i) Maximum workpiece length (mm)

(ii) Maximum workpiece width (mm)

(iii) Maximum workpiece height (mm)

5. Maximum workpiece weight
6. Tolerance or achievable accuracy
7. Power (P)
8. Spindle speed range [Nmin - Nmax]
9. Feed range (tool post for lathes, table for mills) [Smin - Smax] (mm/rev --> lathes)
10. Change over time (setting up the tooling, programs, etc) ***(to)*** (min)
11. Tool changing time ***(t3)*** (min)
12. Tool numbers

(Tool magazine --> maximum number of tools that can be held)

13. Cost rate ***(C1, x)*** (£/hour)

14. Setting rate *(C2)*
15. Waiting time or non-operation time ***(Tno)***
16. Setup time for each operation ***(Tsu, t1)*** (locate the component)

5.3.2.5 Machine / Operation Database Structure

1. Operation code
2. Component description
3. Machine codes

5.3.2.6 Material / Operation Database Structure

1. a) *CNC/NC lathe* (cylindrical components):
   - (i) Area 1: Turning* / Facing* / Boring* (Internal Turning)
     - Roughing time
     - Finishing time
   - (ii) Area 2: Parting-off* / Grooving*
     - Roughing time
   - (iii) Area 3: Threading*
     - Roughing time
   - (iv) Area 4: Drilling* / Reaming*
     - Roughing time

   b) *CNC vertical boring machine* (cylindrical and prismatic components):
   - (i) Area 1: Vertical boring*
     - Roughing time
     - Finishing time

   c) *CNC vertical milling machine / machining centres*
   (99% prismatic, machining centres --> cylindrical):
   - (i) Area 1: Facing* / Shouldering (Square, Radius, Angle) * / Chamfering*
     - Roughing time
     - Finishing time
   - (ii) Area 2: Contouring* / Pocketing* / Copy milling*
     - Roughing time
     - Finishing time

(iii) Area 3: Vertical slotting* / Horizontal slotting* / T-slotting*
Roughing time
Finishing time
(iv) Area 4: Threading*
Roughing time
(v) Area 5: Drilling* / Reaming*
Roughing time

d) *Drilling centres* (prismatic components):
(i) Area 1: Drilling* / Reaming*
Roughing time
(ii) Area 2: Threading*
Roughing time

(* used by route generator)

5.3.2.7 Work Handling Equipment Database Structure
(for reference only)

1. Work handling code and description
2. Weight capacity
3. Length capacity
4. Width capacity
5. Height capacity
6. Cost rate
7. Travel rate

5.3.2.8 Machine / Work Handling / Location Database Structure
(i.e. one for each layout)

1. Machine / work handling code
2. Machine number
3. Machine type
4. *Coordinates:*
   (i) X-initial coordinate
   (ii) Y-initial coordinate
   (iii) X-final coordinate
   (iv) Y-final coordinate

5.3.2.9 Shop Floor Layout Database Structure

1. Overall type of layout (S --> single type; M --> multiple type)
2. Number of different layouts (N) (N=1 for S; N>1 for M)
3. Layout (i) (for i=1...N)
   a) Type - JOB (jobbing shop)
      - FUN (functional)
      - FMS (flexible manufacturing system)
      - GTC (group technology cell)
      - GTL (group technology line)
      - TRL (transfer line)

   b) *Coordinates of layout:*
      (i) X-lower-left coordinate
      (ii) Y-lower-left coordinate
      (iii) X-upper-right coordinate
      (iv) Y-upper-right coordinate

   c) Buffer space (S --> small; A --> average; H --> high)

   d) *Specific material entry:*
      (i) X-entry coordinate
      (ii) Y-entry coordinate

   e) *Specific material exit:*
      (i) X-exit coordinate
      (ii) Y-exit coordinate

   f) Integrated inspection within cell (Y/N)

5.3.2.10 Capacity and Utilisation Constraints Database Structure

(for reference only)

1. Machine code
2. Historical machine utilisation (from analysing shop floor data, statistical analysis) (2 digit figure %)
3. Average work in progress
4. Average queueing / waiting times for components (from SF data collection)
5. Projected loading for current production period (from CRP planning) (probably used only in Phase 2)

6. Quality problems in relation to this machine (field combining scrap rate % and rework rate %)

5.3.2.11 Routing Database Structure
(output)

1. Component code
2. Operation codes
3. Machine codes
4. Processing cost per batch
5. Transportation cost per batch
6. Material cost per batch
7. Total cost per batch
8. Route number
9. Layout number

5.3.2.12 Various Other Database Considerations (for further work in this subject):

1. Work handling equipment codes
2. Skill level
3. Number of operators
4. Auxiliary equipment
5. Environmental problems:
   a) Precautionary measures
   b) Safety equipment needed
6. Ease of maintenance
7. Reliability:
   a) Susceptibility to breakdowns
   b) Amount of maintenance it has required
   c) Cost of this maintenance
8. Paths already set:
   a) To Machine code
   b) Distance
   c) Work handling equipment code

CHAPTER 6
DISCUSSION AND CASE STUDIES

This chapter deals with the computational details of the IRG system, and the analysis of the results obtained. After some research, we concluded that the heuristic algorithm discussed in the last chapter is the most likely algorithm to be used while solving routing problems in discrete manufacturing systems. The results generated by the IRG system can further be improved by incorporating new production rules. It is important to notice that the degree of improvement depends upon the quality of the knowledge collected.

Sample problems have been solved in order to evaluate the quality of solutions generated by the IRG. Three different shop floor layouts, created to test the procedures, have been presented for the examples. Each one of them containing a combination of layout types such as flexible manufacturing systems, functional layouts, group technology cells and lines. These are shown in Figures 22, 23, and 24 in the following section. Machine tool information has been extracted from the manufacturer's catalogs in order to build case studies that could simulate situations close to reality. This machine tool information has been stored in the Machine File. The examples that have been analysed are the ones shown in the Component File. This file contains the information required by the system for the user to input in order to do all necessary calculations and determine the optimal route. The Material File data has been obtained from Tool's Catalogs and average values have been computed in Appendix 3.

Other databases have been created in order to allow ease of computation. Such is the case of the Machine/Operation File. This file is the interface between the Machine File and the Component File, and is used to determine the corresponding machine types for the operations specified for the component. The Shop Floor File contains a general description of the shop floor layouts. A detailed file of the machine tool location within each layout is presented in the Location File. There is one Location File for each shop floor layout definition. These files were defined in DBase III Plus, but their maintenance and actualization is done through the Crystal environment. The DBase file specifications can be found in Appendix 4. For each component, three temporal files are created each time. These files are explained in the next paragraphs.

The Output File contains all the information of the machines that have been selected from the Machine File according to the component specifications input by the user.

One, two, or three Setup Files are presented, depending on the number of setups indicated in the component specification. These files contain the information shown in the Output file, but now it is separated by setup, so calculations can easily be applied to the data.

The last one is the Route File, containing the information related to all the possible routings generated by the system according to the restrictions presented. The optimal route is selected from this file and then stored in the Final File, which contains all the optimal routes for all the components produced in the shop floor.

The rest of this chapter is divided into four sections. In the first section, the three shop floor layout examples are depicted. In the following section, the database files are presented. Then, three component examples are described and the calculations made by the IRG are shown. Step by step results are presented in table form. In the fourth section, the temporal files for each one of the case studies are given.

6.1 SHOP FLOOR LAYOUT EXAMPLES

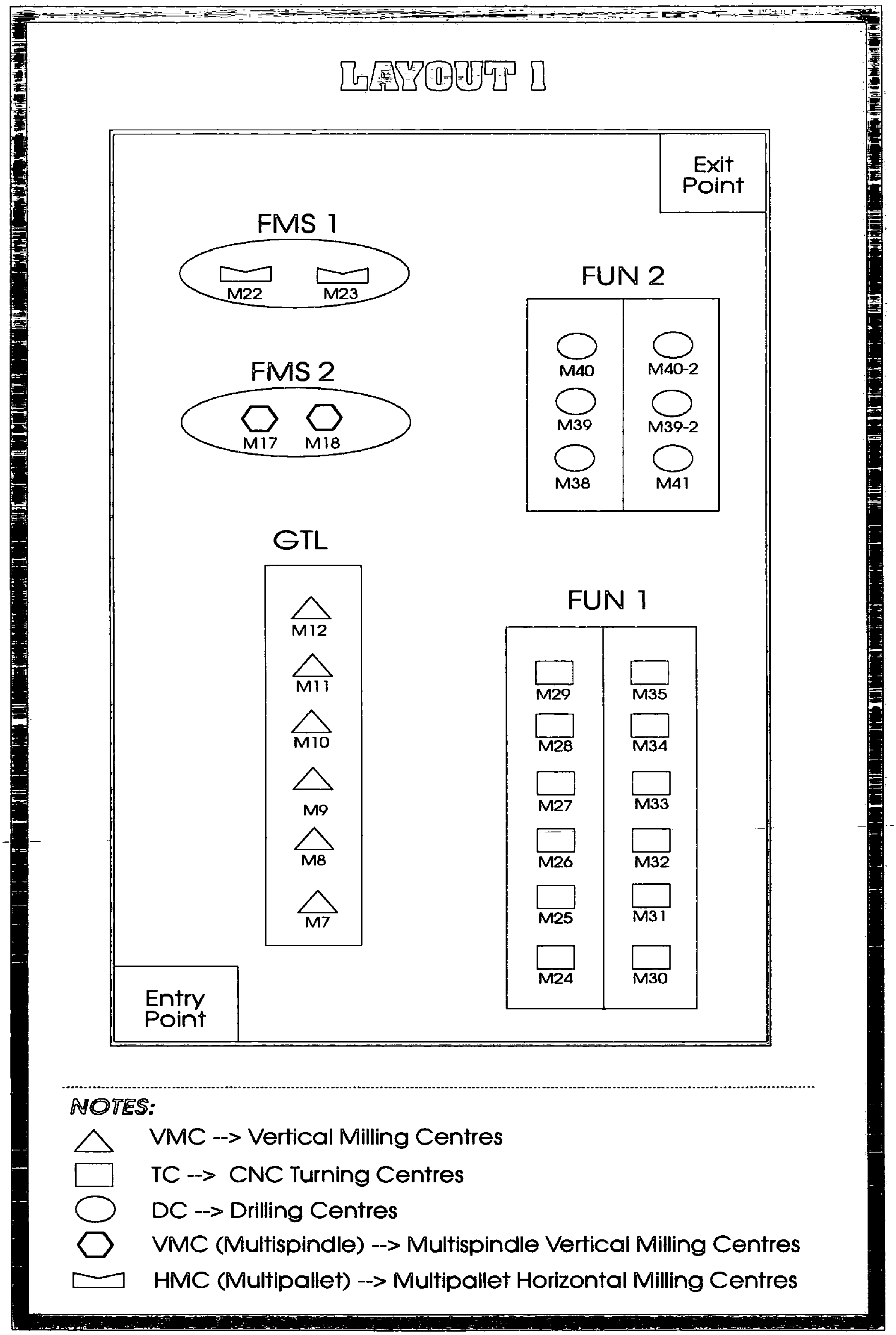


Figure 22. Layout 1

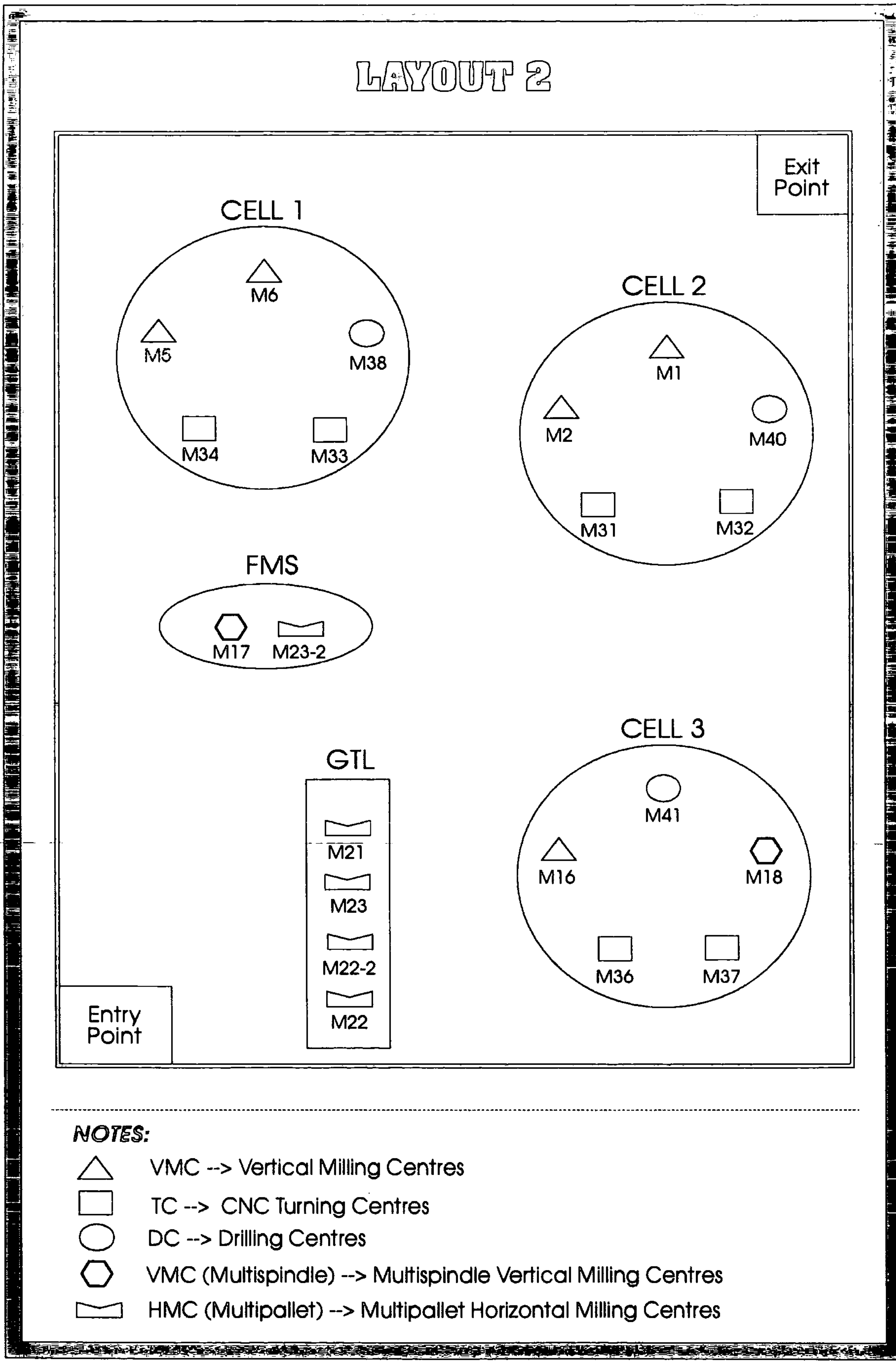


Figure 23. Layout 2

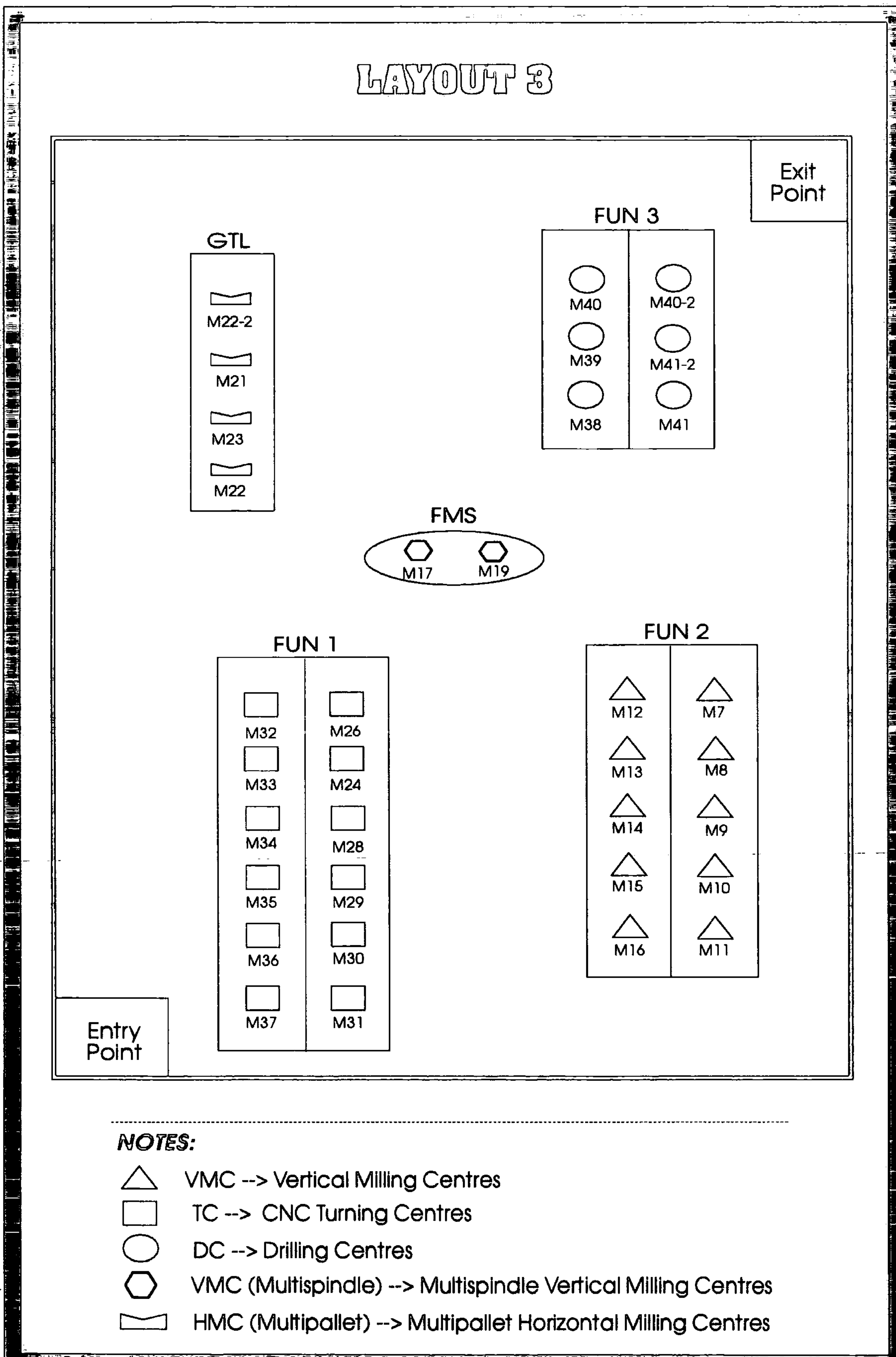


Figure 24. Layout 3

6.2 GENERAL IRG DATABASE FILES

Component Code and Description	Material Type	Material Cost per Component (£)	Solid or Hollow	Length (mm)	Gral. Max. Outside Diameter / Width (mm)	L/D Ratio / Height (mm)	Weight (kgs)	Batch Size	Operation 1	Operation 2	Operation 3	Operation 4	Operation 5
C0001	STAINLESS STEEL	6.17	S	100.00	85.00	1.18	4.26	34	TUR1100302	FCR2100301			
C0002	MILD STEEL	6.17	S	100.00	85.00	1.18	4.26	34	TUR1100301	GRR1100302	FCR2200301	TUF3300301	FCF3300301
P0003	ALLOY STEEL	1.57	H	80.00	30.00	60.00	1.08	25	FPR1100301	TPR1105004	DPR2200301	RPR3300302	SHF3300301

Table 6. Component Database Structure

Machine Number	Machine Type	Machine Code and Manufacturer	Table Size Overall / Max.Turning Dia./(TC only) *(mm)*	Table Load Cap. Weight (for TC) *(kgs)*	X Axis Travel *(mm)*	Y Axis Travel *(mm)*	Z Axis Travel *(mm)*	Spindle Nose to Table Dist. bt. Centres (TC) *(mm)*	Spindle Speed *(rpm)*	Rapid Traverse (X, Y Axis) *(mm/min)*	Rapid Traverse (Z Axis) *(mm/min)*	Feed Rates (X, Y, Z Axis) *(mm/min)*	Magazine Capacity	Spindle Motor (Cont./30 min.) *(kw)*	No. Pallets / Spindles Max. Bar Dia. (TC) *(mm)*	Cost Rate (x) *(£/hr)*	Change Overtime (t0) *(min)*	Tool Chng Time (t3) *(min)*	Setup Time (t1) *(min)*	Non-operation Time (Tno) *(% op. time)*	Setting Rate *(£/hr)*	Tolerance
M1	VMC-CNC	VMC-650-KAFO	950x545	500	650	460	520	670	4000	12000	10000	4000	18 (24")	7.5		60.00	30.0	0.5	1.0	80	50	0.001
M2	VMC-CNC	VMC-800-KAFO	950x545	700	800	460	520	670	4000	12000	10000	4000	18 (24")	7.5		50.00	90.0	2.0	2.0	85	55	0.002
M3	VMC-CNC	VMC-950-KAFO	950x545	700	950	460	520	670	4000	12000	10000	4000	18 (24")	7.5		55.00	40.0	0.6	3.0	70	40	0.003
M4	VMC-CNC	VMC-1050-KAFO	1200x545	1000	1050	460	520	670	4000	12000	10000	4000	18 (24")	7.5		65.00	20.0	2.0	4.0	75	65	0.002
M5	VMC-CNC	VMC-1200-KAFO	1500x630	1500	1200	600	600	600	4000	10000	7000	4000	24 (28")	15		60.00	50.0	0.7	1.0	60	45	0.001
M6	VMC-CNC	VMC-1400-KAFO	1700x730	2000	1400	700	700	900	4000	10000	7000	4000	28 (32")	15		70.00	60.0	1.0	2.0	90	65	0.003
M7	VMC-CNC	VMC-1685-KAFO	1900x850	2500	1600	800	700	950	4000	10000	7000	4000	32 (40")	15		60.00	60.0	0.8	3.0	85	60	0.003
M8	VMC-CNC	VMC-2185-KAFO	2400x850	3000	2100	800	700	950	4000	10000	7000	4000	32 (40")	15		50.00	30.0	1.5	4.0	80	54	0.002
M9	VMC-CNC	ANAK-MATIC-2000	750x355	750	610	355	450	500	3100	10000	7000	4000	18(22)	4.5		40.00	70.0	0.9	4.0	85	55	0.003
M10	VMC-CNC	VMC-100-EMCO	420x125	10	190	95	200	195	4000	3000	3000	2000	10			65.00	25.0	1.6	5.0	85	50	0.001
M11	VMC-CNC	VMC-300-EMCO	650x325	150	420	330	400	480	5000	12000	12000	12000	12			60.00	80.0	1.1	1.0	80	45	0.001
M12	VMC-CNC	VMC-200-EMCO	650x325	150	420	330	400	450	3600	12000	12000	4000	12			70.00	85.0	1.8	2.0	85	30	0.002
M13	VMC-CNC	ANAK-MATIC-6-CNC	900x410	900	800	450	450	450	3500	12000	12000	4000	18(22)	8		60.00	90.0	1.2	4.0	70	35	0.001
M14	VMC-CNC	ANAK-MATIC-8-CNC	1100x480	1100	950	470	510	510	3500	12000	12000	4000	18(22)	8		50.00	75.0	1.9	5.0	75	40	0.002
M15	VMC-CNC	ANAK-MATIC-10-CNC	1400x510	1400	1020	510	510	510	3000	12000	12000	4000	20(18-22)	16		55.00	65.0	1.3	6.0	60	50	0.003
M16	VMC-CNC	190VMC-BOXFORD	370x130	370	190	125	140	202	3500	12000	12000	4000	36	8		30.00	35.0	1.0	6.0	90	55	0.002
M17	VMC-CNC (Multispindle)	ANAK-MATIC-8-CNC-2	1300x480	1300	950	470	450	400	3500	12000	12000	4000	36	8	20	60.00	55.0	1.4	1.0	85	40	0.001
M18	VMC-CNC (Multispindle)	ANAK-MATIC-10-CNC-2	1650x510	1650	1020	510	500	400	3000	12000	12000	4000	36	16	20	70.00	45.0	0.9	2.0	80	65	0.003
M19	VMC-CNC (Multispindle)	ANAK-MATIC-10-CNC-4	1650x510	1650	1020	510	500	400	6000	12000	12000	4000	28	16	20	60.00	65.0	1.5	3.0	85	45	0.003
M20	HMC	H-500-ANAYAK	600x600	600	610	505	460	450	3000	12000	12000	4000	30(60)	16	10	50.00	55.0	0.8	4.0	85	65	0.002
M21	HMC (Multipallet)	H-500-P2-ANAYAK	500x500	500	610	505	460	450	3000	12000	12000	4000	30(60)	16	20	40.00	70.0	1.6	5.0	80	60	0.003
M22	HMC (Multipallet)	H-400-P9-ANAYAK	400x400	400	510	480	407	400	3500	12000	12000	4000	120	7	90	65.00	65.0	0.7	5.0	85	54	0.001
M23	HMC (Multipallet)	H-500-P7-ANAYAK	500x500	500	610	510	460	450	3000	12000	12000	4000	120	16	70	60.00	90.0	1.7	4.0	70	55	0.001
M24	TC-CNC	GR200E-MAHO	410	410	170		350	495	6000	10000	10000	4000	6	8.2	30	70.00	75.0	2.0	3.0	75	50	0.002
M25	TC-CNC	GR300E-MAHO	370	370	250		620	655	5000	10000	13000	4000	12	14.9	36	70.00	90.0	1.8	2.0	60	45	0.001
M26	TC-CNC	GR400E-MAHO	500	500	280		760	750	3500	10000	12000	4000	12	22.4	63	60.00	65.0	1.9	1.0	90	30	0.002
M27	TC-CNC	GR200C-MAHO	410	410	170		350	495	5000	10000	10000	4000	12	11.2	38	50.00	20.0	0.5	1.0	85	36	0.003
M28	TC-CNC	GR300C-MAHO	370	370	250		620	655	4000	10000	13000	4000	12	23.9	45	40.00	25.0	1.5	2.0	80	40	0.002
M29	TC-CNC	GR350C-MAHO	370	370	250		620	655	5000	10000	13000	4000	12	23.9	60	55.00	85.0	0.8	3.0	65	60	0.001
M30	TC-CNC	GR400C-MAHO	500	500	280		760	1250	3500	10000	12000	4000	12	22.4	82	60.00	30.0	1.6	4.0	65	54	0.003
M31	TC-CNC	GR500C-MAHO	620	620	280		1590	2250	2500	15000	18000	4000	12	52.9	82	70.00	30.0	0.7	5.0	60	55	0.003
M32	TC-CNC	GR500S-MAHO	620	620	320		1590	2250	2500	15000	18000	4000	24	52.9	82	50.00	40.0	1.7	3.0	90	50	0.002
M33	TC-CNC	ECOSTAR-2-WHACHEON	280	280	150		420	400	3200	10000	5000	5000	12	6		40.00	35.0	0.6	2.0	65	45	0.003
M34	TC-CNC	280-TURNMASTER-BOXFORD	270	270	300		300	400	5000	10000	5000	5000	24	3.75		30.00	50.0	2.0	4.0	80	30	0.001
M35	TC-CNC	EMCOTURN-120	270	270	90		180	100	4000	2000	2000	2000	12	4		60.00	80.0	0.9	5.0	85	36	0.001
M36	TC-CNC	EMCOTURN-140	270	270	300		300	200	2500	3000	3000	3000	12	5.5		70.00	60.0	1.6	1.0	85	40	0.002
M37	TC-CNC	MT36-MHP	200	10	150		270	250	6000	10000	10000	10000	12	5.4	35	60.00	85.0	1.0	1.0	85	50	0.003
M38	DC	PD4-BOXFORD	280x254	280	410	330	440	400	1100	10000	10000	10000	10	1.5		30.00	70.0	1.5	2.0	60	30	0.001
M39	DC	PD5-BOXFORD	280x254	280	410	330	440	400	1330	10000	10000	10000	10	2.2		60.00	75.0	1.1	3.0	90	36	0.001
M40	DC	PD8-BOXFORD	280x254	280	410	330	440	400	550	10000	10000	10000	10	1.5		70.00	80.0	0.7	3.0	65	40	0.002
M41	DC	MAC-V1E-TAKISAWA	600x350	250	430	350	480	680	6000	8000	8000	8000	10	1.5		60.00	25.0	1.2	6.0	80	50	0.003

NOTES:

1) Number of Tools (N°)
2) Manufacturer and machine code are one field
3) Table Size Overall = lenght x width for mills and drills (prismatic components)
4) Table Load Capacity / Weight = maximum component weight
5) X Axis Travel = maximum component diameter for TC (cylindrical components)
6) Z Axis Travel = maximum component length for TC (cylindrical components)
7) Spindle Nose to Table = maximum component height for mills and drills (prismatic components)
8) Rapid Traverse in (X, Y Axis) and (Z Axis) = Srapid
9) Feed Rates = Feed Range
10) Spindle Motor = Power

Table 7. Machine Database Structure

Operation Code	Component Description	Machine Code 1	Machine Code 2	Machine Code 3	Machine Code 4	Machine Code 5
TU	C	TC-CNC				
FC	C	TC-CNC	VBM			
BO	C	TC-CNC	VBM			
TC	C	TC-CNC				
GR	C	TC-CNC				
PA	C	TC-CNC				
DC	C	TC-CNC				
RC	C	TC-CNC				
FP	P	VMC-CNC	VMC-CNC (Multispindle)	HMC	HMC (Multipallet)	
DP	P	VMC-CNC	VMC-CNC (Multispindle)	HMC	HMC (Multipallet)	DC
CH	P	VMC-CNC	VMC-CNC (Multispindle)	HMC	HMC (Multipallet)	
SH	P	VMC-CNC	VMC-CNC (Multispindle)	HMC	HMC (Multipallet)	
TP	P	VMC-CNC	VMC-CNC (Multispindle)	HMC	HMC (Multipallet)	DC
TS	P	VMC-CNC	VMC-CNC (Multispindle)	HMC	HMC (Multipallet)	
SL	P	VMC-CNC	VMC-CNC (Multispindle)	HMC	HMC (Multipallet)	
CO	P	VMC-CNC	VMC-CNC (Multispindle)	HMC	HMC (Multipallet)	
PM	P	VMC-CNC	VMC-CNC (Multispindle)	HMC	HMC (Multipallet)	
RP	P	VMC-CNC	VMC-CNC (Multispindle)	HMC	HMC (Multipallet)	DC

Table 8. Machine / Operation Database Structure

Operation Code	Mild Steel Velocity (m/min)	Mild Steel Feed Rate (mm/rev)	Alloy Steel Velocity (m/min)	Alloy Steel Feed Rate (mm/rev)	Stainless Steel Velocity (m/min)	Stainless Steel Feed Rate (mm/rev)	Cast Steel Velocity (m/min)	Cast Steel Feed Rate (mm/rev)	Cast Iron Velocity (m/min)	Cast Iron Feed Rate (mm/rev)	Non Ferrous Mat. Velocity (m/min)	Non Ferrous Mat. Feed Rate (mm/rev)	Max. Cutter Diameter (mm)	Number of Teeth
TUR	203.33	0.64	127.04	0.64	97.36	0.67	151.90	0.64	109.44	0.64	0.00	0.00	0.00	0
TUF	330.46	0.20	198.97	0.20	170.28	0.20	251.73	0.20	184.37	0.20	0.00	0.00	0.00	0
FCR	203.33	0.64	127.04	0.64	97.36	0.67	151.90	0.64	109.44	0.64	0.00	0.00	0.00	0
FCF	330.46	0.20	198.97	0.20	170.28	0.20	251.73	0.20	184.37	0.20	0.00	0.00	0.00	0
BOR	203.33	0.64	127.04	0.64	97.36	0.67	151.90	0.64	109.44	0.64	0.00	0.00	0.00	0
BOF	330.46	0.20	198.97	0.20	170.28	0.20	251.73	0.20	184.37	0.20	0.00	0.00	0.00	0
PAR	126.67	0.21	92.50	0.17	100.00	0.14	82.50	0.16	65.00	0.15	0.00	0.00	0.00	0
GRR	178.33	0.21	127.50	0.17	140.00	0.14	117.50	0.16	50.00	0.15	0.00	0.00	0.00	0
TCR	166.67	0.00	132.50	0.00	115.00	0.00	120.00	0.00	155.00	0.00	0.00	0.00	0.00	0
TPR	166.67	0.00	132.50	0.00	115.00	0.00	120.00	0.00	155.00	0.00	0.00	0.00	30.67	1
DCR	114.17	0.25	93.13	0.25	55.00	0.14	106.25	0.25	127.50	0.38	245.00	0.38	36.50	2
RCR	114.17	0.25	93.13	0.25	55.00	0.14	106.25	0.25	127.50	0.38	245.00	0.38	36.50	2
DPR	114.17	0.25	93.13	0.25	55.00	0.14	106.25	0.25	127.50	0.38	245.00	0.38	36.50	2
RPR	114.17	0.25	93.13	0.25	55.00	0.14	106.25	0.25	127.50	0.38	245.00	0.38	36.50	2
FPR	92.78	0.40	72.78	0.40	96.67	0.40	68.33	0.40	78.33	0.40	0.00	0.00	105.77	4
FPF	158.89	0.10	118.75	0.10	167.50	0.10	115.00	0.10	130.00	0.10	0.00	0.00	105.77	4
SHR	92.78	0.40	72.78	0.40	96.67	0.40	68.33	0.40	78.33	0.40	0.00	0.00	105.77	4
SHF	158.89	0.10	118.75	0.10	167.50	0.10	115.00	0.10	130.00	0.10	0.00	0.00	105.77	4
CHR	92.78	0.40	72.78	0.40	96.67	0.40	68.33	0.40	78.33	0.40	0.00	0.00	49.18	2
CHF	158.89	0.10	118.75	0.10	167.50	0.10	115.00	0.10	130.00	0.10	0.00	0.00	0.00	0
COR	92.78	0.40	72.78	0.40	96.67	0.40	68.33	0.40	78.33	0.40	0.00	0.00	45.99	2
COF	158.89	0.10	118.75	0.10	167.50	0.10	115.00	0.10	130.00	0.10	0.00	0.00	45.99	2
PMR	92.78	0.40	72.78	0.40	96.67	0.40	68.33	0.40	78.33	0.40	0.00	0.00	45.99	2
PMF	158.89	0.10	118.75	0.10	167.50	0.10	115.00	0.10	130.00	0.10	0.00	0.00	45.99	2
CMR	92.78	0.40	72.78	0.40	96.67	0.40	68.33	0.40	78.33	0.40	0.00	0.00	45.99	2
CMF	158.89	0.10	118.75	0.10	167.50	0.10	115.00	0.10	130.00	0.10	0.00	0.00	45.99	2
VSR	92.78	0.40	72.78	0.40	96.67	0.40	68.33	0.40	78.33	0.40	0.00	0.00	43.80	5
VSF	158.89	0.10	118.75	0.10	167.50	0.10	115.00	0.10	130.00	0.10	0.00	0.00	43.80	5
HSR	92.78	0.40	72.78	0.40	96.67	0.40	68.33	0.40	78.33	0.40	0.00	0.00	43.80	5
HSF	158.89	0.10	118.75	0.10	167.50	0.10	115.00	0.10	130.00	0.10	0.00	0.00	43.80	5
TSR	92.78	0.40	72.78	0.40	96.67	0.40	68.33	0.40	78.33	0.40	0.00	0.00	28.00	5
TSF	158.89	0.10	118.75	0.10	167.50	0.10	115.00	0.10	130.00	0.10	0.00	0.00	28.00	5
SLR	92.78	0.40	72.78	0.40	96.67	0.40	68.33	0.40	78.33	0.40	0.00	0.00	43.80	5
SLF	158.89	0.10	118.75	0.10	167.50	0.10	115.00	0.10	130.00	0.10	0.00	0.00	43.80	5

NOTES:

1) The finishing and roughing feed rates for prismatic components are given in (mm/tooth)
2) The finishing and roughing feed rates for cylindrical components are given in (mm/rev)
3) The finishing and roughing feed rates for drilling and reaming operations are given in (mm/rev) for any component type

Table 9. Material / Operation Database Structure

Layout Code	Overall Type of Layout (S/M)	Number of Different Layouts	Layout Type 1	Layout Type 2	Layout Type 3	Layout Type 4	Layout Type 5	General Layout Coordinates	Layout 1 Coordinates	Layout 2 Coordinates	Layout 3 Coordinates	Layout 4 Coordinates	Layout 5 Coordinates	Buffer Space (S/A/H)	Specific Material Entry	Specific Material Exit	Integrated Inspection within Cell
L01	M	5	GTL	FUN1	FMS2	FMS1	FUN2	(0.0-0.0-23.0-35.0)	(5.0-4.0-7.5-18.5)	(11.0-2.0-17.5-15.5)	(3.0-23.0-7.5-25.5)	(2.0-29 0-7.5-31.5)	(13.0-22.0-18.5-28.5)	S	(0.0-0.0)	(23.0-35.0)	Y
L02	M	5	GTL	CELL3	FMS	CELL1	CELL2	(0.0-0.0-23.0-35.0)	(6.0-1.0-8.5-9.5)	(12.0-3.0-22.5-12.0)	(15.0-14.0-11.5-17.0)	(2.0-21.0-11.5-31.0)	(13.0-20.0-22.0-29.0)	A	(0.0-0.0)	(23.0-35.0)	N
L03	M	5	FUN1	FUN2	FMS	GTL	FUN3	(0.0-0.0-23.0-35.0)	(6.0-2.0-11.5-14.5)	(15.0-5.0-20.5-15.5)	(8.0-17.5-14.0-20.5)	(4.0-22.0-6.5-30.5)	(13.0-23.0-18.5-29.5)	H	(0.0-0.0)	(23.0-35.0)	Y

Table 10. Shop Floor Layout Database Structure

Machine Code	Machine Number	Machine Type	Layout Type	Location Coordinates			
				X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right
VMC-1685-KAFO	M7	VMC-CNC	GTL	6	5	6.5	5.5
VMC-2185-KAFO	M8	VMC-CNC	GTL	6	7	6.5	7.5
ANAK-MATIC-2000	M9	VMC-CNC	GTL	6	10	6.5	10.5
VMC-100-EMCO	M10	VMC-CNC	GTL	6	12	6.5	12.5
VMC-300-EMCO	M11	VMC-CNC	GTL	6	14	6.5	14.5
VMC-200-EMCO	M12	VMC-CNC	GTL	6	17	6.5	17.5
GR200E-MAHO	M24	TC-CNC	FUN1	12	3	12.5	3.5
GR300E-MAHO	M25	TC-CNC	FUN1	12	5	12.5	5.5
GR400E-MAHO	M26	TC-CNC	FUN1	12	7	12.5	7.5
GR200C-MAHO	M27	TC-CNC	FUN1	12	10	12.5	10.5
GR300C-MAHO	M28	TC-CNC	FUN1	12	12	12.5	12.5
GR350C-MAHO	M29	TC-CNC	FUN1	12	14	12.5	14.5
GR400C-MAHO	M30	TC-CNC	FUN1	16	3	16.5	3.5
GR500C-MAHO	M31	TC-CNC	FUN1	16	5	16.5	5.5
GR500S-MAHO	M32	TC-CNC	FUN1	16	7	16.5	7.5
ECOSTAR-2-WHACHEON	M33	TC-CNC	FUN1	16	10	16.5	10.5
280-TURNMASTER-BOXFORD	M34	TC-CNC	FUN1	16	12	16.5	12.5
EMCOTURN-120	M35	TC-CNC	FUN1	16	14	16.5	14.5
ANAK-MATIC-8-CNC-2	M17	VMC-CNC (Multispindle)	FMS2	4	24	4.5	24.5
ANAK-MATIC-10-CNC-2	M18	VMC-CNC (Multispindle)	FMS2	6	24	6.5	24.5
H-400-P9-ANAYAK	M22	HMC (Multipallet)	FMS1	3	30	3.5	30.5
H-500-P7-ANAYAK	M23	HMC (Multipallet)	FMS1	6	30	6.5	30.5
PD4-BOXFORD	M38	DC	FUN2	14	23	14.5	23.5
PD5-BOXFORD	M39	DC	FUN2	14	25	14.5	25.5
PD8-BOXFORD	M40	DC	FUN2	14	27	14.5	27.5
MAC-V1E-TAKISAWA	M41	DC	FUN2	17	23	17.5	23.5
PD5-BOXFORD	M39-2	DC	FUN2	17	25	17.5	25.5
PD8-BOXFORD	M40-2	DC	FUN2	17	27	17.5	27.5

Table 11. Machine Location Database Structure for Layout 1

Machine Code	Machine Number	Machine Type	Layout Type	Location Coordinates			
				X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right
H-400-P9-ANAYAK	M22	HMC (Multipallet)	GTL	7	2	7.5	2.5
H-400-P9-ANAYAK	M22-2	HMC (Multipallet)	GTL	7	4	7.5	4.5
H-500-P7-ANAYAK	M23	HMC (Multipallet)	GTL	7	6	7.5	6.5
H-500-P2-ANAYAK	M21	HMC (Multipallet)	GTL	7	8	7.5	8.5
MT35-MHP	M37	TC-CNC	CELL3	19	4	19.5	4.5
EMCOTURN-140	M36	TC-CNC	CELL3	15	4	15.5	4.5
ANAK-MATIC-10-CNC-2	M18	VMC-CNC (Multispindle)	CELL3	20	7	20.5	7.5
MAC-V1E-TAKISAWA	M41	DC	CELL3	17	10	17.5	10.5
190VMC-BOXFORD	M16	VMC-CNC	CELL3	14	7	14.5	7.5
ANAK-MATIC-8-CNC-2	M17	VMC-CNC (Multispindle)	FMS	6	15	6.5	15.5
H-500-P7-ANAYAK	M23-2	HMC (Multipallet)	FMS	10	15	10.5	15.5
280-TURNMASTER-BOXFORD	M34	TC-CNC	CELL1	4	23	4.5	23.5
ECOSTAR-2-WHACHEON	M33	TC-CNC	CELL1	9	23	9.5	23.5
PD4-BOXFORD	M38	DC	CELL1	10	27	10.5	27.5
VMC-1200-KAFO	M5	VMC-CNC	CELL1	3	27	3.5	27.5
VMC-1400-KAFO	M6	VMC-CNC	CELL1	7	30	7.5	30.5
GR500C-MAHO	M31	TC-CNC	CELL2	15	21	15.5	21.5
GR500S-MAHO	M32	TC-CNC	CELL2	19	21	19.5	21.5
PD8-BOXFORD	M40	DC	CELL2	20	25	20.5	25.5
VMC-650-KAFO	M1	VMC-CNC	CELL2	17	27	17.5	27.5
VMC-800-KAFO	M2	VMC-CNC	CELL2	14	25	14.5	25.5

Table 12. Machine Location Database Structure for Layout 2

Machine Code	Machine Number	Machine Type	Layout Type	Location Coordinates			
				X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right
MT35-MHP	M37	TC-CNC	FUN1	7	3	7.5	3.5
EMCOTURN-140	M36	TC-CNC	FUN1	7	5	7.5	5.5
EMCOTURN-120	M35	TC-CNC	FUN1	7	7	7.5	7.5
280-TURNMASTER-BOXFORD	M34	TC-CNC	FUN1	7	9	7.5	9.5
ECOSTAR-2-WHACHEON	M33	TC-CNC	FUN1	7	11	7.5	11.5
GR500S-MAHO	M32	TC-CNC	FUN1	7	13	7.5	13.5
GR500C-MAHO	M31	TC-CNC	FUN1	10	3	10.5	3.5
GR400C-MAHO	M30	TC-CNC	FUN1	10	5	10.5	5.5
GR350C-MAHO	M29	TC-CNC	FUN1	10	7	10.5	7.5
GR300C-MAHO	M28	TC-CNC	FUN1	10	9	10.5	9.5
GR200E-MAHO	M24	TC-CNC	FUN1	10	11	10.5	11.5
GR400E-MAHO	M26	TC-CNC	FUN1	10	13	10.5	13.5
190VMC-BOXFORD	M16	VMC-CNC	FUN2	16	6	16.5	6.5
ANAK-MATIC-10-CNC	M15	VMC-CNC	FUN2	16	8	16.5	8.5
ANAK-MATIC-8-CNC	M14	VMC-CNC	FUN2	16	10	16.5	10.5
ANAK-MATIC-6-CNC	M13	VMC-CNC	FUN2	16	12	16.5	12.5
VMC-200-EMCO	M12	VMC-CNC	FUN2	16	14	16.5	14.5
VMC-300-EMCO	M11	VMC-CNC	FUN2	19	6	19.5	6.5
VMC-100-EMCO	M10	VMC-CNC	FUN2	19	8	19.5	8.5
ANAK-MATIC-2000	M9	VMC-CNC	FUN2	19	10	19.5	10.5
VMC-2185-KAFO	M8	VMC-CNC	FUN2	19	12	19.5	12.5
VMC-1685-KAFO	M7	VMC-CNC	FUN2	19	14	19.5	14.5
ANAK-MATIC-8-CNC-2	M17	VMC-CNC (Multispindle)	FMS	9	19	9.5	19.5
ANAK-MATIC-10-CNC-4	M19	VMC-CNC (Multispindle)	FMS	12	19	12.5	19.5
H-400-P9-ANAYAK	M22	HMC (Multipallet)	GTL	5	23	5.5	23.5
H-500-P7-ANAYAK	M23	HMC (Multipallet)	GTL	5	25	5.5	25.5
H-500-P2-ANAYAK	M21	HMC (Multipallet)	GTL	5	27	5.5	27.5
H-400-P9-ANAYAK	M22-2	HMC (Multipallet)	GTL	5	29	5.5	29.5
PD4-BOXFORD	M38	DC	FUN3	14	24	14.5	24.5
PD5-BOXFORD	M39	DC	FUN3	14	26	14.5	26.5
PD8-BOXFORD	M40	DC	FUN3	14	28	14.5	28.5
MAC-V1E-TAKISAWA	M41	DC	FUN3	17	24	17.5	24.5
MAC-V1E-TAKISAWA	M41-2	DC	FUN3	17	26	17.5	26.5
PD8-BOXFORD	M40-2	DC	FUN3	17	28	17.5	28.5

Table 13. Machine Location Database Structure for Layout 3

Component Code	Operation 1	Operation 2	Operation 3	Operation 4	Operation 5	Machine 1	Machine 2	Machine 3	Machine 4	Machine 5	Processing Cost	Transportation Cost	Material Cost	Total Cost	Route Number	Layout Number
C0001	TUR1100302	FCR2100301				M27	M27				126.16	1.19	209.81	337.16	R1	L01
C0002	TUR1100301	GRR1100302	FCR2200301	TUF3300301	FCF3300301	M33	M33	M30	M37	M37	428.60	50.61	209.81	689.03	R11	L03
P0003	FPR1100301	TPR1105004	DPR2200301	RPR3300302	SHF3300301	M18	M18	M6	M21	M21	485.60	5.86	39.15	530.61	R5	L02

Table 14. Optimal Routes Database Structure

6.3 INTELLIGENT ROUTE GENERATOR EXAMPLE CASES

In this section, three case studies are presented. Each case study shows the information input by the user (i.e., machine number for each setup, component information, layout number, and work handling equipment to be used), and the results of the calculations generated after applying the different rules and constraints of the system. At the end, the optimal route selected is shown. The calculations are not shown in detail. They are presented in a table form for ease of understanding. These calculations are based on the algorithm described in the previous chapter, and implemented in the IRG system.

With these examples, it is easy to observe that the selection of machine tools by IRG is done in a systematic way, according to the priorities established by a group of experts. The layout may contain a considerable number of machine tools that at first glance could execute a required job. But there are other considerations like transportation time and cost, processing and material costs, and machine capacity, that should be considered in order to obtain an optimal and objective result.

6.3.1 Case Study 1

6.3.1.1 Component Description

Component code	C0001
Material type:	Stainless Steel (SS)
Material cost per component:	£6.17 (MCc) (See Step 1 of Algorithm in Chapter 5)
Weight:	4.26 kgs. (Wc) (See Step 1 of Algorithm in Chapter 5)
Batch size:	34 (Q)
Solid/hollow:	Solid (S)
Length:	100 mm (Lc)
General max. outside diameter:	85 mm (Dc)
Lc/Dc:	1.18
Number of setups:	2
Operation 1:	Turning / Roughing (TUR)
Tolerance:	0.003
Number of passes:	2
Setup number:	1

Machine number:	1 (See Step 1 (f-iii) of Algorithm in Chapter 5)
Operation 2:	Facing / Roughing (FCR)
Tolerance:	0.003
Number of passes:	1
Setup number:	2
Machine number:	1 (See Step 1 (f-iii) of Algorithm in Chapter 5)

6.3.1.2 Selection of Machine Types According to List of Operations

For each one of the operations specified in the component description, the system selects the machine types capable of executing them.

TUR operation array 1: [TC]
FCR operation array 2: [TC,VBM]

These operations are then grouped according to the setup number, and just compatible machine types in each setup are considered.

Setup 1 array: [TC]
Setup 2 array: [TC]

6.3.1.3 Selection of Machine Tools According to Shop Floor Capabilities

The user selects the layout number and the work handlilng equipment.

Layout: L01
Work Handling Equipment: Forklift Track

The machines in the layout selected matching the machine types in each setup array are extracted (See Table 30 in Section 6.4).

Machine array 1: [M24, M25, M26, M27, M28, M29, M30, M31, M32, M33, M34, M35]
Machine array 2: [M24, M25, M26, M27, M28, M29, M30, M31, M32, M33, M34, M35]

6.3.1.4 Selection of Machine Tools According to Component Geometry

The component geometrical characteristics are compared with the ones of the machines selected in the last step, in order to determine if the machines are capable of executing the job on that specific component or not. After comparing the component length (Lc=100mm), diameter (Dc=85mm), and weight (Wc=4.26kgs) against all the machines previously selected, all of them where accepted according to the geometric characteristics.

Machine	Length *(mm)*	Diameter *(mm)*	Weight *(kgs)*
M24	350	170	410
M25	620	250	370
M26	760	280	500
M27	350	170	410
M28	620	250	370
M29	620	250	370
M30	760	280	500
M31	1590	280	620
M32	1590	320	620
M33	420	150	280
M34	300	300	270
M35	160	90	270

Table 15. Machine Geometric Contraints

6.3.1.5 Time and Cost Calculations

The calculations generated for the time and cost constraints are illustrated in the following tables.

Operation	Cutting Speed *(m/min)*	Feed Rate *(mm/rev)*	Processing Time *(min)*
TUR	97.36	0.67	0.84
FCR	97.36	0.67	0.41

Table 16. Processing Times

Machine	x (£/hr)	t0 (min)	t1 (min)	t3 (min)	Tolerance
M24	70	75	3	2.0	0.002
M25	70	90	2	1.8	0.002
M26	60	85	1	1.9	0.002
M27	50	20	1	0.5	0.003
M28	40	25	2	1.5	0.002
M29	55	85	3	0.6	0.001
M30	60	30	4	1.6	0.003
M31	70	30	5	0.7	0.003
M32	50	40	3	1.7	0.002
M33	40	35	2	0.8	0.003
M34	30	50	4	2.0	0.001
M35	60	80	5	0.9	0.001

Table 17. Tolerance

Machine	Setup	Cost per Part (£)	Cost per Batch (£)
M27	S1	1.55	69.30
	S2	1.18	56.86
M30	S1	4.90	196.55
	S2	4.44	180.91
M31	S1	6.84	267.65
	S2	6.33	250.08
M33	S1	1.91	88.36
	S2	1.62	78.28

Note: See Tables 31 and 32 in Section 6.4

Table 18. Processing Costs

6.3.1.6 Selection of Optimal Route

All the possible routes are depicted and the total cost per batch for each route is calculated (See Table 33 in Section 6.4). The optimal route is the one with the lowest total cost per batch. In this example, the optimal route is Route One.

Route Number	Machine Sequence	Cost per Batch for Processing (£)	Transportation Time (min)	Transportation Cost for Batch (£)	Material Cost per Batch (£)	Total Cost per Batch (£)
R1	27 - 27	126.16	14.29	1.19	209.81	337.16
R2	30 - 30	377.46	14.61	1.22	209.81	588.49
R3	31 - 31	517.73	14.54	1.21	209.81	728.75
R4	33 - 33	166.64	14.39	1.20	209.81	377.65

Table 19. Routes and Total Cost per Batch

In this case, there are four possible routes in order to produce component *C0001*. As shown by the total cost per batch, the difference between choosing Route One and Route Three could have a great impact in the company outcomes.

6.3.2 Case Study 2

6.3.2.1 Component Description

Component code	C0002
Material type:	Mild Steel (MS)
Material cost per component:	£6.17 (MCc) (See Step 1 of Algorithm in Chapter 5)
Weight:	4.26 kgs. (Wc) (See Step 1 of Algorithm in Chapter 5)
Batch size:	34 (Q)
Solid/hollow:	Solid (S)
Length:	100 mm (Lc)
General max. outside diameter:	85 mm (Dc)
Lc/Dc:	1.18
Number of setups:	3
Operation 1:	Turning / Roughing (TUR)
Tolerance:	0.003
Number of passes:	1
Setup number:	1
Machine number:	1 (See Step 1 (f-iii) of Algorithm in Chapter 5)
Operation 2:	Grooving / Roughing (GRR)
Tolerance:	0.003
Number of passes:	2
Setup number:	1
Machine number:	1 (See Step 1 (f-iii) of Algorithm in Chapter 5)
Operation 3:	Facing / Roughing (FCR)
Tolerance:	0.003
Number of passes:	1
Setup number:	2
Machine number:	2 (See Step 1 (f-iii) of Algorithm in Chapter 5)
Operation 4:	Turning / Finishing (TUF)
Tolerance:	0.003
Number of passes:	1
Setup number:	3
Machine number:	3 (See Step 1 (f-iii) of Algorithm in Chapter 5)

Operation 5:	Facing / Finishing (FCF)
Tolerance:	0.003
Number of passes:	1
Setup number:	3
Machine number:	3 (See Step 1 (f-iii) of Algorithm in Chapter 5)

6.3.2.2 Selection of Machine Types According to List of Operations

For each one of the operations specified in the component description, the system selects the machine types capable of executing them.

TUR operation array 1:	[TC]
GRR operation array 2:	[TC]
FCR operation array 3:	[TC,VBM]
TUF operation array 4:	[TC]
FCF operation array 5:	[TC,VBM]

These operations are then grouped according to the setup number, and just compatible machine types in each setup are considered.

Setup 1 array:	[TC]
Setup 2 array:	[TC]
Setup 3 array:	[TC]

6.3.2.3 Selection of Machine Tools According to Shop Floor Capabilities

The user selects the layout number and the work handling equipment.

Layout: L03
Work Handling Equipment: Crane

The machines in the layout selected matching the machine types in each setup array are extracted (See Table 34 in Section 6.4).

Machine array 1: [M24, M26, M28, M29, M30, M31, M32, M33, M34, M35, M36, M37]

Machine array 2: [M24, M26, M28, M29, M30, M31, M32, M33, M34, M35, M36, M37]

Machine array 3: [M24, M26, M28, M29, M30, M31, M32, M33, M34, M35, M36, M37]

6.3.2.4 Selection of Machine Tools According to Component Geometry

The component geometrical characteristics are compared with the ones of the machines selected in the last step, in order to determine if the machines are capable of executing the job on that specific component or not. After comparing the component length (Lc=100mm), diameter (Dc=85mm), and weight (Wc=4.26kgs) against all the machines previously selected, all of them where accepted according to the geometric characteristics.

Machine	Length *(mm)*	Diameter *(mm)*	Weight *(kgs)*
M24	350	170	410
M26	760	280	500
M28	620	250	370
M29	620	250	370
M30	760	280	500
M31	1590	280	620
M32	1590	320	620
M33	420	150	280
M34	300	300	270
M35	160	90	270
M36	300	300	270
M35	270	150	10

Table 20. Machine Geometric Constraints

6.3.2.5 Time and Cost Calculations

The calculations generated for the time and cost constraints are illustrated in the following tables.

Operation	Cutting Speed (*m/min*)	Feed Rate (*mm/rev*)	Processing Time (*min*)
TUR	203.33	0.64	0.21
GRR	178.33	0.21	1.45
FCR	203.33	0.64	0.21
TUF	330.46	0.20	0.40
FCF	330.46	0.20	0.40

Table 21. Processing Times

Machine	x (*£/hr*)	t0 (*min*)	t1 (*min*)	t3 (*min*)	Tolerance
M37	**60**	**85**	**1**	**1.0**	**0.003**
M36	70	60	1	1.6	0.002
M35	60	80	5	0.9	0.001
M34	30	50	4	2.0	0.001
M33	**40**	**35**	**2**	**0.8**	**0.003**
M32	50	40	3	1.7	0.002
M31	**70**	**30**	**5**	**0.7**	**0.003**
M30	**60**	**30**	**4**	**1.6**	**0.003**
M29	55	85	3	0.6	0.001
M28	40	25	2	1.5	0.002
M24	70	75	3	2.0	0.002
M26	60	85	1	1.9	0.002

Table 22. Tolerance

Machine	Setup	Cost per Part (£)	Cost per Batch (£)
M37	S1	2.72	177.65
	S2	1.21	126.29
	S3	1.84	147.70
M33	S1	2.47	107.43
	S2	1.48	73.48
	S3	1.89	87.63
M31	S1	7.82	300.88
	S2	6.08	241.73
	S3	6.81	266.38
M30	S1	5.77	226.15
	S2	4.22	173.47
	S3	4.87	195.43

Note: *See Tables 35, 36 and 37 in Section 6.4*

Table 23. Processing Costs

6.3.2.6 Selection of Optimal Route

All the possible routes are depicted and the total cost per batch for each route is calculated (See Table 38 in Section 6.4). The optimal route is the one with the lowest total cost per batch. In this example, the optimal route is Route Eleven.

Route Number	Machine Sequence	Cost per Batch for Processing ($)	Transportation Time (min)	Transportation Cost for Batch ($)	Material Cost per Batch ($)	Total Cost per Batch ($)
R1	37-37-33-31-31	517.51	605.74	50.48	209.81	777.80
R2	37-37-33-30-30	446.56	591.77	50.15	209.81	706.52
R3	37-37-31-33-33	507.01	593.70	49.47	209.81	766.30
R4	37-37-31-30-30	614.81	586.03	49.23	209.81	873.85
R5	37-37-30-33-33	438.75	592.22	49.35	209.81	697.92
R6	37-37-30-31-31	617.50	585.98	49.51	209.81	876.82
R7	33-33-37-31-31	500.10	605.85	50.49	209.81	760.40
R8	33-33-37-30-30	429.15	593.25	50.36	209.81	689.32
R9	33-33-31-37-37	496.86	608.58	50.71	209.81	757.39
R10	33-33-31-30-30	544.59	591.81	50.27	209.81	804.67
R11	33-33-30-37-37	428.60	593.46	50.61	209.81	689.03
R12	33-33-30-31-31	547.28	596.78	50.35	209.81	807.45
R13	31-31-37-33-33	514.80	596.96	49.75	209.81	774.36
R14	31-31-37-30-30	622.60	590.47	49.68	209.81	882.10
R15	31-31-33-37-37	522.06	610.50	50.87	209.81	782.75
R16	31-31-33-30-30	569.79	594.51	50.46	209.81	830.07
R17	31-31-30-37-37	622.05	587.72	49.90	209.81	881.77
R18	31-31-30-33-33	561.98	592.12	49.48	209.81	821.28
R19	30-30-37-33-33	440.07	598.56	49.88	209.81	699.76
R20	30-30-37-31-31	618.82	594.80	49.95	209.81	878.58
R21	30-30-33-37-37	447.33	609.41	50.78	209.81	707.93
R22	30-30-33-31-31	566.01	601.53	50.71	209.81	826.53
R23	30-30-31-37-37	615.58	587.94	49.99	209.81	875.38
R24	30-30-31-33-33	555.51	594.79	49.79	209.81	815.12

Table 24. Routes and Total Cost per Batch

For component *C0002* there is a wide range of possibilities. Selecting the best possibility could be time consuming if the user is not working with a system like the one described in this thesis. All the calculations cannot otherwise be done so easily by the manufacturing engineer.

6.3.3 Case Study 3

6.3.3.1 Component Description

Component code	P0003
Material type:	Alloy Steel (AS)
Material cost per component:	£1.57 (MCc) (See Step 1 of Algorithm in Chapter 5)
Weight:	1.08 kgs. (Wc) (See Step 1 of Algorithm in Chapter 5)
Batch size:	25 (Q)
Solid/hollow:	Hollow (H)

Length:	80 mm (Lc)
Width:	30 mm (WDc)
Height:	60 mm (Hc)
Number of setups:	3
Operation 1:	Facing / Roughing (FPR)
Tolerance:	0.003
Number of passes:	1
Setup number:	1
Machine number:	1 (See Step 1 (f-iii) of Algorithm in Chapter 5)
Operation 2:	Threading / Roughing (TPR)
Pitch:	0.50 mm
Number of passes:	4
Setup number:	1
Machine number:	1 (See Step 1 (f-iii) of Algorithm in Chapter 5)
Operation 3:	Drilling / Roughing (DPR)
Tolerance:	0.003
Number of passes:	1
Setup number:	2
Machine number:	2 (See Step 1 (f-iii) of Algorithm in Chapter 5)
Operation 4:	Reaming / Roughing (RPR)
Tolerance:	0.003
Number of passes:	2
Setup number:	3
Machine number:	3 (See Step 1 (f-iii) of Algorithm in Chapter 5)
Operation 5:	Shouldering / Finishing (SHF)
Tolerance:	0.003
Number of passes:	1
Setup number:	3
Machine number:	3 (See Step 1 (f-iii) of Algorithm in Chapter 5)

6.3.3.2 Selection of Machine Types According to List of Operations

For each one of the operations specified in the component description, the system selects the machine types capable of executing them.

FPR operation array 1: [VMC, VMC (Multispindle), HMC, HMC (Multipallet)]
TPR operation array 2: [VMC, VMC (Multispindle), HMC, HMC (Multipallet), DC]
DPR operation array 3: [VMC, VMC (Multispindle), HMC, HMC (Multipallet), DC]
RPR operation array 4: [VMC, VMC (Multispindle), HMC, HMC (Multipallet), DC]
SHF operation array 5: [VMC, VMC (Multispindle), HMC, HMC (Multipallet)]

These operations are then grouped according to the setup number, and just compatible machine types in each setup are considered.

Setup 1 array: [VMC, VMC (Multispindle), HMC, HMC (Multipallet)]
Setup 2 array: [VMC, VMC (Multispindle), HMC, HMC (Multipallet), DC]
Setup 3 array: [VMC, VMC (Multispindle), HMC, HMC (Multipallet)]

6.3.3.3 Selection of Machine Tools According to Shop Floor Capabilities

The user selects the layout number and the work handling equipment.

Layout: L02
Work Handling Equipment: Conveyor Belt

The machines inthe layout selected matching the machine types in each setup array are extracted (See Table 39 in Section 6.4).

Machine array 1: [M22, M22-2, M23, M21, M18, M16, M17, M23-2, M5, M6, M1, M2]
Machine array 2: [M22, M22-2, M23, M21, M18, M41, M16, M17, M23-2, M38, M5, M6, M40, M1, M2]
Machine array 3: [M22, M22-2, M23, M21, M18, M16, M17, M23-2, M5, M6, M1, M2]

6.3.3.4 Selection of Machine Tools According to Component Geometry

The component geometrical characteristics are compared with the ones of the machines selected in the last step, in order to determine if the machines are capable of executing the job on that specific component or not. After comparing the component length (Lc=80mm), diameter (WDc=30mm), height (Hc=60mm), and weight

(Wc=1.08kgs) against all the machines previously selected, all of them where accepted according to the geometric characteristics.

Machine	Length *(mm)*	Width *(mm)*	Height *(mm)*	Weight *(kgs)*
M22	400	400	400	400
M22-2	400	400	400	400
M23	500	500	450	500
M21	500	500	450	500
M18	1650	510	400	1650
M41	600	350	660	250
M16	370	130	202	370
M17	1300	480	400	1300
M23-2	500	500	450	500
M38	280	254	400	280
M5	1500	630	800	1500
M6	1700	730	900	2000
M40	280	254	400	280
M1	950	545	670	500
M2	950	545	670	700

Table 25. Machine Geometric Constraints

6.3.3.5 Time and Cost Calculations

The calculations generated for the time and cost constraints are illustrated in the following tables.

Operation	Cutting Speed *(m/min)*	Feed Rate *(mm/rev)*	Processing Time *(min)*
TUR	72.78	0.40	0.24
GRR	132.50	0.50	0.50
FCR	93.13	0.25	0.92
TUF	93.13	0.25	1.84
FCF	118.75	0.10	0.57

Table 26. Processing Times

Machine	x (£/hr)	t0 (min)	t1 (min)	t3 (min)	Tolerance
M16	30	35	6	1.0	0.002
M5	60	50	1	0.7	0.001
M6	70	80	2	1.0	0.003
M1	60	30	1	0.5	0.001
M2	60	85	1	1.9	0.002
M18	70	45	2	0.9	0.003
M17	60	55	1	1.4	0.001
M22	65	65	5	0.7	0.001
M22-2	65	65	5	0.7	0.001
M23	60	90	4	1.7	0.001
M21	40	70	5	1.6	0.003
M23-2	60	90	4	1.7	0.001
M41	60	25	6	1.2	0.003
M38	30	70	2	1.5	0.001
M40	70	80	3	0.7	0.002

Table 27. Tolerance

Machine	Setup	Cost per Part (£)	Cost per Batch (£)
M6	S1	3.23	174.03
	S2	3.45	179.61
	S3	5.26	224.85
M18	S1	3.22	133.10
	S2	3.45	138.66
	S3	5.25	183.70
M21	S1	3.86	143.11
	S2	3.99	146.38
	S3	5.05	172.89
M41	S1		
	S2	6.97	199.16
	S3		

Note: *See Tables 40, 41 and 42 in Section 6.4*

Table 28. Processing Costs

6.3.3.6 Selection of Optimal Route

All the possible routes are depicted and the total cost per batch for each route is calculated (See Table 43 in Section 6.4). The optimal route is the one with the lowest total cost per batch. In this example, the optimal route is Route Five.

Route Number	Machine Sequence	Cost per Batch for Processing ($)	Transportation Time (min)	Transportation Cost for Batch ($)	Material Cost per Batch ($)	Total Cost per Batch ($)
R1	6-6-18-21-21	485.58	69.22	5.91	39.15	530.64
R2	6-6-21-18-18	504.11	60.42	5.55	39.15	548.81
R3	6-6-41-18-18	556.89	56.05	5.18	39.15	601.22
R4	6-6-41-21-21	546.08	65.63	5.61	39.15	590.84
R5	18-18-6-21-21	485.60	68.69	5.86	39.15	530.61
R6	18-18-21-6-6	504.33	55.25	4.60	39.15	548.08
R7	18-18-41-6-6	557.11	50.68	4.22	39.15	600.48
R8	18-18-41-21-21	505.15	50.75	4.37	39.15	548.67
R9	21-21-6-18-18	506.42	56.61	5.23	39.15	550.80
R10	21-21-18-6-6	506.62	51.65	4.30	39.15	550.07
R11	21-21-41-6-6	567.12	47.89	3.99	39.15	610.26
R12	21-21-41-18-18	525.97	38.37	3.71	39.15	568.83

Table 29. Routes and Total Cost per Batch

In the case of component *P0003*, the difference between the possible routes is almost intangible. One advantage in this case is that if there is any problem in executing the optimal route, the selection of another appropriate route is effortless.

6.4 TEMPORAL DATABASE FILES

6.4.1 Case Study 1

Machine Code	Machine Number	Machine Type	Layout Type	Layout Coordinates X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right	Setup Number	Machine	Cost Rate	Change Over Time (t0)	Tool Chng. Time (t3)	Setup Time (t1)	Non-Operation Time (Tno)	Setting Rate	Tolerance	Cost per Machine	Cost per Batch
GR200E-MAHO	M24	TC-CNC	FUN1	12.00	3.00	12.50	3.50	120	110	70.00	75.0	2.0	3.0	75.00	50.00	0.002	0.00	0.00
GR300E-MAHO	M25	TC-CNC	FUN1	12.00	5.00	12.50	5.50	120	110	70.00	90.0	1.8	2.0	60.00	45.00	0.001	0.00	0.00
GR400E-MAHO	M26	TC-CNC	FUN1	12.00	7.00	12.50	7.50	120	110	60.00	85.0	1.9	1.0	90.00	30.00	0.002	0.00	0.00
GR200C-MAHO	M27	TC-CNC	FUN1	12.00	10.00	12.50	10.50	120	110	50.00	20.0	0.5	1.0	85.00	35.00	0.003	0.00	0.00
GR300C-MAHO	M28	TC-CNC	FUN1	12.00	12.00	12.50	12.50	120	110	40.00	25.0	1.5	2.0	80.00	40.00	0.002	0.00	0.00
GR350C-MAHO	M29	TC-CNC	FUN1	12.00	14.00	12.50	14.50	120	110	55.00	85.0	0.8	3.0	85.00	60.00	0.001	0.00	0.00
GR400C-MAHO	M30	TC-CNC	FUN1	16.00	3.00	16.50	3.50	120	110	60.00	30.0	1.6	4.0	85.00	54.00	0.003	0.00	0.00
GR500C-MAHO	M31	TC-CNC	FUN1	16.00	5.00	16.50	5.50	120	110	70.00	30.0	0.7	5.0	60.00	55.00	0.003	0.00	0.00
GR500S-MAHO	M32	TC-CNC	FUN1	16.00	7.00	16.50	7.50	120	110	50.00	40.0	1.7	3.0	90.00	50.00	0.002	0.00	0.00
ECOSTAR-2-WHACHEON	M33	TC-CNC	FUN1	16.00	10.00	16.50	10.50	120	110	40.00	35.0	0.8	2.0	85.00	45.00	0.003	0.00	0.00
280-TURNMASTER-BOXFORD	M34	TC-CNC	FUN1	16.00	12.00	16.50	12.50	120	110	30.00	50.0	2.0	4.0	80.00	30.00	0.001	0.00	0.00
EMCOTURN-120	M35	TC-CNC	FUN1	16.00	14.00	16.50	14.50	120	110	60.00	80.0	0.9	5.0	85.00	35.00	0.001	0.00	0.00

Table 30. Temporal Database (Output) for First Machine Selection for Component "C0001"

Machine Code	Machine Number	Machine Type	Layout Type	Layout Coordinates				Setup Number	Machine	Cost Rate	Change Over Time (t0)	Tool Chng. Time (t3)	Setup Time (t1)	Non-Operation Time (Tno)	Setting Rate	Tolerance	Cost per Machine	Cost per Batch
				X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right											
GR200C-MAHO	M27	TC-CNC	FUN1	12.00	10.00	12.50	10.50	120	110	50.00	20.0	0.5	1.0	85.00	35.00	0.003	1.55	69.30
GR400C-MAHO	M30	TC-CNC	FUN1	16.00	3.00	16.50	3.50	120	110	60.00	30.0	1.6	4.0	85.00	54.00	0.003	4.90	196.55
GR500C-MAHO	M31	TC-CNC	FUN1	16.00	5.00	16.50	5.50	120	110	70.00	30.0	0.7	5.0	60.00	55.00	0.003	6.84	267.65
ECOSTAR-2-WHACHEON	M33	TC-CNC	FUN1	16.00	10.00	16.50	10.50	120	110	40.00	35.0	0.8	2.0	85.00	45.00	0.003	1.91	88.36

Table 31. Temporal Database (Setup 1) for Component "C0001"

Machine Code	Machine Number	Machine Type	Layout Type	Layout Coordinates				Setup Number	Machine	Cost Rate	Change Over Time (t0)	Tool Chng. Time (t3)	Setup Time (t1)	Non-Operation Time (Tno)	Setting Rate	Tolerance	Cost per Machine	Cost per Batch
				X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right											
GR200C-MAHO	M27	TC-CNC	FUN1	12.00	10.00	12.50	10.50	120	110	50.00	20.0	0.5	1.0	85.00	35.00	0.003	1.18	56.86
GR400C-MAHO	M30	TC-CNC	FUN1	16.00	3.00	16.50	3.50	120	110	60.00	30.0	1.6	4.0	85.00	54.00	0.003	4.44	180.91
GR500C-MAHO	M31	TC-CNC	FUN1	16.00	5.00	16.50	5.50	120	110	70.00	30.0	0.7	5.0	60.00	55.00	0.003	6.33	250.08
ECOSTAR-2-WHACHEON	M33	TC-CNC	FUN1	16.00	10.00	16.50	10.50	120	110	40.00	35.0	0.8	2.0	85.00	45.00	0.003	1.62	78.28

Table 32. Temporal Database (Setup 2) for Component "C0001"

Route	M/C	M/C	M/C	M/C	M/C	Cost per Batch	Cost per Batch	Cost per Batch	Total Cost	Coord. M/C 1				Coord. M/C 2				Coord. M/C 3				Coord. M/C 4				Coord. M/C 5				Total Cost of	Total Cost	Total
Number	No. 1	No. 2	No. 3	No. 4	No. 5	Setup1	Setup 2	Setup 3	per Batch	X-LL	Y-LL	X-UR	Y-UR	X-LL	Y-LL	X-UR	Y-UR	X-LL	Y-LL	X-UR	Y-UR	X-LL	Y-LL	X-UR	Y-UR	X-LL	Y-LL	X-UR	Y-UR	Transportation	of Material	Cost
R 1	M27	M27				69.30	56.86	0.00	126.16	12.0	10.0	12.5	10.5	12.0	10.0	12.5	10.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.19	209.81	337.16
R 2	M30	M30				196.55	180.91	0.00	377.46	16.0	3.0	16.5	3.5	16.0	3.0	16.5	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.22	209.81	588.49
R 3	M31	M31				267.65	250.08	0.00	517.73	16.0	5.0	16.5	5.5	16.0	5.0	16.5	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.21	209.81	728.75
R 4	M33	M33				88.36	78.28	0.00	166.64	16.0	10.0	16.5	10.5	16.0	10.0	16.5	10.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.20	209.81	377.65

Table 33. Possible Routes for Component "C0001"

6.4.2 Case Study 2

Machine Code	Machine Number	Machine Type	Layout Type	Layout Coordinates X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right	Setup Number	Machine	Cost Rate	Change Over Time (t0)	Tool Chng. Time (t3)	Setup Time (t1)	Non-Operation Time (Tno)	Setting Rate	Tolerance	Cost per Machine	Cost per Batch
MT35-MHP	M37	TC-CNC	FUN1	7.00	3.00	7.50	3.50	123	123	60.00	85.0	1.0	1.0	85.00	50.00	0.003	0.00	0.00
EMCOTURN-140	M36	TC-CNC	FUN1	7.00	5.00	7.50	5.50	123	123	70.00	60.0	1.6	1.0	85.00	40.00	0.002	0.00	0.00
EMCOTURN-120	M35	TC-CNC	FUN1	7.00	7.00	7.50	7.50	123	123	60.00	80.0	0.9	5.0	85.00	35.00	0.001	0.00	0.00
280-TURNMASTER-BOXFORD	M34	TC-CNC	FUN1	7.00	9.00	7.50	9.50	123	123	30.00	50.0	2.0	4.0	80.00	30.00	0.001	0.00	0.00
ECOSTAR-2-WHACHEON	M33	TC-CNC	FUN1	7.00	11.00	7.50	11.50	123	123	40.00	35.0	0.8	2.0	85.00	45.00	0.003	0.00	0.00
GR500S-MAHO	M32	TC-CNC	FUN1	7.00	13.00	7.50	13.50	123	123	50.00	40.0	1.7	3.0	90.00	50.00	0.002	0.00	0.00
GR500C-MAHO	M31	TC-CNC	FUN1	10.00	3.00	10.50	3.50	123	123	70.00	30.0	0.7	5.0	60.00	55.00	0.003	0.00	0.00
GR400C-MAHO	M30	TC-CNC	FUN1	10.00	5.00	10.50	5.50	123	123	60.00	30.0	1.6	4.0	85.00	54.00	0.003	0.00	0.00
GR350C-MAHO	M29	TC-CNC	FUN1	10.00	7.00	10.50	7.50	123	123	55.00	85.0	0.6	3.0	65.00	60.00	0.001	0.00	0.00
GR300C-MAHO	M28	TC-CNC	FUN1	10.00	9.00	10.50	9.50	123	123	40.00	25.0	1.5	2.0	80.00	40.00	0.002	0.00	0.00
GR200E-MAHO	M24	TC-CNC	FUN1	10.00	11.00	10.50	11.50	123	123	70.00	75.0	2.0	3.0	75.00	50.00	0.002	0.00	0.00
GR400E-MAHO	M26	TC-CNC	FUN1	10.00	13.00	10.50	13.50	123	123	60.00	85.0	1.9	1.0	90.00	30.00	0.002	0.00	0.00

Table 34. Temporal Database (Output) for First Machine Selection for Component "C0002"

Machine Code	Machine Number	Machine Type	Layout Type	Layout Coordinates				Setup Number	Machine	Cost Rate	Change Over Time (t0)	Tool Chng. Time (t3)	Setup Time (t1)	Non-Operation Time (Tno)	Setting Rate	Tolerance	Cost per Machine	Cost per Batch
				X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right											
MT35-MHP	M37	TC-CNC	FUN1	7.00	3.00	7.50	3.50	123	123	60.00	85.0	1.0	1.0	85.00	50.00	0.003	2.72	177.65
ECOSTAR-2-WHACHEON	M33	TC-CNC	FUN1	7.00	11.00	7.50	11.50	123	123	40.00	35.0	0.8	2.0	85.00	45.00	0.003	2.47	107.43
GR500C-MAHO	M31	TC-CNC	FUN1	10.00	3.00	10.50	3.50	123	123	70.00	30.0	0.7	5.0	60.00	55.00	0.003	7.82	300.88
GR400C-MAHO	M30	TC-CNC	FUN1	10.00	5.00	10.50	5.50	123	123	60.00	30.0	1.6	4.0	85.00	54.00	0.003	5.77	226.15

Table 35. Temporal Database (Setup 1) for Component "C0002"

Machine Code	Machine Number	Machine Type	Layout Type	Layout Coordinates				Setup Number	Machine	Cost Rate	Change Over Time (t0)	Tool Chng. Time (t3)	Setup Time (t1)	Non-Operation Time (Tno)	Setting Rate	Tolerance	Cost per Machine	Cost per Batch
				X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right											
MT35-MHP	M37	TC-CNC	FUN1	7.00	3.00	7.50	3.50	123	123	60.00	85.0	1.0	1.0	85.00	50.00	0.003	1.21	126.29
ECOSTAR-2-WHACHEON	M33	TC-CNC	FUN1	7.00	11.00	7.50	11.50	123	123	40.00	35.0	0.8	2.0	85.00	45.00	0.003	1.48	73.48
GR500C-MAHO	M31	TC-CNC	FUN1	10.00	3.00	10.50	3.50	123	123	70.00	30.0	0.7	5.0	60.00	55.00	0.003	6.08	241.73
GR400C-MAHO	M30	TC-CNC	FUN1	10.00	5.00	10.50	5.50	123	123	60.00	30.0	1.6	4.0	85.00	54.00	0.003	4.22	173.47

Table 36. Temporal Database (Setup 2) for Component "C0002"

Machine Code	Machine Number	Machine Type	Layout Type	Layout Coordinates				Setup Number	Machine	Cost Rate	Change Over Time (t0)	Tool Chng. Time (t3)	Setup Time (t1)	Non-Operation Time (Tno)	Setting Rate	Tolerance	Cost per Machine	Cost per Batch
				X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right											
MT35-MHP	M37	TC-CNC	FUN1	7.00	3.00	7.50	3.50	123	123	60.00	85.0	1.0	1.0	85.00	50.00	0.003	1.84	147.70
ECOSTAR-2-WHACHEON	M33	TC-CNC	FUN1	7.00	11.00	7.50	11.50	123	123	40.00	35.0	0.8	2.0	85.00	45.00	0.003	1.89	87.63
GR500C-MAHO	M31	TC-CNC	FUN1	10.00	3.00	10.50	3.50	123	123	70.00	30.0	0.7	5.0	60.00	55.00	0.003	6.81	266.38
GR400C-MAHO	M30	TC-CNC	FUN1	10.00	5.00	10.50	5.50	123	123	60.00	30.0	1.6	4.0	85.00	54.00	0.003	4.87	195.43

Table 37. Temporal Database (Setup 3) for Component "C0002"

Route	M/C	M/C	M/C	M/C	M/C	Cost per Batch	Cost per Batch	Cost per Batch	Total Cost	Coord. M/C 1				Coord. M/C 2				Coord. M/C 3				Coord. M/C 4				Coord. M/C 5				Total Cost of	Total Cost	Total
Number	No. 1	No. 2	No. 3	No. 4	No. 5	Setup1	Setup 2	Setup 3	per Batch	X-LL	Y-LL	X-UR	Y-UR	X-LL	Y-LL	X-UR	Y-UR	X-LL	Y-LL	X-UR	Y-UR	X-LL	Y-LL	X-UR	Y-UR	X-LL	Y-LL	X-UR	Y-UR	Transportation	of Material	Cost
R 1	M37	M37	M33	M31	M31	177.65	73.48	266.38	517.51	7.0	3.0	7.5	3.5	7.0	3.0	7.5	3.5	7.0	11.0	7.5	11.5	10.0	3.0	10.5	3.5	10.0	3.0	10.5	3.5	50.48	209.81	777.80
R 2	M37	M37	M33	M30	M30	177.65	73.48	195.43	446.56	7.0	3.0	7.5	3.5	7.0	3.0	7.5	3.5	7.0	11.0	7.5	11.5	10.0	5.0	10.5	5.5	10.0	5.0	10.5	5.5	50.15	209.81	706.52
R 3	M37	M37	M31	M33	M33	177.65	241.73	87.63	507.01	7.0	3.0	7.5	3.5	7.0	3.0	7.5	3.5	10.0	3.0	10.5	3.5	7.0	11.0	7.5	11.5	7.0	11.0	7.5	11.5	49.47	209.81	766.30
R 4	M37	M37	M31	M30	M30	177.65	241.73	195.43	614.81	7.0	3.0	7.5	3.5	7.0	3.0	7.5	3.5	10.0	3.0	10.5	3.5	10.0	5.0	10.5	5.5	10.0	5.0	10.5	5.5	49.23	209.81	873.65
R 5	M37	M37	M30	M33	M33	177.65	173.47	87.63	438.75	7.0	3.0	7.5	3.5	7.0	3.0	7.5	3.5	10.0	5.0	10.5	5.5	7.0	11.0	7.5	11.5	7.0	11.0	7.5	11.5	49.35	209.81	697.92
R 6	M37	M37	M30	M31	M31	177.65	173.47	266.38	617.50	7.0	3.0	7.5	3.5	7.0	3.0	7.5	3.5	10.0	5.0	10.5	5.5	10.0	3.0	10.5	3.5	10.0	3.0	10.5	3.5	49.51	209.81	876.82
R 7	M33	M33	M37	M31	M31	107.43	126.29	266.38	500.10	7.0	11.0	7.5	11.5	7.0	11.0	7.5	11.5	7.0	3.0	7.5	3.5	10.0	3.0	10.5	3.5	10.0	3.0	10.5	3.5	50.49	209.81	760.40
R 8	M33	M33	M37	M30	M30	107.43	126.29	195.43	429.15	7.0	11.0	7.5	11.5	7.0	11.0	7.5	11.5	7.0	3.0	7.5	3.5	10.0	5.0	10.5	5.5	10.0	5.0	10.5	5.5	50.36	209.81	689.32
R 9	M33	M33	M31	M37	M37	107.43	241.73	147.70	496.86	7.0	11.0	7.5	11.5	7.0	11.0	7.5	11.5	10.0	3.0	10.5	3.5	7.0	3.0	7.5	3.5	7.0	3.0	7.5	3.5	50.71	209.81	757.39
R 10	M33	M33	M31	M30	M30	107.43	241.73	195.43	544.59	7.0	11.0	7.5	11.5	7.0	11.0	7.5	11.5	10.0	3.0	10.5	3.5	10.0	5.0	10.5	5.5	10.0	5.0	10.5	5.5	50.27	209.81	804.67
R 11	M33	M33	M30	M37	M37	107.43	173.47	147.70	428.60	7.0	11.0	7.5	11.5	7.0	11.0	7.5	11.5	10.0	5.0	10.5	5.5	7.0	3.0	7.5	3.5	7.0	3.0	7.5	3.5	50.61	209.81	689.03
R 12	M33	M33	M30	M31	M31	107.43	173.47	266.38	547.28	7.0	11.0	7.5	11.5	7.0	11.0	7.5	11.5	10.0	5.0	10.5	5.5	10.0	3.0	10.5	3.5	10.0	3.0	10.5	3.5	50.35	209.81	807.45
R 13	M31	M31	M37	M33	M33	300.88	126.29	87.63	514.80	10.0	3.0	10.5	3.5	10.0	3.0	10.5	3.5	7.0	3.0	7.5	3.5	7.0	11.0	7.5	11.5	7.0	11.0	7.5	11.5	49.75	209.81	774.36
R 14	M31	M31	M37	M30	M30	300.88	126.29	195.43	622.60	10.0	3.0	10.5	3.5	10.0	3.0	10.5	3.5	7.0	3.0	7.5	3.5	10.0	5.0	10.5	5.5	10.0	5.0	10.5	5.5	49.68	209.81	882.10
R 15	M31	M31	M33	M37	M37	300.88	73.48	147.70	522.06	10.0	3.0	10.5	3.5	10.0	3.0	10.5	3.5	7.0	11.0	7.5	11.5	7.0	3.0	7.5	3.5	7.0	3.0	7.5	3.5	50.87	209.81	782.75
R 16	M31	M31	M33	M30	M30	300.88	73.48	195.43	569.79	10.0	3.0	10.5	3.5	10.0	3.0	10.5	3.5	7.0	11.0	7.5	11.5	10.0	5.0	10.5	5.5	10.0	5.0	10.5	5.5	50.46	209.81	830.07
R 17	M31	M31	M30	M37	M37	300.88	173.47	147.70	622.05	10.0	3.0	10.5	3.5	10.0	3.0	10.5	3.5	10.0	5.0	10.5	5.5	7.0	3.0	7.5	3.5	7.0	3.0	7.5	3.5	49.90	209.81	881.77
R 18	M31	M31	M30	M33	M33	300.88	173.47	87.63	561.98	10.0	3.0	10.5	3.5	10.0	3.0	10.5	3.5	10.0	5.0	10.5	5.5	7.0	11.0	7.5	11.5	7.0	11.0	7.5	11.5	49.46	209.81	821.26
R 19	M30	M30	M37	M33	M33	226.15	126.29	87.63	440.07	10.0	5.0	10.5	5.5	10.0	5.0	10.5	5.5	7.0	3.0	7.5	3.5	7.0	11.0	7.5	11.5	7.0	11.0	7.5	11.5	49.88	209.81	699.76
R 20	M30	M30	M37	M31	M31	226.15	126.29	266.38	618.82	10.0	5.0	10.5	5.5	10.0	5.0	10.5	5.5	7.0	3.0	7.5	3.5	10.0	3.0	10.5	3.5	10.0	3.0	10.5	3.5	49.95	209.81	878.58
R 21	M30	M30	M33	M37	M37	226.15	73.48	147.70	447.33	10.0	5.0	10.5	5.5	10.0	5.0	10.5	5.5	7.0	11.0	7.5	11.5	7.0	3.0	7.5	3.5	7.0	3.0	7.5	3.5	50.78	209.81	707.93
R 22	M30	M30	M33	M31	M31	226.15	73.48	266.38	566.01	10.0	5.0	10.5	5.5	10.0	5.0	10.5	5.5	7.0	11.0	7.5	11.5	10.0	3.0	10.5	3.5	10.0	3.0	10.5	3.5	50.71	209.81	826.53
R 23	M30	M30	M31	M37	M37	226.15	241.73	147.70	615.58	10.0	5.0	10.5	5.5	10.0	5.0	10.5	5.5	10.0	3.0	10.5	3.5	7.0	3.0	7.5	3.5	7.0	3.0	7.5	3.5	49.99	209.81	875.38
R 24	M30	M30	M31	M33	M33	226.15	241.73	87.63	555.51	10.0	5.0	10.5	5.5	10.0	5.0	10.5	5.5	10.0	3.0	10.5	3.5	7.0	11.0	7.5	11.5	7.0	11.0	7.5	11.5	49.79	209.81	815.12

Table 38. Possible Routes for Component "C0002"

6.4.3 Case Study 3

Machine Code	Machine Number	Machine Type	Layout Type	Layout Coordinates X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right	Setup Number	Machine	Cost Rate	Change Over Time (t0)	Tool Chng. Time (t3)	Setup Time (t1)	Non-Operation Time (Tno)	Setting Rate	Tolerance	Cost per Machine	Cost per Batch
190VMC-BOXFORD	M16	VMC-CN(	CELL3	14.00	7.00	14.50	7.50	123	123	30.00	35.0	1.0	6.0	90.00	55.00	0.002	0.00	0.00
VMC-1200-KAFO	M5	VMC-CN(	CELL1	3.00	27.00	3.50	27.50	123	123	60.00	50.0	0.7	1.0	60.00	45.00	0.001	0.00	0.00
VMC-1400-KAFO	M6	VMC-CN(	CELL1	7.00	30.00	7.50	30.50	123	123	70.00	80.0	1.0	2.0	90.00	65.00	0.003	0.00	0.00
VMC-650-KAFO	M1	VMC-CN(	CELL2	17.00	27.00	17.50	27.50	123	123	60.00	30.0	0.5	1.0	80.00	50.00	0.001	0.00	0.00
VMC-800-KAFO	M2	VMC-CN(	CELL2	14.00	25.00	14.50	25.50	123	123	50.00	90.0	2.0	2.0	85.00	55.00	0.002	0.00	0.00
ANAK-MATIC-10-CNC-2	M18	VMC-CN(	CELL3	20.00	7.00	20.50	7.50	123	123	70.00	45.0	0.9	2.0	80.00	65.00	0.003	0.00	0.00
ANAK-MATIC-8-CNC-2	M17	VMC-CN(	FMS	6.00	15.00	6.50	15.50	123	123	60.00	55.0	1.4	1.0	85.00	40.00	0.001	0.00	0.00
H-400-P9-ANAYAK	M22	HMC (Mu	GTL	7.00	2.00	7.50	2.50	123	123	65.00	65.0	0.7	5.0	85.00	54.00	0.001	0.00	0.00
H-400-P9-ANAYAK	M22-2	HMC (Mu	GTL	7.00	4.00	7.50	4.50	123	123	65.00	65.0	0.7	5.0	85.00	54.00	0.001	0.00	0.00
H-500-P7-ANAYAK	M23	HMC (Mu	GTL	7.00	6.00	7.50	6.50	123	123	60.00	90.0	1.7	4.0	70.00	55.00	0.001	0.00	0.00
H-500-P2-ANAYAK	M21	HMC (Mu	GTL	7.00	8.00	7.50	8.50	123	123	40.00	70.0	1.6	5.0	80.00	60.00	0.003	0.00	0.00
H-500-P7-ANAYAK	M23-2	HMC (Mu	FMS	10.00	15.00	10.50	15.50	123	123	60.00	90.0	1.7	4.0	70.00	55.00	0.001	0.00	0.00
MAC-V1E-TAKISAWA	M41	DC	CELL3	17.00	10.00	17.50	10.50	020	020	60.00	25.0	1.2	6.0	80.00	50.00	0.003	0.00	0.00
PD4-BOXFORD	M38	DC	CELL1	10.00	27.00	10.50	27.50	020	020	30.00	70.0	1.5	2.0	60.00	30.00	0.001	0.00	0.00
PD8-BOXFORD	M40	DC	CELL2	20.00	25.00	20.50	25.50	020	020	70.00	80.0	0.7	3.0	85.00	40.00	0.002	0.00	0.00

Table 39. Temporal Database (Output) for First Machine Selection for Component "P0003"

Machine Code	Machine Number	Machine Type	Layout Type	Layout Coordinates				Setup Number	Machine	Cost Rate	Change Over Time (t0)	Tool Chng. Time (t3)	Setup Time (t1)	Non-Operation Time (Tno)	Setting Rate	Tolerance	Cost per Machine	Cost per Batch
				X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right											
VMC-1400-KAFO	M6	VMC-CNC	CELL1	7.00	30.00	7.50	30.50	123	123	70.00	80.0	1.0	2.0	90.00	65.00	0.003	3.23	174.03
ANAK-MATIC-10-CNC-2	M18	VMC-CNC (Multispindle)	CELL3	20.00	7.00	20.50	7.50	123	123	70.00	45.0	0.9	2.0	80.00	65.00	0.003	3.22	133.10
H-500-P2-ANAYAK	M21	HMC (Multipallet)	GTL	7.00	8.00	7.50	8.50	123	123	40.00	70.0	1.6	5.0	80.00	60.00	0.003	3.86	143.11

Table 40. Temporal Database (Setup 1) for Component "P0003"

Machine Code	Machine Number	Machine Type	Layout Type	Layout Coordinates				Setup Number	Machine	Cost Rate	Change Over Time (t0)	Tool Chng. Time (t3)	Setup Time (t1)	Non-Operation Time (Tno)	Setting Rate	Tolerance	Cost per Machine	Cost per Batch
				X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right											
VMC-1400-KAFO	M6	VMC-CNC	CELL1	7.00	30.00	7.50	30.50	123	123	70.00	80.0	1.0	2.0	90.00	65.00	0.003	3.45	179.61
ANAK-MATIC-10-CNC-2	M18	VMC-CNC (Multispindle)	CELL3	20.00	7.00	20.50	7.50	123	123	70.00	45.0	0.9	2.0	80.00	65.00	0.003	3.45	138.66
H-500-P2-ANAYAK	M21	HMC (Multipallet)	GTL	7.00	8.00	7.50	8.50	123	123	40.00	70.0	1.6	5.0	80.00	60.00	0.003	3.99	146.38
MAC-V1E-TAKISAWA	M41	DC	CELL3	17.00	10.00	17.50	10.50	020	020	60.00	25.0	1.2	6.0	80.00	50.00	0.003	6.97	199.16

Table 41. Temporal Database (Setup 2) for Component "P0003"

Machine Code	Machine Number	Machine Type	Layout Type	Layout Coordinates X-Lower-Left	Y-Lower-Left	X-Upper-Right	Y-Upper-Right	Setup Number	Machine	Cost Rate	Change Over Time (t0)	Tool Chng. Time (t3)	Setup Time (t1)	Non-Operation Time (Tno)	Setting Rate	Tolerance	Cost per Machine	Cost per Batch
VMC-1400-KAFO	M6	VMC-CNC	CELL1	7.00	30.00	7.50	30.50	123	123	70.00	80.0	1.0	2.0	90.00	65.00	0.003	5.26	224.85
ANAK-MATIC-10-CNC-2	M18	VMC-CNC (Multispindle)	CELL3	20.00	7.00	20.50	7.50	123	123	70.00	45.0	0.9	2.0	80.00	65.00	0.003	5.25	183.70
H-500-P2-ANAYAK	M21	HMC (Multipallet)	GTL	7.00	8.00	7.50	8.50	123	123	40.00	70.0	1.6	5.0	80.00	60.00	0.003	5.05	172.89

Table 42. Temporal Database (Setup 3) for Component "P0003"

Route Number	M/C No. 1	M/C No. 2	M/C No. 3	M/C No. 4	M/C No. 5	Cost per Batch Setup1	Cost per Batch Setup 2	Cost per Batch Setup 3	Total Cost per Batch	Coord. M/C 1				Coord. M/C 2				Coord. M/C 3				Coord. M/C 4				Coord. M/C 5				Total Cost of Transportation	Total Cost of Material	Total Cost
										X-LL	Y-LL	X-UR	Y-UR	X-LL	Y-LL	X-UR	Y-UR	X-LL	Y-LL	X-UR	Y-UR	X-LL	Y-LL	X-UR	Y-UR	X-LL	Y-LL	X-UR	Y-UR			
R 1	M6	M6	M18	M21	M21	174.03	138.66	172.89	485.58	7.0	30.0	7.5	30.5	7.0	30.0	7.5	30.5	20.0	7.0	20.5	7.5	7.0	8.0	7.5	8.5	7.0	8.0	7.5	8.5	5.91	39.15	530.64
R 2	M6	M6	M21	M18	M18	174.03	146.38	183.70	504.11	7.0	30.0	7.5	30.5	7.0	30.0	7.5	30.5	7.0	8.0	7.5	8.5	20.0	7.0	20.5	7.5	20.0	7.0	20.5	7.5	5.55	39.15	548.81
R 3	M6	M6	M41	M18	M18	174.03	199.16	183.70	556.89	7.0	30.0	7.5	30.5	7.0	30.0	7.5	30.5	17.0	10.0	17.5	10.5	20.0	7.0	20.5	7.5	20.0	7.0	20.5	7.5	5.18	39.15	601.22
R 4	M6	M6	M41	M21	M21	174.03	199.16	172.89	546.08	7.0	30.0	7.5	30.5	7.0	30.0	7.5	30.5	17.0	10.0	17.5	10.5	7.0	8.0	7.5	8.5	7.0	8.0	7.5	8.5	5.61	39.15	590.84
R 5	M18	M18	M6	M21	M21	133.10	179.61	172.89	485.60	20.0	7.0	20.5	7.5	20.0	7.0	20.5	7.5	7.0	30.0	7.5	30.5	7.0	8.0	7.5	8.5	7.0	8.0	7.5	8.5	5.86	39.15	530.61
R 6	M18	M18	M21	M6	M6	133.10	146.38	224.85	504.33	20.0	7.0	20.5	7.5	20.0	7.0	20.5	7.5	7.0	8.0	7.5	8.5	7.0	30.0	7.5	30.5	7.0	30.0	7.5	30.5	4.60	39.15	548.08
R 7	M18	M18	M41	M6	M6	133.10	199.16	224.85	557.11	20.0	7.0	20.5	7.5	20.0	7.0	20.5	7.5	17.0	10.0	17.5	10.5	7.0	30.0	7.5	30.5	7.0	30.0	7.5	30.5	4.22	39.15	600.48
R 8	M18	M18	M41	M21	M21	133.10	199.16	172.89	505.15	20.0	7.0	20.5	7.5	20.0	7.0	20.5	7.5	17.0	10.0	17.5	10.5	7.0	8.0	7.5	8.5	7.0	8.0	7.5	8.5	4.37	39.15	548.67
R 9	M21	M21	M6	M18	M18	143.11	179.61	183.70	506.42	7.0	8.0	7.5	8.5	7.0	8.0	7.5	8.5	7.0	30.0	7.5	30.5	20.0	7.0	20.5	7.5	20.0	7.0	20.5	7.5	5.23	39.15	550.80
R 10	M21	M21	M18	M6	M6	143.11	138.66	224.85	506.62	7.0	8.0	7.5	8.5	7.0	8.0	7.5	8.5	20.0	7.0	20.5	7.5	7.0	30.0	7.5	30.5	7.0	30.0	7.5	30.5	4.30	39.15	550.07
R 11	M21	M21	M41	M6	M6	143.11	199.16	224.85	567.12	7.0	8.0	7.5	8.5	7.0	8.0	7.5	8.5	17.0	10.0	17.5	10.5	7.0	30.0	7.5	30.5	7.0	30.0	7.5	30.5	3.99	39.15	610.26
R 12	M21	M21	M41	M18	M18	143.11	199.16	183.70	525.97	7.0	8.0	7.5	8.5	7.0	8.0	7.5	8.5	17.0	10.0	17.5	10.5	20.0	7.0	20.5	7.5	20.0	7.0	20.5	7.5	3.71	39.15	568.83

Table 43. Possible Routes for Component "P0003"

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

In an era when the cost of capital is increasing, it is essential to improve the total utilisation of resources, facilitated by accurate scheduling. Until now, manufacturing has been the area used as an objective for the reduction and control of costs. All the areas involved in the transformation of raw material into final product are being investigated. "Design research has been concerned with the aim of improving and simplifying these manufacturing processes" [62]. This work aims to outline organisational issues of current design management, the influence of new technology and techniques on design management, to propose a central area for research, and methodology by which an improved understanding of design in the industrial context may be achieved.

The general requirements of a system for allocating and managing resources are:

(i) To assign tasks
(ii) To control access to expert advice
(iii) To control access to services
(iv) To minimise the effects of unforeseen problems by the above methods

In practice it is often the fourth task which occupies the managers time. This must be achieved by the balancing of resources.

Knowledge-based systems have found many applications in manufacturing. Their importance is even greater in automated manufacturing facilities due to the following:

- Considerable capital investment and therefore the need of high utilisation of manufacturing resources such as machines, robots and expert systems.

- Increased number of variables because of the introduction of new resources, such as fixtures, pallets, and automated material carriers.

The knowledge of an expert is a very vulnerable resource to a firm. Extensive damage can be done by a an expert who leaves a firm, whereas often little attention is given to the contribution of an expert. It is therefore required to change the role of an expert from one with large capacity to damage a company to one with a large capacity to enhance a firm. The way to achieve this switch from negative to positive is firstly to understand the nature of the methods an expert uses to accomplish a task - reducing the damage which could be done by losing that expert's output, and then use this understanding to enhance the value of the expert's output, and the use to which that output is put. This would be achieved by developing expert systems and using this increased accuracy to demand better utilisation of the expert's views. In new product development, the ability to estimate the time and cost a task will take to complete would be the skill in question. It is needed to prepare routes and schedules which are workable, that is the most vital element to the smooth running of all development projects.

A method which has been used in research to find ways to automate design work is protocol analysis. The aim of the technique is to gain insights into the cognitive strategies of people undertaking a task of interest. This is achieved by tutoring a subject in thinking aloud. The aim of protocol analysis in this project has been to develop a generic set of rules for increasing the accuracy of route generation. This was then extended into a rule base system introducing knowledge for specific environments, which would act as a tool to increase confidence in the accuracy of route, and to make the knowledge of temporal estimation more robust.

The Intelligent Route Generator works as a communication platform between CAD and CAPP. IRG is an integrating tool/concept used by both design and process planning. The system provides the designer with feedback related to manufacturability and performs aggregate process planning tasks (i.e., selection of resources and routes). Addtionally, the IRG system calculates costs and times using 'standard' parameters in order to have cost and lead time indications. Hence, IRG dos 'job estimating' functions.

It is expected that the time and cost estimates will be updated and optimised as part of the detailed process planning. Feedback cycles should be implemented from optimised plans and shop floor data. This feedback information should be stored in a knowledge base in order to compare new IRG routes to historical ones. This closed loop system is future work.

No especification has been done related to the work handling arrangements. The type of work handling equipment should be established and their corresponding coordinates should be added to the Machine/Work Handling/Location database.

In the layout database, the types of layout already identify groups and functional areas, but this information is not yet fully utilised by the expert system.

Buffer zones such as WIP (work-in-progress) and KANBAN items areas or KANBAN relationship in cells create the interface with the SFC (shop floor control), having information about WIP per area, per product or per machine. Information related to waiting times is as well needed.

Besides this, predominant flow direction for each area or for the overall layout should be determined, linked with the customer/supplier link in JIT operation.

The interface with the MPC system should be done, using historical machine utilisation data, and planned capacity schedules based on MRP production, i.e. when production in a given time slot is needed.

Another aspect yet to be developed is related with the quality feedback. Maintaining life cycle monitoring of various problems, such as operations, testings, inspection, surface, finish, or tolerances. All this information should be linked with what is already done with the IRG system (See Figure 15 in Chapter 3). All of this will give raise to a complete feedback analysis and processing.

Areas like dedicated inspection areas, tool room or tool stores, establishment of a predetermined direction within each cell in the layout are of great importance for a complete expert system. The size of the container in the buffer should also be specified.

It is possible to establish a relationship between the component code and the cell in which it is made. This will become a constraint that will relate a component code to and assigned layout in a GT system. If this is not the case, then any machine can be evaluated.

Some other parameters such as capacity plans, historical machine loading (machine utilisation), work-in-progress, waiting times, quality problems in relation to processes/machines (or other contraints) should be evaluated. A weighting system could be used in order to evaluate them, using for example lower weighting for greater probability.

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APPENDIX 1

PRODUCTION TERMS FOR MANUFACTURING PRODUCTION SYSTEMS (MPSs)

	Meaning	Examples
Production system	All aspects of men, machines, materials, and information, considered collectively, needed to manufacture parts or products; integration of all units of the system is critical.	Company that makes engines, assembly plant, glassmaking factory, foundry
Manufacturing system (Sequence of operations) (Collection of processes)	A series of manufacturing operations resulting in specific end products; an arrangement or layout of many processes.	Rolling steel plants, manufacturing of auto bodies, series of connected operations or processes, a job shop, a flow shop, a continuous process
Machine or machine tool or manufacturing process	A specific piece of equipment designed to accomplish specific processes, often called a *machine tool*; machine tools link together to make a manufacturing system.	Spot welder, milling machine, lathe, drill press, forge, drop hammer, die caster
Job (sometimes called a station)	A collection of operations done on machines or a collection of tasks performed by one man at one location on an assembly line.	Operation of machines, inspection, final assembly. Forklift driver has the job of moving materials

Operation (sometimes called a process)	A specific action or treatment, the collection of which makes up the job of a worker.	Drill, ream, bend, solder, turn, face, mill, extrude, inspect, load
Tools	Refers to the devices used to hold, cut, shape, or deform the work materials; called *cutting tools* if referring to machining; can refer to *jigs and fixtures* in workholding and *punches and dies* in metal forming.	Grinding wheel, drill bit, tap, end milling cutter, die, mold, clamp, three-jaw vise

APPENDIX 2
MANUFACTURER'S RESOURCES AND CAPABILITIES

LIST OF MACHINES

A. Turning (lathes) (C) *
B. Boring (C/P) *
C. Milling (P) *
D. Drilling (C/P) *
E. Machining Centres (C/P) *
F. NC Machine Tools (C/P) *
G. Grinding
H. Pressing
I. Broaching (C/P)
J. Sawing
K. Planer (P)
L. Shaper (P)

(* Machines used for the routing project)

MACHINE CLASSIFICATION

A. TURNING

Classification 1 [1]

1. Horizontal turning machines
   - a) conventional centre lathes
   - b) CNC lathes
     - (i) conventional turret machines
     - (ii) sliding head machines

Classification 2 [2]

1. Lathes Group
   - a) engine lathes
   - b) turret lathes
   - c) tape-controlled turret lathe
   - d) vertical turret lathe
   - e) automatic vertical multistation lathe
   - f) duplicating or tracer lathes
   - g) automatic lathes
   - h) multispindle automatic

Classification 3 [3]

1. Jeweler's or precision lathes
2. Massive lathes
3. Heavy-duty engine lathes
4. Toolmaker's lathe
5. Vertical boring mills
6. Vertical turret lathe
7. Ram-type turret lathe

8. Saddle-type turret lathe
9. Small precision manually operated turret lathe
10. Numerically controlled chucking lathe with turret
11. Floturn lathe

B. BORING

Classification 1 [1]

1. Jig borers

2. Horizontal borers

3. Vertical borers
   a) single column elevating rail vertical borers
   b) double column elevating rail vertical borers

Classification 2 [2]

1. Boring Machine Tool Group
   a) boring machines
   b) jig boring machine
   c) vertical boring mill
   d) horizontal boring machine

C. MILLING

Classification 1 [1]

1. Standard knee type mills
   a) horizontal configuration
   b) vertical configuration
   c) horizontal with motorised overarm

2. Milling bed type
   a) fixed bed vertical spindle milling machines
   b) plano mills

Classification 2 [1]

1. Vertical mills
2. Universal mills
3. Toolroom universal overarm mills

Classification 3 [2]

1. Milling Machine Group
   a) milling machines
   b) hand milling machine
   c) plain milling machine
   d) vertical milling machines
   e) planer-type milling machine
   f) machining centres
   g) planetary milling machine
   h) duplicating machines

Classification 4 [3]

1. Vertical milling machines

2. Horizontal milling machines
    a) Bed-type
    b) Knee and column milling machines

D. DRILLING

Classification 1 [1]

1. Fixed height radial arm drills
2. Conventional fixed bed elevating radial arm drills
3. Bench top floor-mounted
4. Pedestal floor-mounted
5. Drill centre

Classification 2 [2]

1. Drill Press Group
    a) drill presses
    b) portable and sensitive drills
    c) upright drills
    d) radial drilling machine
    e) gang drilling machine
    f) turret machines
    g) multispindle drilling machines
    h) transfer-type production drilling machines
    i) deep-hole drilling machine

Classification 3 [3]

1. Sensitive drill
2. Upright drill press
3. Radial drill press
4. Microscopic drilling machine
5. Deep-hole drilling machines
6. Turret head drills
7. Gang drilling machine
8. Multisplindle drilling machine
9. Turret drilling machines

E. MACHINING CENTRES

Classification 1 [1]

1. Horizontal machining centres
2. Vertical machining centres
3. Universal machining centres
4. Double column machining centre

F. NC MACHINE TOOLS

Classification 1 [1]

1. CNC turning centres (CNC lathes)
2. CNC Electro Discharge Machines (EDM)
3. Slant bed CNC lathes
4. Fanuc CNC training lathe
5. Training computer lathe

6. CNC miller
7. CNC router

Classification 2 [3]

1. Vertical spindle NC and CNC machining centres
2. Horizontal spindle NC and CNC machining centres
3. NC and CNC turning centres

G. GRINDING

Classification 1 [1]

1. Surface grinders
2. Cylindrical grinders

Classification 2 [2]

1. Cylindrical grinder
    a) work between centres
    b) centreless
    c) tool post
    d) crankshaft and other special applications

2. Internal grinder
    a) work rotated in chuck
    b) work rotated and held by rolls
    c) work stationary

3. Surface grinder
    a) planer type (reciprocating table)
        (i) horizontal spindle
        (ii) vertical spindle
    b) rotating table
        (i) horizontal spindle
        (ii) vertical spindle
    c) disk
    d) loose grit
    e) flap wheel
    f) wire sawing

4. Universal
    a) cylindrical work
    b) thread form work
    c) gear form work
    d) oscillating

5. Tool grinder

6. Special grinding machines
    a) swinging frame, snagging
    b) cutting off, sawing
    c) portable, offhand grinding
    d) flexible shaft, general purpose
    e) profiling, contouring

7. Surface preparing

8. Abrasive grinding belt, single multihead

9. Mass media
   a) barrel tumbling
   b) vibratory

Classification 3 [3]

1. Surface grinder
   a) horizontal spindle reciprocating table surface grinder

2. Cylindrical grinder
   a) center type
   b) roll type
   c) centerless
   d) internal cylindrical
   e) tool and cutter

3. Miscellaneous grinding machines
   a) form type gear grinding machines
   b) generating-type gear grinding machines
   c) precision thread grinding machines
   d) thread grinders

H. PRESSING

Classification 1 [2]

1. Metal forming
   a) inclinable presses
   b) eccentric geared presses
   c) C-frame presses

2. Compression moulding
   a) hydraulic compression presses

Classification 2 [3]

1. Inclined press
2. Gap press
3. Arch press
4. Straight-side press
5. Horn press
6. Knuckle joint press
7. Press brake
8. Squaring shears
9. Turret press
10. Hydraulic press
11. Transfer press
12. Fourslide machine

I. BROACHING

Classification 1 [2]

1. Vertical single-slide surface machines
2. Vertical push broaching
3. Vertical pull-down broaching machines
4. Vertical pull-up broaching machines
5. Horizontal broaching machines
6. Rotary broaching machines
7. Continuous or tunnel broaching machines

J. SAWING

Classification 1 [2]

1. Reciprocating saw
   a) horizontal hacksaw
   b) vertical sawing and filing

2. Circular saw
   a) metal saw
   b) steel friction disk
   c) abrasive disk

3. Band saw
   a) saw blade
   b) friction blade
   c) wire blade

Classification 2 [3]

1. Cutoff machines
   a) reciprocating saws
   b) horizontal band cutoff machine
   c) universal tilt frame cutoff
   d) abrasive cutoff machine
   e) cold saw cutoff machines

2. Vertical band machines
   a) general purpose band machine with fixed worktable
   b) band machines with power-fed worktables
   c) high tool velocity band machines
   d) large capacity band machines

K. PLANER

Classification 1 [2]

1. Double housing
2. Open side
3. Pit type
4. Plate or edge

L. SHAPER

Classification 1 [2]

1. Horizontal push cut
   a) plain (production work)
   b) universal (toolroom work)

2. Horizontal draw cut

3. Vertical
   a) slotter
   b) key seater

4. Special purpose as for cutting gears

LIST OF MACHINES AND THEIR OPERATIONS

MACHINES	TYPES OF OPERATION
1. Lathe	***Classification 1*** [2] cylindrical surfaces drilling boring reaming facing ***Classification 2*** [2] turning boring facing threading taper turning ***Classification 3*** [3] turning threading boring drilling reaming facing spinning grinding tapping recessing grooving parting knurling ***Classification 4*** [4] turning facing grooving parting off threading boring drilling reaming
2. Horizontal boring machine	***Classification 1*** [2] flat surfaces ***Classification 2*** [4] drilling boring

3. Vertical boring machine

Classification 1 [2]
(drilling)
boring
reaming
facing

Classification 2 [4]
boring

4. Horizontal milling machine

Classification 1 [2]
flat surfaces
gears
cams
drilling
boring
reaming
facing

Classification 2 [5]
facing
(gears)
(cams)
boring
reaming
drilling
slotting

5. Vertical milling machine

Classification 1 [3]
milling
drilling
boring
slotting

Classification 2 [4]
boring
reaming

Classification 3 [5]
facing
square shoulder
radius shoulder
angle shoulder
vertical slot
horizontal slot
drilling
chamfering
T-slotting
threading
contouring
square pocket
copy milling

6. Milling machine

Classification 1 [3]
machining steps and squaring
milling a cavity
end milling a shaft keyseat
machining T-slots, dovetails, angle milling, and drilling

Classification 2 [4]
parting
slotting (grooving)
milling
threading
facing (planing)
drilling
square shoulder

7. Drill press

Classification 1 [2]
drilling
boring
facing
threading

Classification 2 [2]
counterboring
core drilling
countersinking
reaming
centre drilling
drilling
step drilling
gun drilling

Classification 3 [4]
drilling
boring
reaming
threading

8. NC Machine Tools

Classification 1 [3]
NC turning
NC boring
NC milling
NC drilling
NC tapping
NC contouring

9. Cylindrical grinder

Classification 1 [2]
cylindrical surfaces (grinding)

10. Broaching	*Classification 1* [2] external and internal surfaces *Classification 2* [4] drilling boring shaping milling planing broaching
11. Saw	*Classification 1* [2] cut off *Classification 2* [4] Conventional and contour sawing Friction sawing Band filing and band polishing
12. Planer	*Classification 1* [2,4] flat surfaces (planing)
13. Shaper	*Classification 1* [2,4] flat surfaces (shaping)

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APPENDIX 3
CUTTING SPEED AVERAGES

I. CNC/NC LATHES *(cylindrical components)*

A. TURNING / FACING / BORING (Internal Turning)

SECO (30 min. tool life)

1. ***Mild Steel:***

TP10, TP15, TP20, TP30

	Finishing Velocity 0.15 mm/rev	Roughing Velocity 0.65 mm/rev
1	392.50	222.50
2	333.75	188.75
3	283.75	166.25
4	235.00	135.00
	311.25 m/min	**178.13 m/min**

2. ***Alloy Steel:***

TP10, TP15, TP20, TP30

	Finishing Velocity 0.15 mm/rev	Roughing Velocity 0.65 mm/rev
3	283.75	166.25
5	200.00	102.50
6	178.75	75.00
7	76.25	--------
	184.69 m/min	**114.58 m/min**

3. ***Stainless Steel:***

TP10, TP15, TP20, TP30

	Finishing Velocity 0.15 mm/rev	Roughing Velocity 0.65 mm/rev
8	227.50	123.33
9	180.00	75.00
10	95.00	55.00
	167.50 m/min	**84.44 m/min**

4. *Cast Steel:*

TP10, TP15, TP20, TP30

	Finishing Velocity 0.15 mm/rev	Roughing Velocity 0.65 mm/rev
2	333.75	188.75
3	283.75	166.25
4	235.00	135.00
5	200.00	102.50
	263.13 m/min	**148.13 m/min**

5. *Cast Iron:*

TP10, TP15, TP20, TP30

	Finishing Velocity 0.15 mm/rev	Roughing Velocity 0.65 mm/rev
11	223.75	127.50
12	180.00	115.00
13	163.33	95.00
14	126.67	70.00
15	102.50	50.00
	199.06 m/min	**114.38 m/min**

SECO (15 min tool life)

1. *Mild Steel:*

TP10, TP15, TP20, TP35, S1F

	Finishing Velocity 0.25 mm/rev	Roughing Velocity 0.63 mm/rev
1	427.00	275.00
2-3	359.00	232.00
4	263.00	178.00
	349.67 m/min	**228.33 m/min**

2. ***Alloy Steel:***

TP10, TP15, TP20, TP35, S1F

	Finishing Velocity 0.25 mm/rev	Roughing Velocity 0.63 mm/rev
3	299.00	193.00
5	229.00	156.00
6	179.00	116.00
7	146.00	93.00
	213.25 m/min	**139.50 m/min**

3. ***Stainless Steel:***

TP20, TP35, S1F

	Finishing Velocity 0.25 mm/rev	Roughing Velocity 0.68 mm/rev
8	221.67	136.67
9	175.00	111.67
10	122.50	82.50
	173.06 m/min	**110.28 m/min**

4. ***Cast Steel:***

TP10, TP15, TP20, TP35, S1F

	Finishing Velocity 0.25 mm/rev	Roughing Velocity 0.63 mm/rev
2-3	299.00	193.00
4	223.00	138.00
5	199.00	136.00
	240.33 m/min	**155.67 m/min**

5. ***Cast Iron:***

TP10, TP15, TP20

	Finishing Velocity 0.25 mm/rev	Roughing Velocity 0.62 mm/rev
11	240.00	151.67
12	200.00	126.67
13	168.33	106.67
14	130.00	77.50
15	110.00	60.00
	169.67 m/min	**104.50 m/min**

B. PARTING-OFF

SECO

1. ***Mild Steel:***

GC235/P45, GC435/P35

Roughing Velocity: 126.67 m/min

2. ***Alloy Steel:***

GC235/P45, GC435/P35

Roughing Velocity: 92.50 m/min

3. ***Stainless Steel:***

GC235/P45, GC435/P35

Roughing Velocity: 100.00 m/min

4. ***Cast Steel:***

GC235/P45, GC435/P35

Roughing Velocity: 82.50 m/min

5. ***Cast Iron:***

H20/K20

Roughing Velocity: 65.00 m/min

C. GROOVING

SECO

1. ***Mild Steel:***

GC435/P35, GC225/P25

Roughing Velocity: 178.33 m/min

2. ***Alloy Steel:***

GC435/P35, GC225/P25

Roughing Velocity: 127.50 m/min

3. ***Stainless Steel:***

GC435/P35, GC225/P25

Roughing Velocity: 140.00 m/min

4. ***Cast Steel:***

GC435/P35, GC225/P25

Roughing Velocity: 117.50 m/min

5. ***Cast Iron:***

Roughing Velocity: 50.00 m/min

D. THREADING

SECO

1. ***Mild Steel:***

Roughing Velocity: 166.67 m/min

2. ***Alloy Steel:***

Roughing Velocity: 132.50 m/min

3. ***Stainless Steel:***

Roughing Velocity: 115.00 m/min

4. ***Cast Steel:***

Roughing Velocity: 120.00 m/min

5. ***Cast Iron:***

Roughing Velocity: 155.00 m/min

II. CNC VERTICAL MILLING MACHINES / MACHINING CENTRES

(99% prismatic, machining centres --> cylindrical)

A. FACING / SHOULDERING (Square, Radius, Angle) / CHAMFERING

SECO

1. ***Mild Steel:***

S10M, S25M, S60M

	Finishing Velocity 0.1 mm/rev	Roughing Velocity 0.4 mm/rev
1	193.33	118.33
2	160.00	91.67
3	123.33	68.33
	158.89 m/min	**92.78 m/min**

2. ***Alloy Steel:***

S10M, S25M, S60M

	Finishing Velocity 0.1 mm/rev	Roughing Velocity 0.4 mm/rev
2	158.33	90.00
3	126.67	68.33
4	60.00	112.50
5	-------	77.50
	118.75 m/min	**72.78 m/min**

3. ***Stainless Steel:***

S10M, S25M, S60M

	Finishing Velocity 0.1 mm/rev	Roughing Velocity 0.4 mm/rev
6	180.00	108.33
7	155.00	85.00
	167.50 m/min	**96.67 m/min**

4. ***Cast Steel:***

S10M, S25M, S60M

	Finishing Velocity 0.1 mm/rev	Roughing Velocity 0.4 mm/rev
2	141.67	83.33
3	111.67	65.00
4	91.67	56.67
	115.00 m/min	**68.33 m/min**

5. ***Cast Iron:***

T25M, HX

	Finishing Velocity 0.1 mm/rev	Roughing Velocity 0.4 mm/rev
8	175.00	90.00
9	125.00	65.00
10	90.00	80.00
	130.00 m/min	**78.33 m/min**

III. VERTICAL MILLING MACHINES AND DRILLING CENTRES
(prismatic components)

A. DRILLING

SECO

1. ***Mild Steel:***

	Roughing Velocity mm/rev
1	130.00
2-3	112.50
4-5	100.00
	114.17 m/min

2. ***Alloy Steel:***

	Roughing Velocity mm/rev
2-3	112.50
4-5	100.00
6	80.00
7	80.00
	93.13 m/min

3. ***Stainless Steel:***

	Roughing Velocity mm/rev
8-9	60.00
10	50.00
	55.00 m/min

4. ***Cast Steel:***

	Roughing Velocity mm/rev
2-3	112.50
4-5	100.00
	106.25 m/min

5. ***Cast Iron:***

	Roughing Velocity mm/rev
11-12	100.00
13-14	85.00
15	70.00
	127.50 m/min

6. ***Non Ferrous Material:***

	Roughing Velocity mm/rev
16	450.00
17	115.00
18	350.00
22	65.00
	245.00 m/min

FEED RATE AVERAGES

I. CNC/NC LATHES *(cylindrical components)*

A. PARTING-OFF / GROOVING

SECO

1. ***Mild Steel:***

   Feed Rate: 0.21 mm/rev

2. ***Alloy Steel:***

   Feed Rate: 0.17 mm/rev

3. ***Stainless Steel:***

   Feed Rate: 0.14 mm/rev

4. ***Cast Steel:***

   Feed Rate: 0.16 mm/rev

II. VERTICAL MILLING MACHINES AND DRILLING CENTRES
(prismatic components)

A. DRILLING

SECO

1. ***Mild Steel:***

   3mm - 18mm

	mm/rev
1	0.25
2-3	0.25
4-5	0.25
	0.25

2. ***Alloy Steel:***

3mm - 18mm

	<u>mm/rev</u>
2-3	0.25
4-5	0.25
6	0.25
7	0.24
	0.25

3. ***Stainless Steel:***

3mm - 18mm

	mm/rev
8-9	0.14
10	0.14
	0.14

4. ***Cast Steel:***

3mm - 18mm

	mm/rev
2-3	0.25
4-5	0.25
	0.25

5. ***Cast Iron:***

3mm - 18mm

	mm/rev
11-12	0.49
13-14	0.42
15	0.24
	0.38

6. ***Non Ferrous Material:***

3mm - 18mm

	mm/rev
16	0.49
17	0.49
18	0.49
22	0.24
	0.38

GUIDE CUTTING CONDITIONS USING CARBIDE TOOLS

I. CNC/NC LATHES *(cylindrical components)*

A. TURNING / FACING / BORING (Internal Turning)

Material Type	Finishing Velocity v_F (m/min)	Finishing Feed Rate s_F (mm/rev)	Roughing Velocity v_R (m/min)	Roughing Feed Rate s_R (mm/rev)
Mild Steel	330.46	0.2	203.33	0.64
Alloy Steel	198.97	0.2	127.04	0.64
Stainless Steel	170.28	0.2	97.36	0.67
Cast Steel	251.73	0.2	151.90	0.64
Cast Iron	184.37	0.2	109.44	0.64

NOTE: Average of data for 15/30 min. tool life.

B. PARTING-OFF

Material Type	Roughing Velocity v_R (m/min)	Roughing Feed Rate s_R (mm/rev)
Mild Steel	126.67	0.21
Alloy Steel	92.50	0.17
Stainless Steel	100.00	0.14
Cast Steel	82.50	0.16
Cast Iron	65.00	0.15

C. GROOVING

Material Type	Roughing Velocity v_R (m/min)	Roughing Feed Rate s_R (mm/rev)
Mild Steel	178.33	0.21
Alloy Steel	127.50	0.17
Stainless Steel	140.00	0.14
Cast Steel	117.50	0.16
Cast Iron	50.00	0.15

D. THREADING

Material Type	Roughing Velocity v_R (m/min)
Mild Steel	166.67
Alloy Steel	132.50
Stainless Steel	115.00
Cast Steel	120.00
Cast Iron	155.00

p (mm)	No. of Passes
0.50	4-6
0.75	4-7
1.00	4-8
1.25	5-9
1.50	6-10
1.75	7-12
2.00	7-12
2.50	8-14
3.00	10-16
3.50	11-18
4.00	11-18
4.50	11-19
5.00	12-20
5.50	12-20
6.00	12-20
8.00	15-24

NOTE: Pitch (p) is going to be used as the feed for threading.

II. CNC VERTICAL MILLING MACHINES / MACHINING CENTRES / CNC HORIZONTAL MILLING MACHINES

(99% prismatic, machining centres --> cylindrical)

A. FACING / SHOULDERING (Square, Radius, Angle) / CHAMFERING / CONTOURING / POCKETING / COPY MILLING / VERTICAL SLOTTING / HORIZONTAL SLOTTING / T-SLOTTING

Material Type	**Finishing Velocity** v_F **(m/min)**	**Finishing Feed Rate** s_{z_F} **(mm/tooth)**	**Roughing Velocity** v_R **(m/min)**	**Roughing Feed Rate** s_{z_R} **(mm/tooth)**
Mild Steel	158.89	0.1	92.78	0.4
Alloy Steel	118.75	0.1	72.78	0.4
Stainless Steel	167.50	0.1	96.67	0.4
Cast Steel	115.00	0.1	68.33	0.4
Cast Iron	130.00	0.1	78.33	0.4

III. VERTICAL MILLING MACHINES AND DRILLING CENTRES / CNC/NC LATHES

(cylindrical and prismatic components)

A. DRILLING / REAMING

Material Type	**Roughing Velocity** v_R **(m/min)**	**Roughing Feed Rate** s_R **(mm/rev)**
Mild Steel	114.17	0.25
Alloy Steel	93.13	0.25
Stainless Steel	55.00	0.14
Cast Steel	106.25	0.25
Cast Iron	127.50	0.38
Non Ferrous Mat.	245.00	0.38

GUIDE MAXIMUM CUTTER DIAMETER AND NUMBER OF TEETH

I. CNC VERTICAL MILLING MACHINES / MACHINING CENTRES / CNC HORIZONTAL MILLING MACHINES

(99% prismatic, machining centres --> cylindrical)

Cutter (Operation Type)	**Maximum Cutter Diameter *D* (mm)**	**Number of Teeth *z***
Facing	105.77	4
Shouldering	105.77	4
Chamfering	49.18	2
Contouring	45.99	2
Pocketing	45.99	2
Copy Milling	45.99	2
Vertical Slotting	43.80	5
Horizontal Slotting	43.80	5
T-Slotting	28.00	5
Drilling	36.50	2
Reaming	36.50	2
Threading	30.67	1

APPENDIX 4
DATABASE FILE SPECIFICATIONS

Structure for database: C:COMPO01.dbf
Number of data records: 6
Date of last update : 01/19/93

Field	Field Name	Type	Width	Dec
1	COMPO_CODE	Character	5	
2	COMPO_DESC	Character	1	
3	MAT_CLASS	Character	5	
4	MAT_TYPE	Character	5	
5	MAT_COST	Numeric	5	
6	S_H	Character	1	
7	LENGTH	Numeric	5	
8	DIA_WIDTH	Numeric	5	
9	LD_HEI_THI	Numeric	5	
10	WEIGHT	Numeric	5	
11	BATCH	Numeric	5	
12	OP_CODE1	Character	5	
13	SETUP_NO1	Numeric	5	
14	OP_CODE2	Character	5	
15	SETUP_NO2	Numeric	5	
16	OP_CODE3	Character	5	
Press any key to continue...				
17	SETUP_NO3	Numeric	5	
18	OP_CODE4	Character	5	
19	SETUP_NO4	Numeric	5	
20	OP_CODE5	Character	5	
21	SETUP_NO5	Numeric	5	
22	TOLERANCE	Numeric	5	
23	LEAD_TIME	Numeric	5	
24	COST	Numeric	5	
** Total **			113	

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Structure for database: C:MC03.dbf
Number of data records:       41
Date of last update   : 04/21/13
Field  Field Name  Type       Width    Dec
    1  MC_NO       Character      3
    2  MC_TYPE     Character     25
    3  MC_CODE     Character     28
    4  TASZ_TUDIA  Character     11
    5  TACAP_WGHT  Numeric        4
    6  X_AXIS_TVL  Numeric        4
    7  Y_AXIS_TVL  Numeric        4
    8  Z_AXIS_TVL  Numeric        4
    9  SPTA_DISTC  Numeric        4
   10  SPINDLE_SP  Numeric        4
   11  RAP_TRA_XY  Numeric        5
   12  RAP_TRA_Z   Numeric        5
   13  FEED_RATES  Numeric        5
   14  MAG_CAP     Character     11
   15  SP_MOTOR    Numeric        4      1
   16  PA_SP_BDIA  Character      4
Press any key to continue...
   17  COST_RT_X   Numeric        6      2
   18  COT_T0      Numeric        5      1
   19  TCT_T3      Numeric        5      1
   20  SUT_T1      Numeric        5      1
   21  NOT_TNO     Numeric        5      2
   22  SET_RATE    Numeric        6      2
   23  TOLERANCE   Character      5
** Total **                     163
```

Structure for database: C:MCOP02.dbf
Number of data records: 21
Date of last update : 04/21/13

Field	Field Name	Type	Width	Dec
1	OP_CODE	Character	2	
2	COMP_DESCR	Character	1	
3	MC_CODE_1	Character	22	
4	MC_CODE_2	Character	22	
5	MC_CODE_3	Character	22	
6	MC_CODE_4	Character	22	
7	MC_CODE_5	Character	22	
** Total **			114	

Structure for database: C:MATOP02.dbf
Number of data records: 34
Date of last update : 04/21/13

Field	Field Name	Type	Width	Dec
1	OP_CODE	Character	3	
2	MILD_V	Numeric	6	2
3	MILD_S	Numeric	4	2
4	ALLOY_V	Numeric	6	2
5	ALLOY_S	Numeric	4	2
6	STAIN_V	Numeric	6	2
7	STAIN_S	Numeric	4	2
8	CAST_ST_V	Numeric	6	2
9	CAST_ST_S	Numeric	4	2
10	CAST_IR_V	Numeric	6	2
11	CAST_IR_S	Numeric	4	2
12	NON_FE_V	Numeric	6	2
13	NON_FE_S	Numeric	4	2
14	DIAMETER	Numeric	6	2
15	TEETH	Numeric	1	
** Total **			71	

```
Structure for database: C:SF01.dbf
Number of data records:       3
Date of last update   : 04/21/13
Field  Field Name  Type        Width    Dec
    1  LAY_CODE    Character       3
    2  OVER_TYPE   Character       1
    3  NO_LAYS     Numeric         2
    4  LAY_TYPE_1  Character       5
    5  LAY_TYPE_2  Character       5
    6  LAY_TYPE_3  Character       5
    7  LAY_TYPE_4  Character       5
    8  LAY_TYPE_5  Character       5
    9  GRAL_XLL    Numeric         4      1
   10  GRAL_YLL    Numeric         4      1
   11  GRAL_XRU    Numeric         4      1
   12  GRAL_YRU    Numeric         4      1
   13  LAY1_XLL    Numeric         4      1
   14  LAY1_YLL    Numeric         4      1
   15  LAY1_XRU    Numeric         4      1
   16  LAY1_YRU    Numeric         4      1
Press any key to continue...
   17  LAY2_XLL    Numeric         4      1
   18  LAY2_YLL    Numeric         4      1
   19  LAY2_XRU    Numeric         4      1
   20  LAY2_YRU    Numeric         4      1
   21  LAY3_XLL    Numeric         4      1
   22  LAY3_YLL    Numeric         4      1
   23  LAY3_XRU    Numeric         4      1
   24  LAY3_YRU    Numeric         4      1
   25  LAY4_XLL    Numeric         4      1
   26  LAY4_YLL    Numeric         4      1
   27  LAY4_XRU    Numeric         4      1
   28  LAY4_YRU    Numeric         4      1
   29  LAY5_XLL    Numeric         4      1
   30  LAY5_YLL    Numeric         4      1
   31  LAY5_XRU    Numeric         4      1
   32  LAY5_YRU    Numeric         4      1
Press any key to continue...
   33  BUFF_SPACE  Character       1
   34  MAT_ENTRYX  Numeric         4      1
   35  MAT_ENTRYY  Numeric         4      1
   36  MAT_EXITX   Numeric         4      1
   37  MAT_EXITY   Numeric         4      1
   38  INT_INSPEC  Character       1
** Total **                      146
```

Structure for database: C:L01.dbf
Number of data records: 28
Date of last update : 04/20/13

Field	Field Name	Type	Width	Dec
1	MC_WH_CODE	Character	28	
2	MC_NO	Character	5	
3	MC_TYPE	Character	22	
4	LAY_TYPE	Character	5	
5	XLL	Numeric	5	2
6	YLL	Numeric	5	2
7	XRU	Numeric	5	2
8	YRU	Numeric	5	2
** Total **			81	

Structure for database: C:L02.dbf
Number of data records: 21
Date of last update : 04/21/13

Field	Field Name	Type	Width	Dec
1	MC_WH_CODE	Character	28	
2	MC_NO	Character	5	
3	MC_TYPE	Character	22	
4	LAY_TYPE	Character	5	
5	XLL	Numeric	5	2
6	YLL	Numeric	5	2
7	XRU	Numeric	5	2
8	YRU	Numeric	5	2
** Total **			81	

Structure for database: C:L03.dbf
Number of data records: 34
Date of last update : 04/21/13

Field	Field Name	Type	Width	Dec
1	MC_WH_CODE	Character	28	
2	MC_NO	Character	5	
3	MC_TYPE	Character	22	
4	LAY_TYPE	Character	5	
5	XLL	Numeric	5	2
6	YLL	Numeric	5	2
7	XRU	Numeric	5	2
8	YRU	Numeric	5	2
** Total **			81	

Structure for database: C:OUTPUT01.dbf
Number of data records: 15
Date of last update : 04/21/13

Field	Field Name	Type	Width	Dec
1	MC_WH_CODE	Character	28	
2	MC_NO	Character	5	
3	MC_TYPE	Character	22	
4	LAY_TYPE	Character	5	
5	XLL	Numeric	5	2
6	YLL	Numeric	5	2
7	XRU	Numeric	5	2
8	YRU	Numeric	5	2
9	SETUP	Character	3	
10	MACHINE	Character	3	
11	COST_RT_X	Numeric	6	2
12	COT_T0	Numeric	5	1
13	TCT_T3	Numeric	5	1
14	SUT_T1	Numeric	5	1
15	NOT_TNO	Numeric	5	2
16	SET_RATE	Numeric	6	2
Press any key to continue...				
17	TOLERANCE	Character	5	
18	COSTPERMC	Numeric	8	2
19	COSTPERBTC	Numeric	12	2
** Total **			144	

Structure for database: C:SET01.dbf
Number of data records: 3
Date of last update : 04/21/13

Field	Field Name	Type	Width	Dec
1	MC_WH_CODE	Character	28	
2	MC_NO	Character	5	
3	MC_TYPE	Character	22	
4	LAY_TYPE	Character	5	
5	XLL	Numeric	5	2
6	YLL	Numeric	5	2
7	XRU	Numeric	5	2
8	YRU	Numeric	5	2
9	SETUP	Character	3	
10	MACHINE	Character	3	
11	COST_RT_X	Numeric	6	2
12	COT_T0	Numeric	5	1
13	TCT_T3	Numeric	5	1
14	SUT_T1	Numeric	5	1
15	NOT_TNO	Numeric	5	2
16	SET_RATE	Numeric	6	2
Press any key to continue...				
17	TOLERANCE	Character	5	
18	COSTPERMC	Numeric	8	2
19	COSTPERBTC	Numeric	12	2
** Total **			144	

```
Structure for database: C:SET02.dbf
Number of data records:        4
Date of last update   : 04/21/13
Field  Field Name  Type        Width    Dec
    1  MC_WH_CODE  Character      28
    2  MC_NO       Character       5
    3  MC_TYPE     Character      22
    4  LAY_TYPE    Character       5
    5  XLL         Numeric         5      2
    6  YLL         Numeric         5      2
    7  XRU         Numeric         5      2
    8  YRU         Numeric         5      2
    9  SETUP       Character       3
   10  MACHINE     Character       3
   11  COST_RT_X   Numeric         6      2
   12  COT_T0      Numeric         5      1
   13  TCT_T3      Numeric         5      1
   14  SUT_T1      Numeric         5      1
   15  NOT_TNO     Numeric         5      2
   16  SET_RATE    Numeric         6      2
Press any key to continue...
   17  TOLERANCE   Character       5
   18  COSTPERMC   Numeric         8      2
   19  COSTPERBTC  Numeric        12      2
** Total **                      144
```

```
Structure for database: C:SET03.dbf
Number of data records:       3
Date of last update   : 04/21/13
Field  Field Name  Type       Width    Dec
    1  MC_WH_CODE  Character     28
    2  MC_NO       Character      5
    3  MC_TYPE     Character     22
    4  LAY_TYPE    Character      5
    5  XLL         Numeric        5      2
    6  YLL         Numeric        5      2
    7  XRU         Numeric        5      2
    8  YRU         Numeric        5      2
    9  SETUP       Character      3
   10  MACHINE     Character      3
   11  COST_RT_X   Numeric        6      2
   12  COT_T0      Numeric        5      1
   13  TCT_T3      Numeric        5      1
   14  SUT_T1      Numeric        5      1
   15  NOT_TNO     Numeric        5      2
   16  SET_RATE    Numeric        6      2
Press any key to continue...
   17  TOLERANCE   Character      5
   18  COSTPERMC   Numeric        8      2
   19  COSTPERBTC  Numeric       12      2
** Total **                     144
```

```
Structure for database: C:ROUTES01.dbf
Number of data records:       12
Date of last update   : 04/21/13
Field  Field Name  Type       Width    Dec
    1  ROUTE_NO    Character      6
    2  MC_NO_1     Character      5
    3  MC_NO_2     Character      5
    4  MC_NO_3     Character      5
    5  MC_NO_4     Character      5
    6  MC_NO_5     Character      5
    7  COSTPERBS1  Numeric       12      2
    8  COSTPERBS2  Numeric       12      2
    9  COSTPERBS3  Numeric       12      2
   10  COSTPBTOT   Numeric       15      2
   11  M1_XLL      Numeric        5      1
   12  M1_YLL      Numeric        5      1
   13  M1_XRU      Numeric        5      1
   14  M1_YRU      Numeric        5      1
   15  M2_XLL      Numeric        5      1
   16  M2_YLL      Numeric        5      1
Press any key to continue...
   17  M2_XRU      Numeric        5      1
   18  M2_YRU      Numeric        5      1
   19  M3_XLL      Numeric        5      1
   20  M3_YLL      Numeric        5      1
   21  M3_XRU      Numeric        5      1
   22  M3_YRU      Numeric        5      1
   23  M4_XLL      Numeric        5      1
   24  M4_YLL      Numeric        5      1
   25  M4_XRU      Numeric        5      1
   26  M4_YRU      Numeric        5      1
   27  M5_XLL      Numeric        5      1
   28  M5_YLL      Numeric        5      1
   29  M5_XRU      Numeric        5      1
   30  M5_YRU      Numeric        5      1
   31  COSTTRATOT  Numeric       12      2
   32  COSTMATTOT  Numeric       12      2
Press any key to continue...
   33  COSTTOTAL   Numeric       15      2
** Total **                     222
```

Structure for database: C:FINAL01.dbf
Number of data records: 3
Date of last update : 04/21/13

Field	Field Name	Type	Width	Dec
1	COMP_CODE	Character	5	
2	OPERATION1	Character	10	
3	OPERATION2	Character	10	
4	OPERATION3	Character	10	
5	OPERATION4	Character	10	
6	OPERATION5	Character	10	
7	MC_NO_1	Character	5	
8	MC_NO_2	Character	5	
9	MC_NO_3	Character	5	
10	MC_NO_4	Character	5	
11	MC_NO_5	Character	5	
12	PROC_COST	Numeric	12	2
13	TRANS_COST	Numeric	12	2
14	MAT_COST	Numeric	12	2
15	TOTAL_COST	Numeric	15	2
16	ROUTE_NO	Character	6	
Press any key to continue...				
17	LAYOUT_NO	Character	3	
** Total **			141	