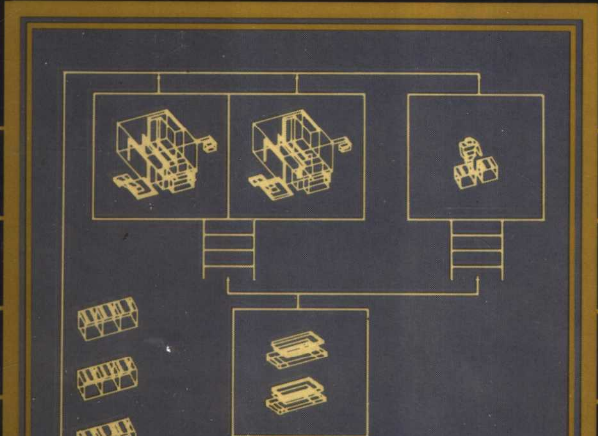
Flexible Manufacturing Systems



DECISION SUPPORT FOR DESIGN AND OPERATION

HORST TEMPELMEIER • HEINRICH KUHN

Wiley Series in Systems Engineering

FLEXIBLE MANUFACTURING SYSTEMS

Decision Support for Design and Operation

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Preface

In the past decade enormous technological advances have led to sophisticated hardware solutions in manufacturing technology. Increased international competition with shortening of product lifetimes and diminishing reaction times to changes in the marketplace has forced companies to make massive investments into flexible manufacturing systems (FMSs). According to forecasts, at the end of the century there will be more than 2000 FMSs worldwide.

Considering the impressive advantages promised by the FMS concept (short lead times, low inventory, high adaptability to changing production requirements) in industrial practice, however, there seems to be a disillusion about the economic advantages associated with this technology. The reason for this is that the design and operation of an FMS cannot be properly accomplished with intuition, rules-of-thumb, or trial-and-error approaches that are often found in industrial practice.

The design and operation of an FMS require a large amount of planning knowledge. This is dispersed in the areas of industrial engineering, computer science, business administration, operations management and management science. Unfortunately this is very often documented in books and scientific journals that are rarely available to the industrial planner of an FMS, who normally has access to a limited number of publications.

To compile this knowledge and present it in a comprehensive way to the reader is the main purpose of this book. A structured survey over the many types of problems, modelling and solution approaches in the design of an

FMS configuration and the operation of an already installed FMS is given. The approaches marking the basic line of development in each problem area are discussed in great detail and illustrated with numerical examples. In order to make the material more comprehensible we have inserted a large number of graphical illustrations.

This book aims at several heterogenous groups of readers. First, it could be used as supporting material for graduate level university courses in operations management, industrial engineering, systems engineering, and operations research. There is a high probability for *students* of these fields to come into contact with some sort of flexible production technology during their industrial career—if not as a systems planner, operator, or software engineer, then hopefully as a decision maker.

The second group of readers we have in mind are *decision makers* in industrial practice facing FMS related problems. For this kind of reader it would be interesting to be informed about the many types of problems and their very complex interdependencies as well as the available solution approaches. Only if the variety of decision variables and their complex interactions are known, the optimal decision may be taken. In this way the decision maker can avoid common (and very expensive) pitfalls in the design and operation of an FMS.

Last but not least the book is intended to be part of the desktop accessories for every professional concerned with the planning of the design or the operation of an FMS. This *FMS planner* may be employed in an FMS manufacturer's marketing department confronted with the task to send an offer for a specific FMS design alternative to a prospective customer as well as in an FMS user's production planning department. He/she may also be a software engineer responsible for the design of FMS control software.

In the technical parts of this book it is assumed that the reader is familiar with the fundamental methodologies of operations research, such as mathematical programming, queueing theory, and probability theory. There is a large number of excellent textbooks available in these fields.

This book first appeared in German in March 1992. The English edition has been translated by Edward Cabot. Due to the rapid development of the knowledge in the FMS field we have included the most noticeable contributions that came to our knowledge up to March 1993 in order to keep the book as up-to-date as possible.

We would like to acknowledge the corrections and suggestions we received from all the people, with which we had many discussions about FMSs during the last years. First of all these are our former students of industrial engineering and computer science at the Technical University of Darmstadt (F.R.G.), who supported us through the implementation of numerical solution

procedures in the acquisition of the insights into this complex field of research.

We also thank Dr. Ulrich Tetzlaff for his support during the conceptional phase of the book as well as for providing some numerical results and for numerous critical comments.

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1. INTRODUCTION

1.1. DEFINITION OF A FLEXIBLE MANUFACTURING SYSTEM

A flexible manufacturing system (FMS) is a production system consisting of a set of identical and/or complementary *numerically controlled machines* which are connected through an *automated transportation system*. Each process in an FMS is controlled by a *dedicated computer* (FMS cell computer). This is often imbedded in a large hierarchical network of computers. An FMS is capable of processing workpieces of a certain workpiece-spectrum in an arbitrary sequence with negligible setup delays between operations. This is possible since in an FMS a set of preadjusted tools is available through a centralized tool magazine with short access time and/or through local tool magazines at the machines with direct access. Furthermore, workpieces are clamped on pallets at separate setup tables thus allowing them to be quickly positioned at the machines. Due to the automation of tool exchange operations, the usually time-consuming interruptions for tool exchanges (including tool preparation, if necessary) are performed while the machine is operating. While a workpiece is being machined by a given tool, the next tool is already picked up by a robotic arm from the tool magazine. After completion of the process it is exchanged with the previous tool. This procedure generally requires only a few seconds. In the case of a workpiece exchange, this time is necessary anyway while the new NC program required to control the next operation to be performed at the machine is loaded.

It is customary to process workpieces of several different product types and production orders simultaneously in an FMS. Usually the workpieces are mounted on pallets with the help of fixtures. Every workpiece is characterized by its specific process advancement, which continuously has to be updated and stored individually by the control system of the FMS. Intermediate storing of unfinished workpieces between operations can be accomplished at central storage areas (central buffer) or, if possible, at local storage areas at the machines.

A set of (ca. 20-200) local tools is assigned to each of the CNC machines[1] (machining centers) in an FMS for direct access. They can be stored in cassettes, drums, discs or chain magazines. For processing parts which require tools not available at the local tool storage, external supply is necessary. In general, this is achieved by exchanging tools which are no longer required. This tool exchange can involve a single tool, or it can involve complete cassettes or discs armed with those tools which are next required at the machine. The exchange procedure can be performed either automatically, through a tool supply system, or manually. Figure

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1 Computer Numerical Control. For a survey of FMS hardware see **Bonetto** (1988); **Greenwood** (1988); **Lenz** (1989).

(1) shows a machine with a tool chain magazine and single tool exchange via an automated tool transportation system.

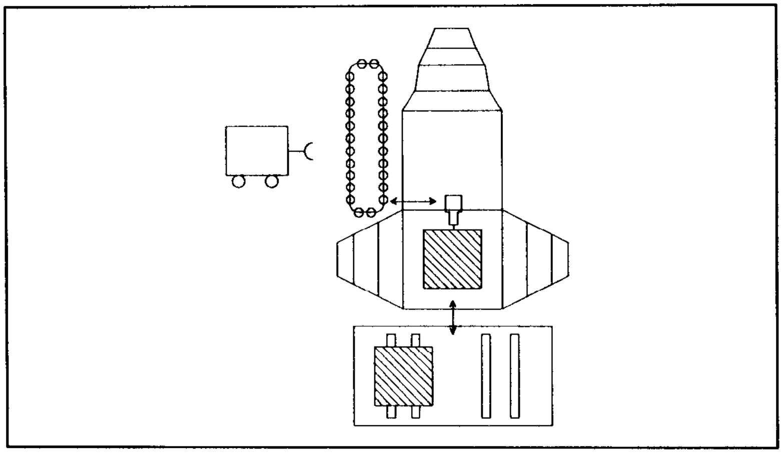

Figure 1: CNC machine with tool chain magazine

Machines with tool *chain magazines* require a (short) tool setup time when changing from one part spectrum to another, because a tool storage chain is not capable of supplying the spindle during the external tool exchange. Machines with tool cassettes or exchangeable tool discs, however, are more flexible, since subsets of tools can be exchanged without interfering with processing and thus can prepare the machine for the next workpiece.

If *tool cassettes* are used [figure (2)], one or more cassettes are assigned to a machine. In contrast to tool chain or tool disc magazines, supplying the spindle with a tool does not require the simultaneous movement of the whole tool set. Rather, a local transportation mechanism[2] is used to pick up the tool from the cassette and to transfer and pass it over to the twin arm[3] which brings the new tool to the spindle. In preparing for a tool cassette exchange (exchange of the tools necessary for two different workpieces) the tools can be presorted with the help of an appropriate control system.

The exchange of a tool cassette can be performed manually (with the help of transportation devices) or automatically through a tool transportation system. In some FMSs the same transportation system is used for workpieces as well as for tools. In this case considerable control problems emerge in synchronizing part and tool flow, however.

The large number of tools used at a single machine leads to a high degree of *functional integration*. Thus, it is found that in an FMS the number of different

2 The correct positioning of tools at tool chain magazines is performed by advancing the chain or, at tool disc magazines, by turning the disc. Depending on the size of the magazine, considerable force might be required.

3 **Kusiak** (1990), p. 41. A twin arm is also applied at tool chain magazines.

types of machines is less than in comparable conventional job shops[4]. Simply through the exchange of tools a machine can fulfill a completely different function.

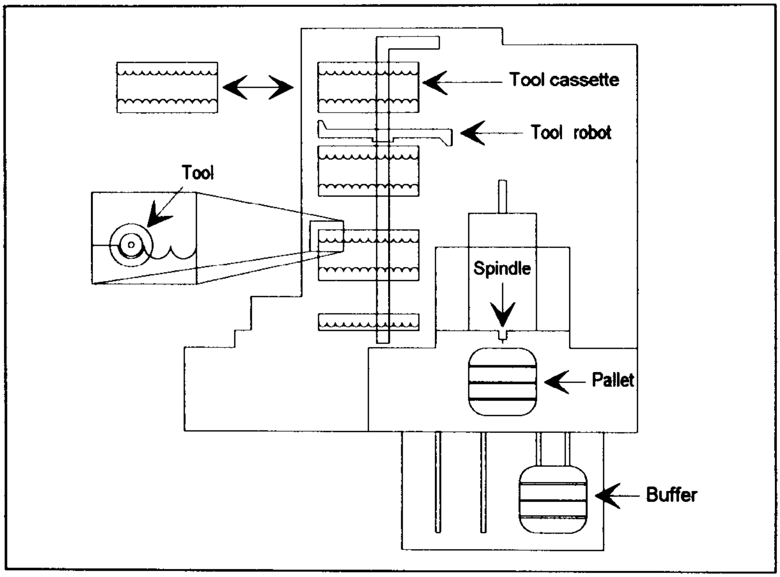

Figure 2: CNC machine with tool cassette magazines

Figure (3) shows the layout of an FMS with several CNC machines which are provided with tool cassettes through a centralized tool supply system. The tools of the cassettes are preadjusted and prepared for operation at a tool setup area. Afterwards they are either stored at a central tool magazine or, if they are to be used immediately, transported to a local tool magazine at a machine. The transportation of the tool cassettes to the machines is achieved in this case through a separate tool transportation system. Obviously, the design of such a tool supply system requires special consideration of the capacity of the tool transportation system so that processing delays due to late tool supply may be avoided. Central buffers are placed around and with their backs oriented toward the center positioned machines. Two setup tables (load/unload stations) are located at the left hand side. They represent the interface between the FMS and its production environment.

Worldwide roughly 1200 FMSs[5] existed at the beginning of 1989. In previous years the rate of growth had been around 20-25% per annum. According to forecasts, around 2500-3500 FMSs will be operating in the year 2000.

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4 **Kusiak** (1990), p. 20

5 **Ranta/Tchijov** (1990). It should be noted that the published numbers of existing FMSs depend on the definition of the term FMS.

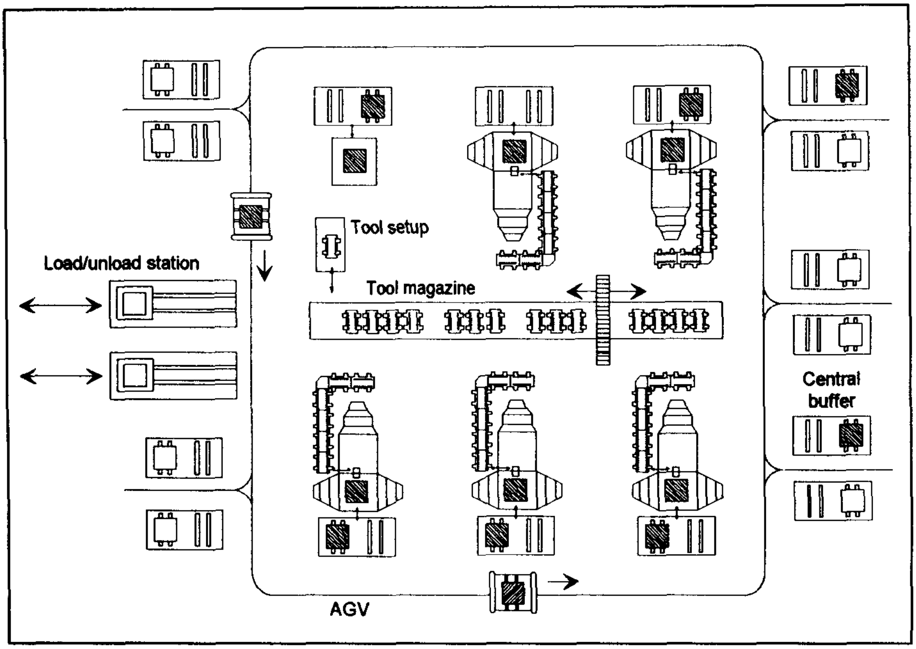

Figure 3: FMS with two AGV carts and a central tool magazine

Flexible production systems come in different forms, yet there does not exist a generally accepted classification in the literature[6]. In the following we base our considerations on the classification shown in figure (4).

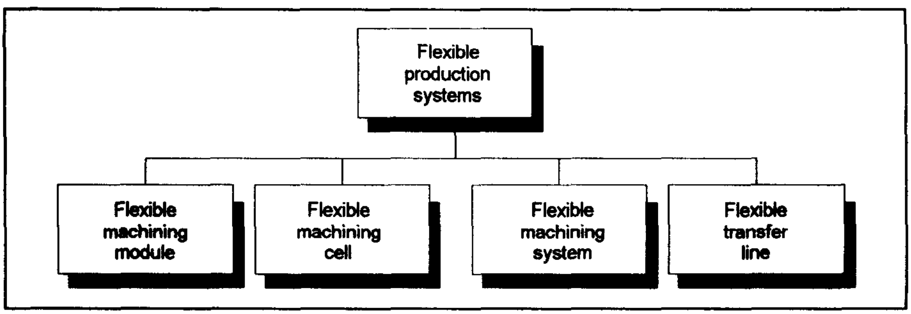

Figure 4: Classification of flexible production systems

- ***Flexible machining modules*** (FMM; also: flexible machining centers) consist of a *single* CNC machine equipped with a tool/workpiece exchange mechanism.

6 One reason for this might be the fact that vendors' and FMS-users' publications tend to broaden their definition for public relations purposes.

The automated tool exchange mechanism makes it possible to perform several different operations in one setup configuration with short tool exchange times. FMMs often possess local input/output buffers, which allow intermediate storage of unprocessed (input) and processed (output) parts. Because of limited workpiece storage capabilities FMMs can only work for a short period of time without external supply. Machining centers are the smallest self-contained production units and constitute the basic components of larger and more highly integrated production systems. FMMs with local buffer spaces are shown in the figures (1)-(3).

- ***Flexible machining cells*** (FMC) are a combination of an FMM with a setup station, machine independent workpiece storage (central storage), and an automated tool transportation system. This enables the cell to run for a longer period of time with little or no supervision. Figure (5) shows a flexible cell in which the local input/output buffer has been replaced by a pallet storage carousel with room for eight pallets and an integrated workpiece transportation mechanism.

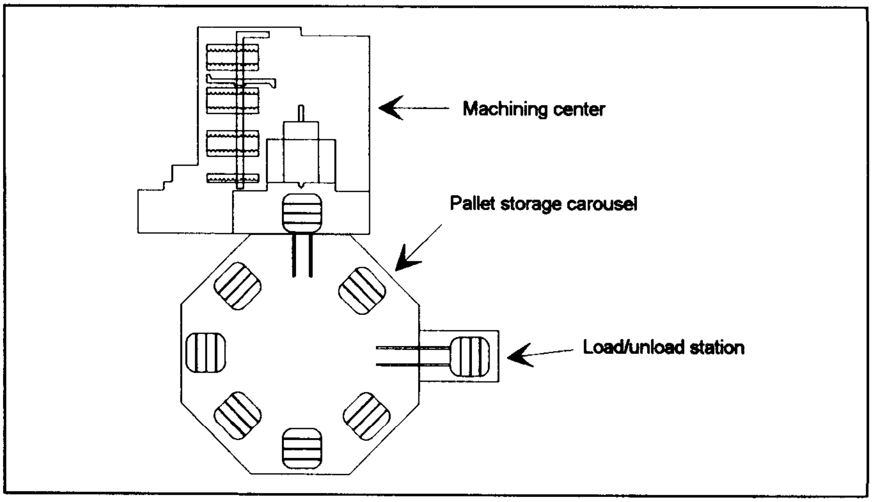

Figure 5: Flexible machining cell with one FMM

- ***Flexible manufacturing systems***[7] (FMS) consist of several identical and/or complementary machining centers as well as machine-independent workpiece and possibly also tool storage. All components are connected through automated workpiece, tool, and information flows. FMSs can be configured to be *process*- or *product*-oriented. In the latter case, the FMS consists of different FMMs and possibly also washing machines, burring machines, gaging machines, centralized tool magazines, etc. Therefore, such a system may be used for the *complete processing* of workpieces. If the FMS is configured to be pro-

7 **Bonetto** (1988)

cess-oriented, then it is only capable of performing one operation for a specific workpiece spectrum, though that operation may be quite complex and require numerous different tools. In figure (6) two identical FMMs are combined with one specialized machine to build an FMS. Workpieces for which there is no room at the local machine buffers are stored in the central buffer. The latter consists of several pallet storage areas. The flow of workpieces is accomplished through an automatic rail-guided vehicle.

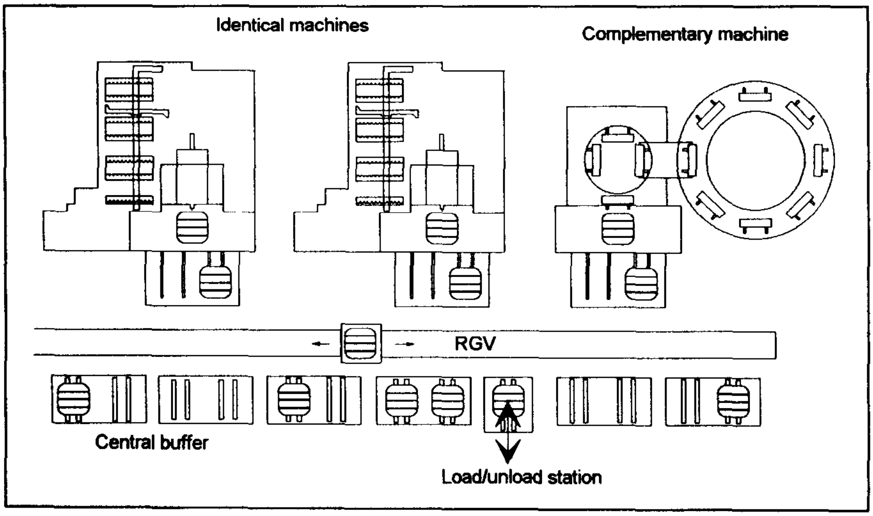

Figure 6: Flexible manufacturing system

The above FMS is quite small. It does, however, show all the characteristic features of an FMS. In reality, much larger FMSs can be found. A selection of different FMS layouts is presented and commented upon in *Carrie*[8].

- ***Flexible transfer lines***[9] consist of several CNC machines, and their layout is process-oriented. The flow of material is paced with an inside interlinkage, i.e. the workpieces are transferred simultaneously in a fixed sequence through the operation area of the machines. A flexible transfer line can process a limited spectrum of different workpieces in an arbitrary order. The flow of material, however, is not arbitrary. Its direction is predetermined by the transport mechanism. A new setup for a change from one workpiece spectrum to another can only be achieved by shutting down the whole transfer line. This requires considerable setup time and thus causes a severe interruption in production.

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8 **Carrie** (1988); see also **Malcki** (1991), pp. 27-41; **Dupont-Gatelmand** (1982)
9 **Bonetto** (1988), pp. 73-75

Further designations for certain configurations of flexible production systems of a more complex order can be found in the literature, e.g. *flexible manufacturing group, flexible production system*[10]. Within the framework of this book, emphasis is placed on flexible manufacturing systems because here the below mentioned problems for planning and operating come clearly into focus.

There exists considerable uncertainty both in theory and in practice about the *economic advantages* of FMSs in comparison to conventional production systems. According to *Ranta and Tchijov*[11], small simply structured FMSs (with 2-4 machines) and large complex FMSs (with 15-30 machines) tend to be the most advantageous. This observation can be explained as follows: small FMSs, e.g. FMSs with identical universal machines which perform only one (though complex) operation, can be easily installed and operated with simple planning procedures. Because of limited functional demands, the expenditures for the development of planning and control software are low. In comparison to the conventional job shop, the positive results considerably outweigh the additional costs for more complex planning software. Medium sized FMSs require far more planning. Here all the basic features of a complex planning and control system have to be integrated, even if each one of them is required only for a single machine type. The resulting costs are sometimes not compensated for by corresponding benefits. As the size of the FMS increases, software with the basic planning and control features for medium sized systems can still be used. The costs for software comprise a large portion of the fixed costs and can only be offset by positive effects when applied in larger systems. It can be assumed, however, that with further increases in size negative effects caused by increasing complexity may again outweigh these positive effects.

1.2. SUBSYSTEMS OF A FLEXIBLE MANUFACTURING SYSTEM

An FMS consists of several closely interconnected subsystems, including the *technical system*, the *human operator system* and the *information system* [see figure (7)[12]].

- **Technical system**

The *technical system* consists of the *processing system*, the *workpiece supply system* and the *tool supply system*. In addition it comprises special logistic subsystems such as the energy system and the auxiliary system, responsible for the supply of lubricants and coolants, and the waste disposal system [see figure (8)].

10 **Kusiak** (1985a)
11 **Ranta/Tchijov** (1990)
12 **Kuhn** (1990), p. 6

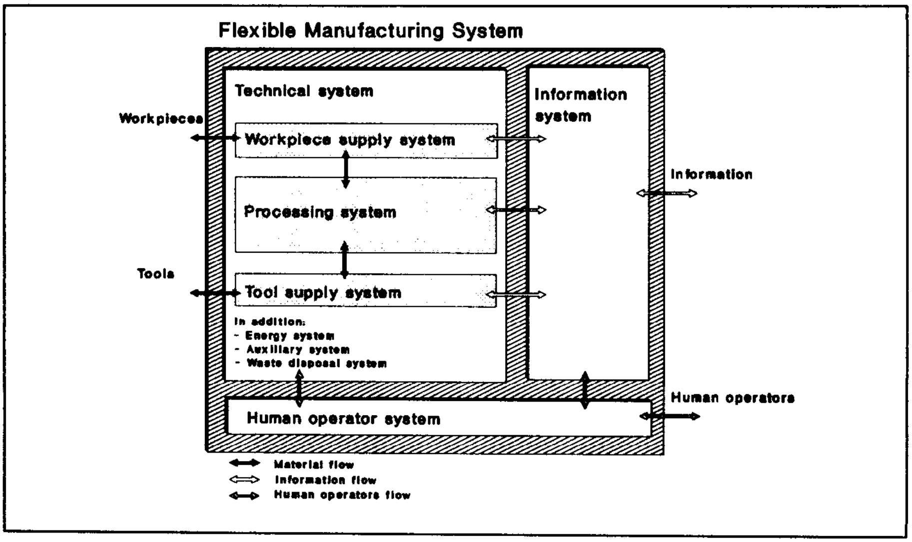

Figure 7: Subsystems of an FMS

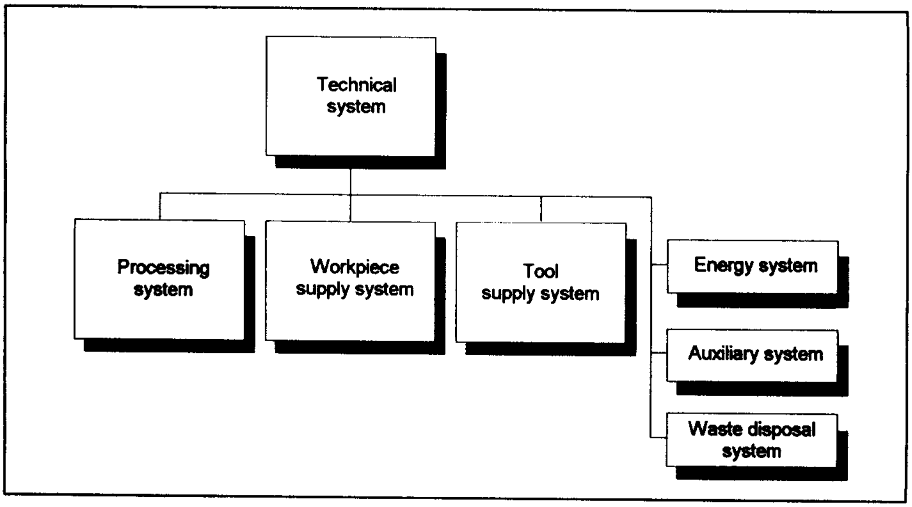

Figure 8: Components of the technical system of an FMS

- **Processing system**

The *processing system* of an FMS consists of *machines*, *local tool exchange* and *tool storage systems*, *quality control* (measuring) *stations* and *washing machines* [see figure (9)]. The machines are generally computer numerical controlled machines