VOLUME 4 NUMBER 1 JANUARY–MARCH ISSN 0953–7287

PRODUCTION PLANNING & CONTROL

Taylor & Francis London and Washington, DC

VOLUME 4 NUMBER 1 JANUARY–MARCH 1993

PRODUCTION PLANNING & CONTROL

CONTENTS

Continued overleaf

0953-7287(1993)4:1-8

PRODUCTION PLANNING & CONTROL, 1993, VOL. 4, NO. 1, 1

Editorial
Beyond TQM

Japanese manufacturing excellence has taught us to appreciate quality. In consumer goods this has led to more quality awareness and quality is a factor considered in addition to prices, when we as consumers buy white goods, brown goods or an automobile.

Of course, this has to reflect back on industry. Quality achievement has grown into a factor of concern and management has had to focus on setting goals and creating visions on assurance of quality. The first steps in quality control were taken in the 1920s when Shewart launched his theory about statistical process control (SPC). He also introduced the control charts that many companies still strive to implement in addition to more sophisticated techniques such as the Taguchi method.

Shewart's theory was based on inspection of products in the manufacturing process. However, it was soon realized that the concept of quality control could be applied also to other activities like engineering, design, procurement, etc. This extended concept was called integrated quality control.

The next step was to develop the technical and organizational means to secure quality. This was called quality assurance (QA) and is still a major concern for many companies. QA involves establishing procedures well documented in QA manuals. These procedures give the necessary guidelines to achieve quality, what to check and how to react on defects, deviations, and misperformance.

But the concept still grew. Now quality became a management issue and philosophy. Quality was given a wide interpretation, to include all activities and to obtain customer satisfaction or even to exceed the customer's management (TQM) and actually deals with all aspects of manufacturing excellence. Concepts like Just-in-Time, Continuous Improvement, Zero Defects, Lean Production, and so on are all total quality management aspects. They tend to overlap rather than complement each other.

Which concept to choose among all these is not important. They all have the ultimate goal of improved competitiveness for the company. However, TQM has received more attention recently at management level than the others. Various awards like the Baldrige award and ISO 9000 standards may be among the reasons for the strong focus on TQM.

An interesting questions to ask is: 'What comes after TQM?' The Boeing company in the US has given one answer to this question. They have launched their D1-9000 quality system which exceeds the ISO 9000 requirements. This system is offered free to their suppliers, and only suppliers complying with the system will in the future remain on the suppliers' list. The system is also used by other industries and might have a chance to develop into an industry standard.

But this does not give a complete answer to the question. What about when all companies have reached their limit TQM performance? TQM may be regarded as a paradigm to improve competitiveness. The previous one was cost reduction. So the question is really: 'What is the next paradigm?' The IFIP Prolamat Conference in Tokyo last year gave the answer: 'Diversity'. This means developing flexibility to provide the customer with a variety of options and alternatives for a product. This product should be offered at a low cost and to the standards of total quality management.

How will our production planning and control systems perform under such a paradigm?

PROFESSOR ASBJØRN ROLSTADÅS
University of Trondheim

PRODUCTION PLANNING & CONTROL, 1993, VOL. 4, NO. 1, 2–16

Production planning and control in automated manufacturing systems

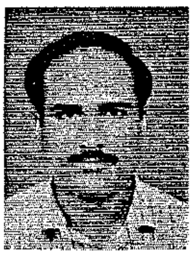
A. GUNASEKARAN, S. K. GOYAL, I. VIRTANEN and P. YLI-OLLI

Abstract. Automated manufacturing systems (AMSs) have the potential for providing a high level of manufacturing performance. Owing to the high cost of capital investment, a high utilization level of AMSs with the help of suitable production planning and control (PPC) is an important feature of AMSs. Realizing the potential of PPC in AMSs, an attempt has been made to review the available techniques/methods for solving the problems of production planning, control and scheduling in AMSs. The need for further research on PPC of AMSs is brought to the fore along with future research directions.

1. Introduction

Automated manufacturing technology, the heart of the 'factory of the future', is getting due recognition in many organizations all over the world. An automated manufacturing system (AMS) performs operations like machining, welding, inspection and assembly in industries ranging from heavy machinery to light electronics.

Authors: A. Gunasekaran, I. Virtanen and P. Yli-Olli, School of Business Studies, University of Vaasa, P.O. Box 297, 65101 Vaasa, Finland. S. K. Goyal, Department of Decision Sciences & MIS, Concordia University, 1455 De Maisonneuve Blvd. West, Montreal, Quebec H3G 1M8, Canada.



A. GUNASEKARAN is assistant professor (visiting) in the Department of Production Economics at the University of Vaasa, Vaasa, Finland. He was awarded a B.E. in mechanical engineering at the University of Madras (India), a M.E. in industrial engineering from the University of Madras, and a Ph.D. in industrial engineering and operations research from the Indian Institute of Technology, Bombay. Dr Gunasekaran has been a research fellow in the Faculty of Management at the University of Toronto, a post-doctoral fellow at Laval University and Concordia University, and an assistant professor at the University of Madras. He has had a number of articles accepted/published in *International Journal of Systems Science*, *International Journal Operations and Production Management*, *Production Planning and Control*, *European Journal of Operational Research*, *Journal of Operational Research Society*, *Applied Financial Economics*, *International Journal of Production Economics*, *International Journal of Quality and Reliability Management*, etc. He has presented papers in conferences and given invited talks in Finland, Sweden, Denmark, United Kingdom, India, Brazil, Austria, Japan, Thailand, Singapore and France. He is currently interested in researching just-in-time manufacturing systems, flexible manufacturing systems and multi-stage product-inventory systems.

SURESH KUMAR GOYAL is currently professor in the Department of Decision Sciences and Management Information Systems at Concordia University. He was awarded a B.Sc. in mechanical engineering at Ranchi University (India), a Dip. Tech. Sci. in production engineering from the University of Manchester Institute of Science and Technology and M.Sc. in operational research from the University of Strathclyde. Professor Goyal has been a research fellow in the Department of Operational Research at the University of Strathclyde, a lecturer at Newcastle-Upon-Tyne Polytechnic, a senior lecturer at the Polytechnic of Wales and an assistant maintenance engineer at Gauhati Refinery in India. He has published over 200 articles in Indian, American, Canadian, Danish and British journals. Professor Goyal's articles have appeared in *Management Science*, *Operations Research*, *Journal of Operational Research Society*, *European Journal of Operational Research*, *International Journal of Production Research*, *International Journal of Operations Management*, *Production Planning and Control*, etc. He has presented over 50 papers in conferences in England, the United States, Canada, Hungary, Brazil and Holland. Application of operational research techniques to production-inventory systems and maintenance problems constitute his present research interest.

ILKKA VIRTANEN, is a professor (full, tenured) of operational research and management science in the Faculty of Accounting and Industrial Management at the University of Vaasa in Finland. Currently, 1987–1994, Professor Virtanen is also the Rector of the university. He was awarded a Ph.D. in applied mathematics at the University of Turku (Finland) in 1977. Professor Virtanen has been an assistant in economic mathematics and statistics at the Turku School of Economics and Business Administration, a senior lecturer in mathematics at the Lappeenranta University of Technology (Finland), and held his current professorship since 1981. He has published numerous papers, e.g. in *American Journal of Mathematical and Management Sciences*, *Empirical Economics*, *European Journal of Operational Research*, *Omega*, *Acta Veterinaria Scandinavica* and the *Finnish Journal of Business Economics*. The total number of published papers is over 100. Professor Virtanen has presented over 30 papers in conferences in different countries in Europe, North and South America, Asia and Australia. Applications of mathematical modelling and statistical techniques in accounting, business finance and production economics constitute his present research interests.

PAAVO YLI-OLLI is professor of accounting and finance in the Faculty of Accounting and Industrial Management at the University of Vaasa, Vaasa, Finland. He received a Ph.D. in accounting and finance from the University of Vaasa in 1978. Currently, Professor Yli-Olli is the chairman of the Department of Accounting and Finance at the University of Vaasa. He has published numerous papers in *American Journal of Mathematical and Management Sciences*, *Empirical Economics*, *Applied Financial Economics*, *Economics Letters*, *European Journal of Operational Research*, *International Journal of Operations and Production Management*, *Journal of Business Finance and Accounting*, *Omega*, *Production Planning and Control*, *Journal of Operational Research Society*, *International Journal of Production Economics*, *International Journal of Systems Science* and the *Finnish Journal of Business Economics*. He has presented a number of papers in conferences in Finland, Japan, Singapore, Australia, Brazil, Denmark and the Soviet Union. During the academic year 1987–1988 he was a visiting professor in the European Institute for Advanced Studies in Management in Brussels, Belgium.

An AMS consists of computer-interfaced machine tools, robots and automated material-handling and storage devices. The processing instructions stored in the computer memory of a machine tool enable it to perform customized operations automatically on each workpiece. Sensory devices in the machines and robots are used for automatic inspection. The machines are linked by an automated material handling system and a central computer. The central computer provides an overall control of the system. The control includes the routeing and sequencing of jobs, tracking their status, downloading instructions to machine tools and taking corrective action. Other components of the system include a tool delivery system and a common central buffer or local buffers at individual workstations (Singhal *et al.* 1987). Hintz and Zimmermann (1989) point out that in order to use all the potentials of FMSs, it is necessary to reorganize the manufacturing area and to develop dedicated systems for production planning and control (PPC). Kusiak (1986a,b) deals with modelling and design of FMSs.

In automated manufacturing systems, production planning includes decisions such as: when to produce items; allocating machines, pallets, fixtures, operators and tools; and determining policies for preventive maintenance and inspection. Scheduling problems include work-releasing, sequencing and priority rules. The production control problems include the determination of policies for defect detection, equipment breakdown, repair and real-time allocation of resources (Singhal *et al.* 1987). The objectives of operations management in PPC of automated manufacturing systems are to increase equipment utilization, reduce labour costs, increase flexibility in meeting changes in product design and demand, improve quality, discover opportunities for improving product design and increase product variety. These objectives will be achieved by improvements in production planning, scheduling and control, especially in terms of preventive maintenance and repair policies, strategies to cope with the consequences of equipment breakdown, and integration of various functions in the firm, especially manufacturing and engineering. Therefore, it is very important to review the available recent trends and ideas for PPC in AMS. Realizing the importance of the role of AMSs in present-day industries, an attempt has been made to look at the recent trends and methods of PPC in AMSs.

An important characteristic of many AMSs is the integration of production stages and the resulting interaction among many hardware and software components. The control of a batch manufacturing system is usually complex with a huge number of inter-relationships between machines, materials, components, tooling and personnel. The problem is extended for automated manufacturing systems by the requirement for short manufacturing lead times and the need to provide detailed control of all manufacturing operations with limited human involvement. The approach that can accommodate such complexity is that of breaking the control into a hierarchy where each level of the hierarchy has higher responsibility. As the hierarchy is descended, the time period considered shortens whilst the level of detail considered increases (Stecke 1986). This paper is organized in the following manner: Section 2 presents the problems of PPC in AMSs. An overall review of recent trends and ideas about PPC in AMSs is presented in Section 3. Limitations of the available ideas/methods and future research directions are indicated in Section 4. Section 5 contains the conclusions drawn from this research.

2. Problems of PPC in AMSs

AMSs involve high capital expenditure, so a high rate of utilization is important to ensure a sufficient level of return on investment. A sufficient rate of AMS utilization can be guaranteed by appropriate planning, scheduling, control and monitoring strategies. The following are some of the major problems involved in the operations of AMSs.

2.1. *Production planning*

The planning problems deal with selecting the appropriate machine tools, parts to be produced and required number of pallets and fixtures to set-up a FMS. These problems can be further sub-classified as follows:

(*i*) *Part type selection*

The part type selection problem consists of splitting up the production requirements for a set of part types into a number of subsets (batches) of part types for simultaneous manufacturing.

(*ii*) *Resource grouping*

The resource grouping problem consists of partitioning the machine tools of each machine type into machine groups such that each machine in a particular group is able to perform the same set of operations.

(*iii*) *Production ratio determination*

The production ratio problem consists of determining the relative ratios at which the part types selected in problem (i) will be produced.

(*iv*) *Resource allocation and loading*

The resource allocation consists of allocating the limited numbers of pallets and fixtures of each type among the selected part types. The loading consists of allocating the operations and associated cutting tools of the selected set of part types among the machine group subject to the technological and capacity constraints of the FMS.

2.2. *Production scheduling*

This is to deal with the control of flow of parts through the system. Scheduling problems include work releasing, sequencing and priority rules. It is the process of matching (orders and preventive maintenance) with shop resources (workers, machines, tooling and material) and of setting order priorities on the shop floor.

2.3. *Production control*

This covers the activities needed to correct an out-of-control situation. Production control problems consist of determining policies for: (i) handling machine breakdowns; (ii) maintenance; (iii) inspection of in-process and/or finished goods inventory; and (iv) real-time allocation of resources.

3. An overview of production planning and control in AMSs

The AMS literature is based on the following classification scheme: (1) production planning; part type selection, resource grouping, production ratio determination, resource allocation and loading, and production support activities, (2) production scheduling, and (3) production control. The purpose of this overall review is to describe new ideas and trends, which should be of interest to both academics and practitioners.

3.1. *Production planning*

Generally, aggregate production planning (APP) in AMS involves determining part types and their respective quantity to be produced during a particular time period, considering machine capacity, due date and production demand. In other words, part type selection and production ratio problems are the rings of APP in a FMS. At the aggregate planning level, Stecke (1986) suggested that a single closed queuing network (CQN) model considering multiple server queues (machines) can be used to solve the problems of FMSs. It is well known that a CQN model needs only aggregate input requirements to average output values, i.e. average production rate and mean queue lengths. Stecke (1986) discussed in detail aggregate production planning in FMSs. Suri and Hildebrant (1984) modelled FMSs by using mean value analysis. Zavannela and Bugini (1992) presented an analytical approach for a planning problem in FMS.

Solot (1990) presented a new concept for managing the running of a FMS. He integrated the planning and scheduling problems and used operations research and expert techniques for solving the real-time scheduling problems. According to Schriber and Stecke (1987) overall machine utilization depends on many of the factors ignored in the aggregate mathematical solution for the machine utilization problem. In particular, machine utilization depends significantly on the quantity of WIP, the number of slack buffers, the level of resources used and the dispatch of WIP to machines. Gray *et al.* (1990) critically reviewed the available models and literature available on tool management issues. Also, they signified the importance of the tool management in AMSs. By using a conceptual model, they identified the major problems in integrating the tool management with that of production. Recently, Mazzola *et al.* (1989) presented a hierarchical production planning model, which integrates FMS production planning into a closed-loop MRP situation. Their FMS/MRP production planning framework consists of the FMS/MRP rough-cut capacity planning, grouping and loading, and detailed scheduling problems. Later Mazzola (1989) focused his attention on the FMS/MRP rough-cut capacity planning (FMRCP) problem. He explored heuristics for the FMRCP problem, and in particular, defined a new FMRCP by a systematic splitting of planning batches. Moreover, the assignment of parts in a subset to the same set of facilities led to fixed route of part flow, and this is against the notion of flexibility in FMSs.

3.1.1. *Part-type selection*

The use of FMSs facilitates the efficient production of a variety of parts with different routeings and operations by having zero set-up times. In practice, however, when the number of part types is extensive and/or the number of operations required by each part is large, the expected improvement in performance from using FMSs may not be achieved. This is because of the constraints included in the design of the system, such as when the number of tools of a particular type on-hand or the number of pallets available is not sufficient to process all parts simultaneously. In such a situation, the most appropriate solution to this problem is to partition the part types into groups (families) so that the parts in each group will be processed simultaneously. Thus, this leads to a part-type selection problem in FMSs.

Generally, part selection methods have emphasized selecting similar parts. Several similarity measures and their associated clustering or heuristic methods have been presented. Furthermore, the similarity measures are often subjective, consisting of a mix of nominal and numerical data. The objective of master production scheduling (MPS) in FMSs is to select the types of part to be produced during a particular period under the constraints such as capacity of the facilities, due date and production demand. For example, Chung and Lee (1989) suggested a heuristic algorithm for scheduling multi-stage production systems. Hwang and Shogan (1989) discussed a part selection problem for a FMS with general-purpose machine tools, but with no tool transportation devices.

Hwang and Shanthikumar (1987) proposed a production planning system for the FMS. This system starts with the part selection module, which selects from the current production order of a batch of part orders and its associated tools for immediate processing. The batch is then fed into the machine balancing module, where the tools are assigned to machines according to their processing times. They have selected a batch of part orders for the next production when the machines are well balanced. However, this model does not account for the constraints on tool availability in the system for processing a group of parts in a particular planning period.

A very important consideration for scheduling is to select an appropriate performance measure. Many researchers and practitioners use operational surrogates that have an indirect impact on costs and revenues. These include the average or weighted tardiness, throughput, machine utilization and WIP inventory, for example. However, a scheduling procedure that does well for one criterion is not necessarily the best for some other. Recently, Stecke and Toczylowski (1992) considered revenue and cost effects of potential schedules directly taking into account in selecting part types and production ratio determination.

3.1.2. *Resource grouping*

The major step in designing a flexible machining cell (FMC) is grouping of parts into families and corresponding machines into manufacturing cells. Further, this can be used to convert a functional layout into a group product layout. The layout deals with a group of machine tools and equipment that are responsible for manufacturing a set of family parts. Group technology (GT) provides a coding and classification scheme for grouping various parts with similar design and/or machining processes into a family of parts and corresponding machines into machine cells. The family of parts is a collection of parts that are similar either because of geometric shape and size and/or because similar processing steps are required in their manufacturing (Chakravarty and Shtub 1987, Kusiak 1987a).

GT is nowadays accepted as the most appropriate approach for improving productivity in large and medium-sized batch production systems. The approaches and models available for solving the grouping problem can be classified into three major categories: group technology, sequential decision procedures and mathematical programming. In general, GT determines part clusters by measuring 'similarities' among parts based on some kind of coding scheme. For the FMS grouping problem, the GT approach needs to code characteristics of the parts and their associated components such as tools, pallets and fixtures. Apart from this, GT has to consider the constraints on the number of part types and associated components in each group.

In the literature, the problem of group formation has been solved by a number of solution procedures. The simplest form of the group formation problem was modified by Kusiak (1987a), in which a part type can be processed by more than one process plan. Further, he suggested a generalized GT concept for the problem of group formation where a specific process plan has to be chosen for each part type, the parts then being grouped into families. Significantly, his formulation adds a dimension of computer-aided process planning to the group formation problem, making it a more generalized group formation problem. However, a number of restrictive assumptions, such as that a machine centre can operate one piece or part at a time and every tool occupies only one slot on the tool magazine, may limit the application of his heuristic algorithm in practice. The major drawback of this model is that it does not consider geometric shape in its similarity measures except that of process plan.

If the applications of GT in manufacturing firms are studied, the demand for flexibility in terms of frequent product changes and smaller batch quantities, in dealing with the desire for shorter throughput times, necessitate reorganization of the existing facilities. Cellular manufacturing systems facilitate the control of manufacturing within or between cells, rather than at the individual machines, by using a combination of computer-controlled machining and handling devices. Most of the firms are involved in fabrication activities and in producing a large number of component parts and/or end items. These firms applied GT to design, process planning, sales, purchasing, cost estimation, tooling, scheduling, new equipment sizing and tool selection. In most cases, firms used classification and coding systems as tools in applying GT. However, users identified managerial and technical barriers that must be overcome in successfully applying GT. It has been observed that most of the firms intend that GT would be an integral and important part of future CAD/CAM activities at their plant.

Much attention has been focused on set-up reduction, pull systems and the application of statistical process control. However, GT philosophy and, in particular, its application to manufacturing systems called cellular manufacturing have not received the same attention. Application of most of the GT approaches assumed that small quantities of parts are produced and parts have similarity in their processing requirements. However, in many cases a mixture of low, medium and high volume parts are desired. In order to solve these kinds of problem, Gupta and Seifoddini (1990) presented a similarity-coefficient based framework to take into account product demand and other processing parameters in machine–component grouping. This method incorporates relevant production data such as part type production volume, routeing sequences and unit operation time. However, the new similarity coefficient assumes that product demand remains the same over a particular planning period.

The literature available on GT is not too realistic, considering that over a time period, the variation in product mix, product design, market situation and other technical factors forces a total system reorganization. It was shown that the utilization of a GT cell can be improved through sub-batch workload transfer. In the context of this study, a detailed and practically oriented computer simulation analysis was found to provide a most useful aid to management decision-making in sensitive situations. (Refer for detailed discussions on the application of GT to Hyer and Wemmerlöv (1989), Wemmerlöv and Hyer (1987) and Kusiak (1987a)). Ventura *et al.* (1990) presented a practical and useful algorithm for grouping of parts and tools in FMSs. Damodaran *et al.* (1992) considered the problem of assigning operations of part types to one or more machines in a cellular manufacturing system. They developed a mixed integer linear model considering trade-off between refixturing and material-handling movement.

In a flexible manufacturing environment, batch production is necessary not only for satisfying some technological constraints, but also to obtain potential reductions in processing time, to reduce WIP and finished goods inventories, and to simplify the production planning process. The central aspect of batch production is the problem of grouping part types and the required tools into families for simultaneous processing. Divakar *et al.* (1990) offered a model for analysing how alternative process plans influence resource utilization when part families and machine groups are formed simultaneously. Askin and Chiu (1990) incorporated first the costs of inventory, machine depreciation, machine set-up and material handling in GT configuration problems. However, consideration should be given to the effects of optimal group size, batch size and lot-size on the design of cell.

3.1.3. *Production ratio determination*

Although mix ratios can be found to begin and end the production of several parts together, it is sufficient to produce parts proportional to their production requirements. As noted earlier, five production planning problems have been defined to address system set-up decisions for FMSs. However, one of these problems, namely production ratio determination, has not been given enough attention either in practice or in the literature. Simulation can provide detailed modelling capabilities necessary to evaluate the performance of the ratios for research purposes. Two main approaches have been proposed for solving the part type selection and production ratio problems. The first one is the batching approach (Hwang 1986). The second approach is flexible approach (Stecke and Kim 1991). The production ratio will be useful to help solve other planning and operating problems. For instance, they can provide guidelines to help in determining part input sequence. They also can be used to select the part types to be produced next (Stecke 1988). Again, Stecke and Kim (1991) offered a production mix ratio determination model. The production ratio should match with the speed of the automated material handling system (MHS)s, while considering the loading/unloading time of parts. Considering this, the determination of production ratio should be treated as an integral part of the decision making with automated guided vehicle (AGV)s. The process of batch splitting and forming may result in efficient flow of materials in the FMSs. Also, appropriate constraints such as operator availability, machine breakdown, etc. must be incorporated in the determination of production ratio in FMSs.

3.1.4. *Resource allocation and loading*

Resource allocation is the allocation of the limited number of pallets and fixtures of each type among the selected part types. The loading problem is concerned with the allocation of part operations and required tools among machine groups for a given product mix. In a random FMS, the loading decisions are dynamic, which leads to the loading decisions to be made for a specified planning horizon. The loading decisions are constrained by a number of factors such as the number of tool slots available on the tool magazine of a machine spindle, the number of slots a tool occupies on the magazine, nonsplitting of jobs, capacity of various machines and so on. Because of the high cost of capital investment in FMSs, the performance measures are quite complex and often involve multiple objectives. The objective may differ from system to system, depending upon the system configuration, types of part to be produced, demand conditions, etc.

Shankar and Srinivasalu (1989) presented heuristic procedures with bi-criterion objective of minimizing the workload imbalance and maximizing the throughput for critical resources such as the number of tool slots on machines and the number of working hours in a scheduling period. Generally, the loading problem in a random FMS wherein the product mix is not completely defined at the time of installing the system and jobs arrive in variety is very important and complex from the view of machine utilization and production rate. Stecke (1986) discussed a hierarchical approach to solving machine grouping and loading problems of FMSs. Recently, FMCs have attracted special interest as a new machining unit for low-volume, variety production, since the investment for FMCs is low in comparison to FMSs. However, set-up operations for workpieces have not been automated in the usual FMCs. Cariapa (1991) introduced a new concept of multi-mode machine tools for improving the operations of FMSs.

Wilson (1989) reformulated the problem of operation-allocation to include the aspects of refixturing and limited tool availability. He proposed a comparatively simple integer programming formulation that avoids the nonlinearities of a previous approach that was proposed by Lashkari *et al.* (1987). Kumar *et al.* (1987) dealt with a nonlinear goal programming model for the loading problem in FMSs. Sarin (1987) was concerned with the computerized analysis of a robotized production cell. Widmer and Solot (1990) considered the impact of breakdowns and maintenance operations on FMS performance by using a queuing model. The loading/dispatch rules are highly influenced by changes in system configuration and to the variation of the product mix. Considering the significance of such influences in FMS loading, Garetti *et al.* (1990) studied the impact of the production mix (characteristics of the routeings, balancing index of the mix) and the characteristics of the system (size of the system buffers, number of machines, transport system utilization level) on the performance of the loading and dispatching rules using the simulated FMS. Moreover, there are further interesting solutions (O'Grady and Menon 1987).

In a FMS where a large number of cutting-tool types are required, the tool loading to different machining centres and the job routeing among the machines are major control functions. Considering the importance of tool management in FMSs, Han *et al.* (1989) analysed the effect of tool loading methods, tool return policies, queue formation methods and job scheduling rules by using simulation. Ammons *et al.* (1985) studied a work-centre loading problem in flexible assembly with the double objectives of work-load balancing and part-movement reduction. Liang and Dutta (1990) developed a mixed-integer programming model for the machine loading and process planning problem in a process layout environment. This model relaxes the most commonly used assumption that each operation can be assigned to only one machine and considers the most important production cost components such as: machining cost, material handling cost, set-up cost and machine idle cost. In addition, the model can be extended to consider the following: (i) the operation sequences are not pre-determined; (ii) breakdown allowed; (iii) random jobs arrival; and (iv) facility re-layout and re-allocation allowed.

Kusiak (1990) designed a knowledge-based system for an automated manufacturing environment. The special feature of the KBSS is to allow us to include basic and alternative plans such as machines, tools, fixtures and material-handling carriers, as well as their sequence. One of the important scheduling and control problems that must be solved concerning the efficient operation of FMSs is finding the optimal sequence of parts to be released into the manufacturing system. Lee and Iwata (1991) presented an approach for solving the problem by using a simulation-optimization technique. Currently, available heuristic approaches can only try to get the optimum at a local level because of the complexities of the system and the dependence of its components, whereas the proposed approach tries to get the global optimum. They have shown that under total grouping, the configuration that minimizes flow time is one in which the size of the machine groups is maximally unbalanced and workload per machine in the larger groups is higher.

3.2 *Production scheduling*

In FMS, production scheduling problems deal with releasing of parts into the system, selection of parts from a pool of parts competing to be processed on the same machine and scheduling of workstations, material-handling carriers, operators, etc. On-line control and scheduling have been widely used in FMSs since its inception. In the operational planning of FMSs, decisions concerning the speed of the delivery of the parts from one stage to the next should be determined in order to increase the efficiency of the material flow in the whole system. Considering the importance of this production flow control in FMSs, Wu and Wysk (1989) presented a control mechanism of job dispatching heuristics by using the results obtained from a simulation. Also, the same authors (Wu and Wysk 1988) offered a multi-pass expert system for controlling the FMCs. Maimon and Gershwin (1988) presented a method for real-time scheduling and routeing of material in a FMS, by considering that different machines perform some of the same operations. Gershwin (1989) generalized the control policy of Kimemia and Gershwin (1983) to a large system with many different kinds of events.

Sharifnia *et al.* (1989) developed a method for flow control of parts in a manufacturing system with machines that require set-ups. They investigated set-up policies in relation to the flow control policies derived in the idea of hierarchical planning. The basic idea considered in their method is to use production rate targets determined at the higher level for the generation of set-up schedules at the level of set-ups. Chakravarty and Shtub (1987) presented an analysis for capacity, cost and scheduling in a multi-product FMC. Maley *et al.* (1988), Sarin and Chen (1987) and Sawik (1990) presented a number of modelling and solution procedures for the design and operational problems of FMSs. The dynamic routeing is established, usually with help of periodic routeings in order to accommodate flexible machining capability, and at the same time to achieve a desirable control of the inventory control flow (Liu 1989). The dynamic routeing and dispatching has shown its importance in accommodating flexible machining capability and managing in-process inventories. The associated routeing problems that need further attention from researchers should include input control and internal dispatching control.

Ranky (1988a,b) suggests that scheduling speeds should be faster than the pallet changing time from one cell to another and the scheduler should react to changes without interrupting the system. Perkins and Kumar (1989) developed a set of scheduling policies that are distributed among a set of machines in a manufacturing system. Real-time implementation is achieved by allowing each individual machine to make localized scheduling decisions based on only its own buffer level for each part. However, there is a need to incorporate more stochastic elements that are present in a system. Maimon (1987) proposed a control system of three levels of control: a scheduler level; a communication level; and a process sequencer level. The scheduler determines an instantaneous production rate for each part in the system in order to utilize the varying capacity of the system. The communication level sends instructions to the controllers and transmits feedback to the scheduler. The process sequencer makes the actual part sequencing decisions and consists of a knowledge base, system status, and inference engine. Young and Rossi (1985) gave some details of a knowledge-based FMS control system in operation at a Texas Instruments manufacturing facility.

Shaw (1988) presented a knowledge-based scheduling approach based on the problem-solving techniques developed in artificial intelligence. The approach is based on three key techniques: (i) pattern-directed inference technique to capture the dynamic nature of the scheduling environment (ii) non-linear planning technique to co-ordinate manufacturing processes and resource assignments; and (iii) search algorithm to expedite the searching procedure. Keeping track of the manufacturing system by a symbolic world model is adaptive to such environmental changes as new job arrivals and machine breakdowns, suitable for making real-time scheduling decisions. O'Grady and Lee (1988) described the application of artificial intelligence techniques of blackboard and actor-based systems for intelligent cell control in a framework termed production logistics and timings organizer. Hintz and Zimmermann (1989) offered fuzzy linear programming to control the release of parts into the FMSs and the scheduling of parts and tools. Solot (1990) dealt with a new concept for controlling the operations of a FMS. This concept is based on the integration of planning and scheduling problem by using the joint modelling of operations research and expert systems. Yao and Buzacott (1986) discussed the state dependent routeing problem and models with limited local buffers for FMSs.

The literature dealing with the design and operational problems of robots in FMSs is rather limited, although it plays a vital role in the system. Blazewicz *et al.* (1989) presented algorithms for scheduling of robot moves and parts in a robotic cell. There are a number of problems in cellular manufacturing that lead to a reduction in the efficiency of the operation of a cell. The operational changes concerning scheduling rules based on the characteristics of cellular manufacturing systems may further reduce the overall machine set-up time and at the same time eliminate some of the deficiencies, while adopting a variety of parts. In order to handle this type of problem, Mahmoodi *et al.* (1990) developed dynamic scheduling heuristics for cellular manufacturing environments (group scheduling or family heuristics) by using simulation. A direct extension of the heuristic is the development of a family of heuristics to consider queue selection schemes and dispatching rule combinations. However, little research has been reported in the group scheduling of FMSs.

Ro and Kim (1990) presented three new process selection rules in FMSs with limited local buffers. These new process selection rules can be applied to the FMSs with limited local buffers and can flexibly cope with the change of system configuration (machine breakdown, etc.). In addition, they developed AGV dispatching and route selection rules for simultaneous scheduling of jobs and material-handling devices. In recent years, generalized manufacturing system simulators that can quickly adjust to model a wide variety of manufacturing systems found extensive application in solving the problems of scheduling. For instance, Montazeri and Van Waasenhove (1990) analysed the characteristics of a general-purpose user-oriented discrete-event simulator for FMSs. This modular FMS simulator can be used to analyse the effect of different scheduling rules on the performance of a specific system. The literature reveals very few general results, i.e. the performance of scheduling rules depends on the criterion chosen as well as on the configuration of the production system considered. Also, results of the scheduling are optimization-dependent and should not carelessly be generalized to other systems.

Hutchinson *et al.* (1991) addressed the problem of scheduling a FMS in a random job-shop environment. As the number of FMSs increases, random job-shop systems become more prevalent, and this trend is expected to continue. Despite this trend, the scheduling of these systems has been relatively neglected in published literature. However, the off-line scheme resulted in significantly better system performance than any of the real-time schemes. It would be desirable to make all scheduling decisions simultaneously, so that the best possible schedule can be found. Because of computational intractability, hierarchical or sequential approaches are often used. Most researchers have decomposed the problem by making tool loading, part input sequencing and routeing decisions prior to actually scheduling parts. However, the research has not determined the magnitude of deterioration in system performance that results from following such an approach. Rachamadugu and Stecke (1987) indicated that the effects of routeing flexibility in job shops have not been adequately addressed. Research findings of routeing flexibility in job-shops have some implications for random FMSs since these two environments are similar.

Ohashi and Hitomi (1991) discussed in their paper the effective use of a single NC machine with multiple functions in order to pursue fully automated, unmanned production. Solving the problem of maximizing the number of workpieces to be machined as a primary objective, as well as maximizing the tool life as a secondary objective, is formulated under the limited capacity of the tool magazine, the available processing time, the restricted machining force, etc. In maximizing the tool life for every tool to be utilized, it is desirable to raise the machining time up to the specified available time, as long as the total machining time does not exceed the maximum available time. Based on this idea, two strategies are proposed for tool selection: one is to select the tool in decreasing order of the machining time, and the other is to select the tool in decreasing order of the tool cost. The important components to be considered while designing an AGV system are flow path, routeing planning, vehicle dispatching and traffic management, Co *et al.* (1990) investigated the purpose of batching in a FMS, and offer various approaches to solve the batching, tool configuration and machine loading problems. FMS batching is similar to that of cellular manufacturing. Later, Co (1992) presented some analytical insights into the benefits of restricting this flexibility and offered a methodology for streamlining the material flow.

3.3 *Production control*

This section deals with the policies to handle breakdowns, maintenance policies, inspection policies for in-process and/or finished goods inventory, tool management and production support activities. Han and McGinnis (1989) presented a flow control method for a FMC to minimize stock-out costs in meeting time-varying demands from downstream cells. Actually, this method finds the optimal control rules by minimizing the stockout cost, based on the periodic application of optimization models with an objective to establish the flow control rules for each stage of a cell during each control period. Nevertheless, the cell operation is controlled by limited buffer space, workstation failures and varying input rates from upstream cells (Gershwin *et al.* 1985, 1986). The same problem was studied by Kimemia and Gershwin (1983), by using an optimal control concept for the case of constant demand rates and random station failures. However, if the length of a control period is too large, control will be overly reactive to changes in the environment, thereby causing operational instability.

Raban and Nagel (1991) presented a framework for the control of a flexible flow line, which is based on constraint-based control (CBC). The CBC method is relatively simple to understand and implement and requires less information processing than a version of a fully decomposed hierarchical control method. It is a very practical approach which can be applied in real-life systems. Yau and Menq (1992) examined the knowledge of relevance to dimensional inspection and three progressive levels of automation technology, ranging from facility automation and decision automation. Their main objective is to create advances in the related knowledge and automation technologies in dimensional inspection. To control a FMS, O'Keefe and Haddock (1991) suggested at least four control strategies necessary for: (i) determining which of a number of parts waiting for resources (such as a machine, the MHS or a fixture) gets preference; (ii) inputting parts into the system; (iii) determining which work-station or load/unload station will be served by the MHS when more than one requires servicing; and (iv) dealing with disruptions, such as machine breakdowns. Simulation seems to be a more suitable modelling tool, especially for FMSs, considering the complexity and less stochastic behaviour of the systems.

4. Comments on PPC in AMSs and future research

This section offers some scope for future research directions in the area of PPC in AMSs.

4.1. *Production planning*

According to Stecke (1986), queuing network models can be used for the purpose of planning at the aggregate level. Since the model requires only average input for average output, this method facilitates the modelling of complex FMSs. Most of the models attempt to balance the workload in order to improve the operations of the FMS. However, there are some conflicts in FMSs while using only the balancing of workload as a performance criterion for efficient operation of the whole system, since the performance of a FMS depends upon a number of other criteria, such as reported by Stecke (1986). Therefore, multiple-criteria decision-making principles can be utilized for the purpose of APP. This particular stage is very important in FMSs, as this decides the future performance of the whole system. Therefore, simulation of a pilot study would facilitate future decisions on FMSs. Stecke *et al.* (1989) proposed a hybrid model-based approach to solve FMS production planning problems. A hybrid model is defined as a combination of analytical models and a simulation model.

4.1.1. *Part-type selection*

Generally, FMS part selection methods have emphasized selecting similar parts. A number of similarity measures and their related clustering or heuristic methods have been proposed. These methods simply ignore the constraints that are present in the part selection problem. Furthermore, the similarity measures are often subjective, consisting of a mix of nominal and numerical data. El-Tamimi *et al.* (1989) developed a discrete modular simulation program for the assessment of real-time part-sequencing systems for flexible assembly cells. The program can be used with different sequencing strategies to study cell performance and decision lead time. Moreover, the following situations are to be considered for more investigation: (i) a part has many attributes, (ii) different part types may share common tools; and (iii) optimal solution requires simultaneously partitioning the production order into the minimal number of batches. Also, various constraints such as tool magazine capacity, pallet size, speed and capacity of the machines and material-handling system, etc. should be considered while modelling the problem of part selection in FMSs.

4.1.2. *Resource grouping*

GT would be an integral and important part of future CAD/CAM activities. The criteria selection for grouping of resources is very important. Also, the criteria differ for different types of resource grouping, for example the criteria for selecting the machine may not be the same for part grouping problems. The GT principle can also be applied to storage systems, jigs and fixtures. Future research is needed to compare the available cell formation procedures in different situations. The main aim of this research would be the development of guidelines pertaining to the selection of cell formation procedures based on the objectives, environments and characteristics of specific firms. Currently similarity coefficients typically rely on substitute measures such as common machines required in processing to evaluate the similarity between parts. Similarity coefficients that employ more direct measures such as similarities between parts in terms of set-ups and tooling may yield better results.

Despite numerous economic benefits and operational advantages offered by the GT concept, its real potential has not been fully explored. A number of factors, including vulnerability to machine breakdown, under-utilization of resources and eventual unbalanced workload distribution in a multi-cell plant, present some problems when using the GT concept. These problems mainly come from the standard principles of GT, such as the avoidance of interaction between the cells, and tendency to setting-up permanent idealistic cells. Other constraints that should be considered while grouping the resources are due dates and part quantities. Only very few firms have applied the concept of GT to design, process planning (including NC programming), sales, purchasing, cost estimation, tooling, scheduling, new equipment sizing and tool selection due to lack of literature available dealing with the application of GT in these problem areas (Wemmerlöv and Hyer 1987 and Hyer and Wemmerlöv 1989).

4.1.3. *Production ratio determination*

Very few models (Stecke *et al.* 1988, 1991) have been reported on this problem in FMSs. Recently, methods have been proposed based on the dynamic application of optimization models in order to generate the flow control directives for each stage of a cell during each control period. For instance, if the length of a control period is too large, control will be much too sensitive to changes in the environment, thereby leading to operational instability, so this problem needs further investigation. Also, transportation time of parts has been neglected while modelling. Therefore, the production ratio should be determined dynamically (on-line control) as the day-to-day operations change frequently owing to various other reasons such as machine breakdowns, emergency orders, etc. The important factors that are to be included in the production ratio determination are: (i) storage capacity, (ii) work-in-process inventory, (iii) material-handling equipment capacity (iv) the speed of the machines and material AGV systems; (v) pallet size, (vi) tool magazine capacity, etc. Usually, planning is to be made until (i) the production requirements are satisfied for some part types, (ii) the part mix is changed; (iii) new production orders are received; and (iv) a machine breaks down.

4.1.4. *Resource allocation and loading*

Many of the existing models treat FMSs as single machine tool replacements with stationary demands, static part families, single-valued input estimates and several other restrictive assumptions. Therefore, considerations should be given to eliminate some of the unrealistic assumptions and restrictions concerning the FMS environment. It may be noted that the models reported in the literature cannot be implemented for large problems because of the 0,1 and general integer programming nature of the formulations (Divakar *et al.* 1990) Hence, there is a need to develop heuristic or approximate procedures to resolve these problems. Some of them can be: (i) suggest suitable algorithms for flow control in FMSs with dynamic set-up for a more realistic FMS, (ii) integrate the concept of JIT in the part-selection problems in multi-stage FMSs, and (iii) develop a prototype simulation system for unmanned FMSs. In FMS literature, tool management has been simply ignored for modelling and analysis, although it has a significant role in influencing the performance of the loading and scheduling of FMSs (Werra and Widmer 1990).

Kumar *et al.* (1990) observed that the solution for some of the objectives of grouping and loading stages is different and that the best system configuration according to the grouping does not necessarily give the best results for the loading objectives. Integrated grouping of parts and tools in FMSs should be considered for future research directions. The research objective may be to obtain general approaches for loading and dispatching of FMSs, considering that the performances of the rules are influenced by the configuration of the plant to run, and on the other that, for a given plant, there is the further influence of the production mix. Developing procedures for low inter-group handling to determine sensitivity to organizational constraints on cell sizes and product mix changes is also a challenging future research area. Since most of the FMSs consist of robots for loading/unloading/welding purpose, the scheduling of robot movement in a FMS cell should be given due attention for further research (Blazewicz *et al.* 1989, Sarin 1987). Further efforts may be worthwhile to extend the existing models. At least the following extensions are possible: (i) the operation sequences are not predetermined, (ii) breakdown allowed, (iii) job arrives randomly; and (iv) facility re-layout or re-allocation allowed. Further, the concept of critical resource can be used for resources like jigs and fixtures (Shankar and Srinivasalu 1989).

4.2. *Production scheduling*

The complexity of FMSs does not permit the use of combinatorial optimization, branch and bound, etc. as they are limited in their applications. More recently, the use of artificial intelligence techniques and simulation methods have been examined with the intention of capturing both the scheduling and control elements necessary for efficient real-time operation of AMSs. Traditionally, real-time refers to the control in a system such as process completions, part arrivals or machine breakdown. The responses would include selecting parts for a machine, starting a machining process, re-routeing a part, etc.

Harmonosky and Robohn (1991) present a working definition of real-time control, review the recent research on real-time control of computer-integrated manufacturing systems in the areas of general approaches, artificial intelligence techniques and simulation methods, and discuss several implementation and feasibility studies. Wu and Wysk (1989) described a scheduling algorithm, that employs discrete simulation in combination with a simple part-dispatching rule in a dynamic fashion. The result is that, instead of scheduling being planned ahead of time and then being applied to a rapidly changing system, a dispatching rule is determined for each short period just before the implementation time. In the long run, the algorithm combines various dispatching rules in response to the dynamic status of the system. They illustrated several advantages of the multi-pass scheduling algorithm: (i) it is more accurate, (ii) higher feasibility due to simulation in case of blocking and locking, and (iii) all the details of the actual system are incorporated in the simulation model.

In scheduling, different types of decisions are taken to perform a particular operation, i.e. the selection of a work station, a transport device and scheduling sequence of the operations. The problems in design, planning, scheduling and control are strongly inter-related. Hutchinson *et al.* (1991) examined the influences that scheduling schemes and the degree of routeing flexibility have on random, job-shop FMSs within a static environment. Akella *et al.* (1990) developed a linear programming model for computing a quadratic approximation to the value function, which makes the off-line computation of a hierarchical FMS scheduling approach previously developed by them. They considered the multiple-part–multiple-machine discounted cost case and illustrated the approach via a simulation example in the context of an industrial setting. However, the assumption that each part has a single route through the system is in fact against the notion of alternative routeings in FMSs. Slomp *et al.* (1988) presented three quasi-on-line scheduling procedures for FMSs consisting of workstations, transport devices and operators.

Four areas that have been neglected in the FMS scheduling literature are: (i) the appropriateness of real-time versus off-line scheduling for a random job-shop FMS in a static environment; (ii) more research is needed for random job-shop FMSs; (iii) additional research is needed to determine the effects of routeing flexibility on scheduling schemes; (iv) there is a need to determine the effects of using the procedure that decomposes the scheduling problem (Hutchinson *et al.* 1991). However, they demonstrated that the off-line schemes are found to be much better than the real-time scheme with respect to make-span. In addition, the off-line schemes take advantage of increased routeing flexibility more than the real-time schemes. Widmer (1991) considered the tool-loading problems in scheduling of the FMSs. The advantages of this method are to provide a feasible schedule with regard to the overlapping and process plan constraints and to balance the workload among identical machines, if any. However, the tooling constraints are not considered. Mukhopadhyay *et al.* (1991) presented an approach to determine an integrating tool allocation, parts scheduling, pallets scheduling, machine scheduling and material-handling equipment scheduling. The problem is formulated as a hierarchical process and solved through eigenvector analysis of priority ordering.

Sabuncuoglu and Hommertzheim (1992) investigated the performances of machine and AGV scheduling rules against the mean flow-time criterion. The scheduling rules are tested under a variety of experimental conditions by using a FMS simulation model. Also, the application of AI and expert systems enhance the operations of FMSs considerably (Park *et al.* 1989, Shaw 1988, Suri and Whitney 1984).

4.3. *Production control*

The research effort in FMSs has been concentrated upon a unique system analysing production control strategies. In some cases, no physical system was available as a reference, necessitating a variety of system assumptions by researchers. It has been very difficult to compare control strategy effectiveness among applications and a general lack of standardization among system definitions. Harmonosky and Sadowski (1990) discussed the development of a system generator procedure, which would greatly enhance generic control strategy research by allowing efficient generation of test system environments. Some of the assumptions that do not represent the real situations of FMSs are: (i) part population is homogeneous; and (ii) machining is fully reliable and flexible.

Moreover, periodic routeing-control problems associated with a variety of FMSs, such as non-homogeneous population systems, non-pre-determined output proportion systems and limited central buffer systems (Liu 1989) may be considered for further investigations. A large number of pallets is desirable for unmanned production (Dirne 1990). The larger this number is, the more capacity can be gained from unmanned night shifts. This leads to the conclusion that during manned production not all pallets should be used, whereas during the night as many pallets as possible should be used. These extra pallets should be loaded (and unloaded) during the manned shifts. The problem of tool and fixture resources dimensioning is considered and examined for a productive environment with flexible features by Zavanella and Bugini (1992). This study dealt with an argument of fundamental interest for industrial processes: tool and fixture management in flexible manufacturing. Reddy *et al.* (1992) analysed the issues at machine-group level to get a better insight into tool management. Akella *et al.* (1984) described the performance of the hierarchical production scheduling policy. The purpose of their policy is to respond to disruptive events that occur as part of the production process, particularly repairs and failures.

4.4. *Additional future research directions*

The following are some additional research directions and pointers for solving problems of PPC in AMSs.

1. Considering the nature of the problems of PPC and the speed with which such problems must be solved, the application of artificial intelligence and expert systems in AMSs (Kusiak 1987b,c, 1989, Kusiak and Chen (1988)) is becoming an important area for further investigation.
2. The aspects of quality control in AMSs, such as location of inspection stations, inspection lot-sizing and type of equipment required for inspection, etc. have not received due attention from researchers. However, this is a very significant field for further improvement in AMSs. Models for determining economic maintenance scheduling and inspection policies in AMSs would help to facilitate quality control performance.
3. There is a need for integrating the issues of part-type selection and production ratio determination for increasing the effectiveness of AMSs.
4. Tool management issues and scheduling of AGVs in AMSs have not received enough attention from production researchers, although they deserve a great deal of attention for improving the operation of AMSs.
5. Establishing re-scheduling polices of machines when there is a breakdown of the machine has a high potential for reducing the impact of disruptions in AMSs.

5. Conclusions

In this paper, the recent trends and ideas reported in the literature on PPC of AMSs have been reviewed. The deficiencies of the available literature on AMSs have been brought to the fore to signify the importance of PPC in AMSs. In addition, future research directions are suggested in this paper with an objective to enhance the performance of the system through appropriate AMS modelling and analysis. The management-science/operations-research models with artificial intelligence and expert systems approaches seem to be promising to solve the problems of production planning and control in automated manufacturing. More importantly, the specific objectives for models at each level of the control system hierarchy are highly dependent on the characteristics of the system and thus cannot always be evaluated without considering the possible alternatives at lower levels.

Acknowledgements

The authors are grateful to Professors Asbjorn Rolstadås and Andrew Kusiak for inviting them to write this paper. The financial support by the Neste Foundation is gratefully acknowledged.

References

AKELLA, R., CHOONG, Y., and GERSHWIN, S. B., 1984, Performance of hierarchical production scheduling policy. *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, 7, 225–240.

AKELLA, R., MAIMON, O., and GERSHWIN, S. B. 1990, Value function approximation via linear programming for FMS scheduling. *International Journal of Production Research*, **28**, 1459-1470.

AMMONS, J. C., LOFGREN, C. B., and MCGINNIS, L. F., 1985, A large scale loading problem in flexible assembly. *Annals of Operations Research*, **3**, 319-328.

ASKIN, R. G., and CHIU, K. S., 1990, A graph partitioning procedure for machine assignment and cell formation in group technology. *International Journal of Production Research*, **28**, 1555-1572.

BLAZEWICZ, J., SETHI, S. P., and SRISKANDARAJAH, C., 1989, Scheduling of robot moves and parts in robotic cells. *Proceedings of the Third ORSA/TIMS Conference on Flexible Manufacturing Systems—Operations Research Models and Applications*, K. E. Stecke and R. Suri (eds), 133-139.

CARIAPA, V., 1991, Multimode machine tools—a concept that improves operations of flexible manufacturing systems. *International Journal of Production Research*, **29**, 1069-1079.

CHAKRAVARTY, A. K., and SHTUB, A., 1987, Capacity, cost and scheduling analysis for a multi-product flexible manufacturing cell. *International Journal of Production Research*, **25**, 1143-1156.

CHUNG, S-H., and LEE, T.-R. 1989, A heuristic method for solving FMS master production scheduling problem. *Proceedings of the Third ORSA/TIMS Conference on Flexible Manufacturing Systems—Operations Research models and Applications* K. E. Stecke and R. Suri (eds), 127-132.

CO, H. C., 1992, Streamlining material flow in flexible manufacturing systems: a lesson in simplicity. *International Journal of Production Research*, **30**, 1483-1499.

CO, H. C., BIERMANN, J., and CHEN, S. K., 1990, A methodical approach to the flexible manufacturing system batching, loading and tool configuration problems. *International Journal of Production Research*, **28**, 2171-2186.

DAMODARAN, V., LASHKARI, R. S., and SINGH, N., 1992, A production planning model for cellular manufacturing systems with refixturing considerations. *International Journal of Production Research*, **30**, 1603-1615.

DIRNE, C. W. G., 1990, The quasi-simultaneous finishing of work orders on a flexible automated manufacturing cell in a job shop. *International Journal of Production Research*, **28**, 1635-1655.

DIVAKAR, R., SINGH, N., and ANEJA, Y. P., 1990, Integrated design of cellular manufacturing systems in the presence of alternative process plans. *International Journal of Production Research*, **28**, 1541-1554.

EL-TAMIMI, A. M., SULIMAN, S. M. A., and WILLIAMS, D. F., 1989, A simulation study of part sequencing in a flexible assembly cell. *International Journal of Production Research*, **27**, 1769-1793.

GARETTI, M., POZZETTI, A., and BAREGGI, A., 1990, On-line loading and dispatching in flexible manufacturing systems. *International Journal of Production Research*, **28**, 1271-1292.

GERSHWIN, S. B., 1989, A hierarchical framework for discrete event scheduling in manufacturing systems, *Proceedings of IEEE*, **77**, 195-209.

GERSHWIN, S. B., AKELLA, R., and CHOONG, Y. F., 1985, A hierarchical framework for discrete event scheduling in manufacturing systems. *IBM Journal of Research and Development*, **29**, 392-400.

GERSHWIN, S. B., HILDEBRANT, R. R., SURI, R., and MITTER, S., 1986, A control perspective on recent trends in manufacturing systems. *IEEE Control System Magazine*, **6**, 3-15.

GRAY, A. E., SEIDMANN, A., and STECKE, K. E., 1990, A synthesis of tool-management issues and decision problems in automated manufacturing. *Working Paper Series, CMOM 88-03* (Center for Manufacturing & Operations Management, University of Rochester, USA).

GUPTA, T., and SEIFODDINI, H., 1990, Production data based similarity coefficient for machine-component grouping decisions in the design of a cellular manufacturing system. *International Journal of Production Research*, **28**, 1247-1269.

HAN, M-H., and MCGINNIS, L. F., 1989, Flow control in flexible manufacturing: minimization of stockout cost. *International Journal of Production Research*, **27**, 701-715.

HAN, M-H., NA, Y. K., and HOGG, G. L., 1989, Real-time tool control and job dispatching in flexible manufacturing systems. *International Journal of Production Research*, **27**, 1257-1267.

HARMONOSKY, C. M., and ROBOHN, S. F., 1991, Real-time scheduling in computer integrated manufacturing: a review of recent research. *International Journal of Computer Integrated Manufacturing*, **4**, 331-340.

HARMONOSKY, C. M., and SADOWSKI, R. P., 1990, The system generator concept for FMS,research and analysis. *International Journal of Production Research* **28**, 559-571.

HINTZ, G. W., and ZIMMERMANN, H.-J., 1989, A method to control flexible manufacturing systems. *European Journal of Operational Research*, **41**, 321-334.

HUTCHINSON, J., LEONG, K., SNYDER, D., and WARD, P., 1991, Scheduling approaches for random job shop flexible manufacturing systems. *International Journal of Production Research*, **29**, 1053-1067.

HWANG, S., 1986, Part selection problems in flexible manufacturing systems planning stage. *Proceedings of the Second ORSA/TIMS Conference on Flexible Manufacturing Systems: Operations Research Models and Applications*, Ann Arbor, MI, USA, K. E. Stecke and R. Suri (eds) (Elsevier, Amsterdam) 297-309.

HWANG, S. S., and SHANTHIKUMAR, J. G., 1987, An FMS production planning system and evaluation of part selection approaches. *Management Science Working Paper No. MS-43*, School of Business Administration, University of California, Berkeley, USA.

HWANG, S. S., and SHOGAN, A. W., 1989, Modelling and solving an EMS part selection problem. *International Journal of Production Research*, **27**, 1349-1366.

HYER, N. L., and WEMMERLOÖV, U., 1989, Group Technology in the US manufacturing industry: a survey of current practices. *International Journal of Production Research*, **27**, 1287-1304.

KIMEMIA, J. G., and GERSHWIN, S. B., 1983, An algorithm for computer control of a flexible manufacturing system. *IIE Transactions*, **15**, 353-362.

KUMAR, P., SINGH, N., and TEWARI, N. K., 1987, A nonlinear goal programming model for the loading problem in a flexible manufacturing system. *International Journal of Production Research*, **25**, 13-20.

KUMAR, P., TEWARI, N. K., and SINGH, N., 1990, Joint consideration of grouping and loading problems in a flexible manufacturing system. *International Journal of Production Research*, **28**, 1345-1356.

KUSIAK, A., 1986a, *Modelling and Design of Flexible Manufacturing Systems* (Elsevier, Amsterdam).

KUSIAK, A., 1986b, Application of operational research models and techniques in flexible manufacturing systems. *European Journal of Operational Research*, **24**, 336–345.

KUSIAK, A., 1987a, The generalized group technology concept. *International Journal of Production Research*, **25**, 561–573.

KUSIAK, A. 1987b, Artificial intelligence and operations research in flexible manufacturing systems. *Information Sciences and Operations Research*, **25**, 2–12.

KUSIAK, A., 1987c, Knowledge engineering and optimization in automated manufacturing systems. *Proceedings of the 2nd International Conference on Production Systems*, INRIA, April 6–10, Paris, France.

KUSIAK, A., 1989, *Intelligent Manufacturing Systems* (Prentice-Hall, Englewood Cliffs, N.J., USA).

KUSIAK, A., 1990, KBSS: A knowledge-based system for scheduling in automated manufacturing. *Mathematical and Computer Modelling: An International Journal*, **13**, 37–55.

KUSIAK, A., and CHEN, M., 1988, Expert systems for planning and scheduling manufacturing systems. *European Journal of Operational Research*, **34**, 113–130.

LASHKARI, R. S. DUTTA, S. P., and PADHYE, A. M., 1987, A new formulation of operation allocation problem in flexible manufacturing systems: mathematical modelling and computational experience. *International Journal of Production Research*, **25**, 1267–1283.

LEE, Y.-H., and IWATA, K., 1991, Part ordering through simulation-optimization in an FMS. *International Journal of Production Research*, **29**, 1309–1323.

LIANG, M., and DUTTA, S. P., 1990, A mixed-integer programming approach to the machine loading and process planning problem in a process layout environment. *International Journal of Production Research*, **28**, 1471–1484.

LIU, J., 1989, The periodic routing of a flexible manufacturing system with centralized in-process inventory flows. *International Journal of Production Research*, **27**, 943–951.

MAHMOODI, F., DOOLEY, K. J., and STARR, P. J., 1990, An investigation of dynamic group scheduling heuristics in a job shop manufacturing cell. *International Journal of Production Research*, **28**, 1695–1711.

MAIMON, O. Z., 1987, Real-time operational control of flexible manufacturing systems. *Journal of Manufacturing Systems*, **6**, 125–136.

MAIMON, O. Z., and GERSHWIN, S. B., 1988, Dynamic scheduling and routing for flexible manufacturing systems that have unreliable machines. *Operations Research*, **36**, 279–292.

MALEY, J., RUIZ-MYER, S., and SOLBERG, J., 1988, Dynamic control in automated manufacturing: A knowledge integrated approach. *International Journal of Production Research*, **26**, 1739–1748.

MAZZOLA, J. B., 1989, Heuristics for the FMS/MRP rough-cut capacity planning problem. *Proceedings of the Third ORSA/TIMS Conference on Flexible Manufacturing Systems—Operations Research models and Applications* K. E. Stecke and R. Suri (eds), 119–126.

MAZZOLA, J. B., NEEBE, A. W., and DUNN, C. V. R., 1989, Production planning of a flexible manufacturing system in a material requirement planning environment. *The International Journal of Flexible Manufacturing Systerms*, **1**, 115–142.

MONTAZERI, M., and VAN WASSENHOVE, L. N., 1990, Analysis of scheduling rules for an FMS *International Journal of Production Research*, **28**, 785–802.

MUKHOPADHYAY, S. K., MAITI, B., and GARG., S., 1991, Heuristic solution to the scheduling problems in flexible manufacturing system. *International Journal of Production Research*, **29**, 2003–2024.

O'GRADY, P., and LEE, K. H., 1988, An intelligent cell control system for automated manufacturing. *International Journal of Production Research*, **26**, 845–861.

O'GRADY, P. J., and MENON, U., 1987, Loading a flexible manufacturing system. *International Journal of Production Research*, **25**, 1053–1068.

OHASHI, K., and HITOMI, K., 1991, Analysis of flexible machining cells for unmanned production. *International Journal of Production Research*, **29**, 1603–1613.

O'KEEFE, R. M., and HADDOCK, J., 1991, Data-driven generic simulators for flexible manufacturing systems. *International Journal of Production Research*, **29**, 1795–1810.

PARK, S., RAMAN, N., and SHAW, M. J., 1989, Heuristic learning for pattern-directed scheduling in a flexible manufacturing system. *Proceedings of the Third ORSA/TIMS Conference on Flexible Manufacturing Systems—Operations Research Models and Applications* K. E. Stecke and R. Suri (eds), 133–139.

PERKINS, J. R., and KUMAR, P. R., 1989, Syllable, distributed, real-time scheduling of flexible manufacturing/assembly/disassembly systems. *IEEE Transactions on Automatic Control*, **34**, 139–148.

RABAN, S., and NAGEL, R. N., 1991, Constraint-based control of flexible flow lines. *International Journal of Production Research*, **29**, 1941–1951.

RACHAMADUGU, R., and STECKE, K., 1987, Classifications and review of FMS scheduling procedures. *Working Paper #481R* (University of Michigan, MI, USA).

RANKY, P. G., 1988a, A real-time, rule-based FMS operation and control strategy in CIM environment—Part I. *International Journal of Computer Integrated Manufacturing*, **1**, 55–72.

RANKY, P. G., 1988b, A real-time, rule-based FMS operation and control strategy in CIM environment—Part II. *International Journal of Computer Integrated Manufacturing*, **1**, 195–196.

REDDY, C. E., KRISHNAIAH CHETTY, O. V. and CHAUDHURI, D., 1992, A Petri net based approach for analysing tool management issues in FMS. *International Journal of Production Research*, **30**, 1427–1446.

RO, I.-K., and KIM, J-L., 1990, Multi-criteria operational control rules in flexible manufacturing systems (FMSs). *International Journal of Production Research*, **28**, 47–63.

SABUNCUOGLU, I., and HOMMERTZHEIM, D. L., 1992, Experimental investigation of FMS machine and AGV scheduling rules against the mean flow-time criterion. *International Journal of Production Research*, **30**, 1617–1635.

SARIN, S. C., 1987, Computerized analysis of robotized, production cell. *Information Processing Science and Operations Research*, **25**, 46–56.

SARIN, S. C., and CHEN, S. C., 1987, The machine loading and tool allocation problem in a flexible manufacturing system. *International Journal of Production Research*, **25**, 1081–1094.

SAWIK, T., 1990, Modelling and scheduling of a flexible manufacturing system. *European Journal of Operational Research*, **45**, 177–190.

SCHRIBER, T. J., and STECKE, K. E., 1987, Using mathematical programming and simulation to study FMS machine utilizations. *Proceedings of the 1987 Winter Simulation Conference* A. Thesen, H. Grant and W. D. Kelton (eds), (The Society for Computer Simulation, San Diego, California, USA).

SHANKAR, K., and SRINIVASALU, A., 1989, Some solution methodologies for loading problems in a flexible manufacturing system. *International Journal of Production Research*, **27**, 1019–1034.

SARIFNIA, A., CARAMANIS, M., and GERSHWIN, S. B., 1989, Dynamic set-up scheduling and flow control in flexible manufacturing systems. *Proceedings of the Third ORSA/TIMS Conference on Flexible Manufacturing Systems—Operations Research Models Applications* K. E. Stecke and R. Suri (eds) 133–139.

SHAW, M. J., 1988, Knowledge-based scheduling in flexible manufacturing systems: An integration of pattern-directed inference and heuristic search. *International Journal of Production Research*, **26**, 821–844.

SINGHAL, K., FINE, C. H., MEREDITH, J. R., and SURI, R., 1987, Research and Models for Automated Manufacturing. *Interfaces*, **17**, 5–14.

SLOMP, J., GAALMAN, G. J. C., and NAWIJN, W. M., 1988, Quasi on-line scheduling procedures for flexible manufacturing systems. *International Journal of Production Research*, **26**, 585–598.

SOLOT, P., 1990, A concept for planning and scheduling in an FMS. *European Journal of Operational Research*, **45**, 85–95.

STECKE, K. E., 1986, A hierarchical approach to solving machine grouping and loading problems of flexible manufacturing systems. *European Journal of Operational Research*, **24**, 369–378.

STECKE, K. E., 1988, Procedures to determine part mix ratios in flexible manufacturing systems. *Working Paper # 587* (Division of Research, School of Business Administration, The University of Michigan, USA).

STECKE, K. E., and KIM, I., 1991, A flexible approach to part type selection in flexible flow systems using part mix ratios *International Journal of Production Research*, **29**, 53–75.

STECKE, K. E., MIN, M., and KIM, I., 1989, A hybrid model-based approach for the production planning of FMSs. *Proceedings of the Third International Conference on Expert Systems and the Leading Edge in Production Planning and Operations Management* Elsevier, Hilton Head Island, South Carolina, USA.

STECKE, K. E., and TOCZYLOWSKI, E., 1992, Profit-based FMS dynamic part type selection over time for mid-term production planning. *European Journal Operational Research*, **63**, 54–65.

SURI, R., and HILDEBRANT, R. R., 1984, Modelling flexible manufacturing systems using mean-value analysis. *Journal of Manufacturing Systems*, **3**, 27–38.

SURI, R., and WHITNEY, C. K., 1984, Decision support requirements in flexible manufacturing. *Journal of Manufacturing Systems*, **3**, 61–69.

VENTURA, J. A., CHEN, F. F., and WU, C-H., 1990, Grouping parts and tools in flexible manufacturing systems production planning. *International Journal of Production Research*, **28**, 1039–1056.

WEMMERLÖV, U., and HYER, N., 1987, Research issues in cellular manufacturing. *International Journal of Production Research*, **25**, 413–431.

WERRA, D. D., and WIDMER, M., 1990, Loading problems with tool management in flexible manufacturing systems: A few integer programming models. *The International Journal of Flexible Manufacturing Systems*, **3**, 71–82.

WIDMER, M., and SOLOT, P., 1990, Do not forget the breakdowns and the maintenance operations in FMS design problems. *International Journal of Production Research*, **28**, 421–430.

WIDMER, M., 1991, Job scheduling with constraits: a Tabu search approach. *Journal of Operational Research Society*, **42**, 75–82.

WILSON, J. M., 1989, An alternative formulation of the operation-allocation problem in flexible manufacturing systems. *International Journal of Production Research*, **27**, 1405–1412.

WU, S-Y. D., and WYSK, R. A., 1988, Multi-pass expert control system—A control/scheduling structure for flexible manufacturing cells. *Journal of Manufacturing Systems*, **7**, 107–120.

WU, S.-Y. D., and WYSK, R. A., 1989, An application of discrete-event simulation to on-line control and scheduling in flexible manufacturing. *International Journal of Production Research*, **27**, 1603–1623.

YAO, D. D., and BUZACOTT, J. A., 1986, Models of flexible manufacturing systems with limited local buffers. *International Journal of Production Research*, **24**, 107–118.

YAU, H.-T., and MENQ, C.-H., 1992, An automated dimensional inspection environment for automated manufactured parts using coordinate measuring machines. *International Journal of Production Research*, **30**, 1517–1536.

YOUNG, R. E., and ROSSI, M., 1985, The use of knowledge-based control in a flexilble manufacturing system. *Autofact '85 Conference Proceedings*, MS85-1115, 1–6.

ZAVANNELA, L., and BUGINI, A., 1992, Planning tool requirements for flexible manufacting: an analytical approach. *International Journal of Production Research*, **30**, 1401–1414.