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The State of the Art in Simulation Study on FMS Scheduling: A Comprehensive Survey

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Scheduling of flexible manufacturing systems (FMSs) has been one of the most attractive areas for both researchers and practitioners. A considerable body of literature has accumulated in this area since the late 1970s when the first batch of papers was published. A number of approaches have been adopted to schedule FMSs, including simulation techniques and analytical methods. Numerous articles can be found on each of these approaches. This paper reviews scheduling studies of FMSs which employ simulation techniques as an analysis tool, since simulation is the most widely used tool for modelling FMSs. Scheduling methodologies are categorised into simulation of general scheduling studies, multi-criteria scheduling approaches, and artificial intelligence (AI) approaches in FMSs. Comments on the publications, and suggestions for further research and development are given.

Keywords: Artificial intelligence (AI); Flexible manufacturing systems; Multi-criteria; Scheduling; Simulation

1. Introduction

1.1 Introduction of FMS

Manufacturing emerged in the 1990s as one of the important keys to organisational success, and a number of comprehensive manufacturing strategies are receiving widespread attention as a result of a renewed emphasis on manufacturing methods [1]. Computer integrated manufacturing, just-in-time (JIT) manufacturing, factory automation, lean manufacturing, and flexible manufacturing systems (FMSs) are some of the recurring themes.

The largest single factor having a positive impact on manufacturing improvement has been the introduction of FMSs. FMSs are the result of the growth in demand for product quantity and the concern for the product quality. Another major motivation for FMS has been based on the perceived need for manufacturing industry to respond to change more rapidly than in the past [2].

FMSs have been defined in a number of ways, but there is not a standard accepted definition for the general term flexible manufacturing system. Most of the definitions are based on the hardware used in the system. For example, Byrkett et al. [3] stated that:

> A flexible manufacturing system (FMS) is a manufacturing system in which *groups of numerically controlled machines (machine centers) and a material handling system* work together under computer control.

O'Keefe and Kasirajan [4] defined an FMS as:

> a *group of workstations connected together by a material handling system (MHS)* producing or assembling a number of different part types under *the central control of a computer*.

Other definitions are based on the capability or performance of the system. For example, Kaltwasser et al. [5] stated that:

> Flexible manufacturing systems (FMSs) are highly automated production systems, *able to produce a great variety of different parts* by using the same equipment and the same control system.

Sarin and Chen [6] stated that:

> FMS is designed to combine the *efficiency of a high-production line and the flexibility of a job shop to best suit the batch production of mid-volume, and mid-variety of products*.

More definitions can be found in the literature (O'Grady [2]; O'Grady and Menon [7]). Despite the range of definitions, it is accepted that an FMS consists of three basic subsystems:

1. A processing system.
2. A material handling and storage system.
3. A computer control system.

Computer control systems and automated equipment are the major differences between FMSs and traditional manufacturing systems.

Different authors classify different types of FMS. Browne et al. [8] classified FMSs into four types: flexible machining

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cell; flexible machining system; flexible transfer line; and flexible transfer multi-line. This classification was based on process attributes and captures the principal attitudes of system design and operation such as the equipment selection, layout, capacity decisions, and other issues. Later, Stecke and Browne [9] extended the classification scheme to include the type of material handling system as a further descriptor. Their classification scheme was based on the flow pattern of parts through the system and emphasises routeing flexibility.

Kusiak [10] discussed FMS in its broadest sense to include fabrication, machining and assembly, and gave a brief structural taxonomy of FMSs. The author listed five classes of FMSs, namely: flexible manufacturing module, flexible manufacturing cell, flexible manufacturing group, flexible production system, and flexible manufacturing line. The author also showed an approximate graphical relationship between the classes with respect to the number of different parts per system per year and also the annual production rate.

MacCarthy and Liu [11] classified FMSs into four types: a single flexible machine, a flexible manufacturing cell, a multi-machine FMS, and a multi-cell FMS. Then they discussed the relationships and boundaries between these four types of FMS. The approach considered the number of characteristics of the material handling devices as well as the configuration of the processing elements.

Based on the mode of operation, Rachamadugu and Stecke [12] classified FMSs into two levels. The classification of the first level was based on the physical flow and the second level was based on the number of part types.

1.2 Introduction to Scheduling of FMS

Production management and scheduling problems in an FMS are more complicated than in job shops and transfer lines. Several reasons can be advanced to support the above statement:

Each machine is versatile and capable of holding different tools to perform different operations. Therefore, different part types can be manufactured at any given time.

In addition to machines, material handling systems such as automated guided vehicles (AGVs), jigs, fixtures, and pallets must also be scheduled. In other words, the number of decision points, where scheduling or operation rules can be varied, is greater in FMSs than in job shops.

There may be a rapid change of demand, or random entering of the new products with high priority.

An operation is capable of being performed on a number of alternative machines with possibly different process times.

Production is continuous even during unexpected events such as breakdown of machines. Because of the large set-up times required for an alternative operation in job shops, if a breakdown occurs, production would be interrupted, but in automated manufacturing systems such as FMSs, programmability of the instructions for operations dramatically reduces set-up times.

Generally, when an FMS is being planned, the objective is to design a system that will be most efficient in the production of the entire range of parts. This cannot be achieved unless all of the following four stages work well:

1. Designing.
2. Production planning.
3. Scheduling.
4. Controlling.

Design of FMSs involves a selection of equipment and layout design, including:

1. The number and capacity of stations.
2. The number and capacity of the storage units.
3. The design of material handling system.

With the advance of automation technology, the associated decision supporting systems, production planning, scheduling and control, have gained importance [13].

Production planning involves establishing production levels for a given length of time. It determines production parameters, such as production mix, production levels, resource availability, and due dates. With the specified production parameters, the goal of scheduling is to make efficient use of resources to complete tasks in a timely manner. Clossen and Malstrom [14] stated that hundreds of robots and millions of dollars worth of computer-controlled equipment are worthless if they are under-utilised or if they spend their time working on the wrong part because of poor planning and scheduling. Control of the system is considered to be part of production planning and scheduling. Shop floor control is concerned with monitoring the process and progress of orders in the system and reporting the current status to management. In considering these four stages of planning in FMSs, scheduling plays a crucial role.

There have been extensive studies on scheduling manufacturing systems. These studies can be divided into three basic approaches [13]:

1. Operations research (OR) approach.
2. Artificial intelligence (AI)-based approach.
3. Combination of OR and AI-based approaches.

Spano et al. [15] divided the scheduling research into two major approaches:

1. Traditional approach.
2. Artificial intelligence (AI)-based approach.

The traditional approach can be further divided into two categories:

Theoretical research dealing with optimisation procedures.

Experimental research dealing with dispatching rules.

Scheduling of FMSs has been extensively investigated over the last three decades and it continues to attract the interest of both the academic and industrial sectors. Ramasesh [16] provided a state-of-the-art survey of simulation-based research on dynamic job shop scheduling a focusing first on simulation modelling and experimental considerations, then on findings about the job shop performance criteria of interest. This excellent review covers simulation studies for job shops from 1960 to 1987.

Theoretical research has focused on the development of mathematical models and optimal or suboptimal algorithms [17–19], using integer, mixed integer, and linear programming [20–22]. The theoretical results have not been widely used in industry because of the associated high computational complexity. Mathematical programming models, which are based on simplified assumptions for the system under study, are specific to individual manufacturing enterprises and processes. These models also require a high degree of accuracy in the data used. Experimental research has been concerned primarily with dispatching rules and heuristic procedures that solve the scheduling problems efficiently. Dispatching rules are used primarily to help the production manager on the shop floor to make decisions. A heuristic procedure is a procedure or set of rules that provides a good solution for a limited class of problems [23,24] This solution may or may not be the optimal solution, but can be derived with less computational effort than in optimisation approaches [15]. In short-term scheduling, as opposed to medium-term scheduling that is implemented through MRP systems, dispatching rules are widely used. For example the first-in-first-out (FIFO) rule selects the part which first entered the input/output buffer at/from a machine, as the next part to be serviced. Dispatching rules are employed extensively in discrete event simulation models [25–38].

Simulation models are widely used as powerful tools for scheduling. Simulation is a descriptive modelling technique that is used to evaluate schedules through computer-based experiments. This type of modelling is a bridge to AI approaches. Simulation has proved to be an excellent tool for dynamic scheduling. Dynamic scheduling has been shown to be a non-deterministic polynomial (NP) complete problem [39], where there are a large number of possibilities in which job operations can be sequenced. Therefore, dynamic scheduling does not lend itself to a satisfactory mathematical analytical solution, especially for a complex manufacturing system such as an FMS of a realistic scale. The dynamic nature of such systems demands a scheduling procedure, which is reactive and sensitive to the system's status, instead of a predictive one. It is not yet known whether policies and procedures designed to schedule and control traditional manufacturing processes are appropriate for an FMS, which is an advanced manufacturing technology. Thus, in order to enhance the performance of existing FMSs and to allow for further development of these automated manufacturing systems, proper procedures for the scheduling and control of these automated systems must be developed and documented. Since all the system's data are available and under computer control, more sophisticated procedures can be designed and implemented.

The objective of this paper is to review simulation study on FMSs scheduling rules. We review the simulation of general FMS scheduling studies in Section 2, multi-criteria scheduling approaches in Section 3, and artificial intelligence (AI) approaches in FMSs in Section 4. In almost all cases, the scheduling problems and the employed performance measures of each approach will be mentioned. Section 5 provides conclusions and some suggestions for further research and development. Section 6 gives the acronyms that are used throughout the paper.

2. General FMS Scheduling Studies

2.1 Introduction

Scheduling of FMSs has been one of the most attractive areas of investigation for both researchers and practitioners in the industrial context, and the literature on FMSs is abundant with papers on scheduling. Several review articles were published which synthesise the literature on different phases of FMSs. For example, Spano et al. [15] reviewed the work on the design of FMSs in the areas of facilities design, material handling systems design, control systems design, and scheduling. Rachamadugu and Stecke [12] classified and reviewed the existing FMSs scheduling procedures. Their classification was based on some key factors such as the FMS type, the mode of system operation, the nature of the demands placed on the system, the scheduling environment, and the responsiveness of the system to disturbance. They also discussed the choice of appropriate scheduling criteria.

Basnet and Mize [40] reviewed the literature concerning the operational aspects of FMSs. They described scheduling methodology under six different categories: mathematical programming, multi-criteria decision making, heuristic oriented, control theoretic, simulation, and artificial intelligence. They concluded that the discrete-event simulation technique has the potential to make major contributions to FMS operation and stressed that simulation can be used to model FMSs comprehensively.

Gupta et al. [41] extended the review to cover simulation approaches to the FMS scheduling problems as well as analytical ones. They pursued two objectives:

1. Developing a framework within which the current literature on dispatching rules can be discussed.
2. Comparing the list of dispatching rules and performance criteria from the surveyed literature.

Buzacott and Yao [42] presented a comprehensive review of the analytical models developed for the design and scheduling of FMSs. They strongly advocated analytical methods as giving a better insight into the system performance than simulation models. This point of view was adopted since, most probably, simulation techniques had not been refined up that time. In the 1980s, there was less attention to the use of simulation in manufacturing applications [43], mainly because of the lack of model building expertise. Rahnejat [43] stated that analytical models are not efficient for reasonably sized problems. These models employ simplified assumptions that are not always valid in practice and also take a static view of the shop floor.

2.2 Statistics on Scheduling Problems and Performance Measures

2.2.1 *Scheduling Problems*

Table 1 summarises the scheduling problems that were considered in the papers under this category. Parts dispatching was the most popular scheduling problem and machine selection was the second one. These are long-lasting problems because papers in 2000 were still considering these problems.

Table 1. Scheduling problem in general FMS scheduling studies.

Scheduling problem	Number of publications	Reference number of publications	Period
Parts dispatching	36	[4], [23], [25], [27], [28], [32], [34], [36], [44], [46–50], [50], [52–54], [57–64], [66], [70–77], [79], [80]	1979–2000
Machine selection	8	[4,] [45], [51], [60], [67–69], [81]	1981–2000
AGV scheduling	4	[54], [67–69]	1986–1998
Others	5	[54–56], [66], [76]	1986–1997

2.2.2 Performance Measures

Table 2 summarises performance measures appearing in papers. Flowtime related measures have attracted the most attention, followed by tardiness related measures and utilisation related measures.

2.3 Review of Related Publications

Nof et al. [44] studied the control problem in an FMS. Three rules were considered for part releasing into the empty system, and two rules for part releasing into the loaded system. Two performance measures were employed, which were system utilisation and production rate. Their work showed that the proposed rules have a significant influence on performance measures.

Table 2. Performance measures used in general FMS scheduling studies.

Performance measures	Number of publications	Reference number of publications	Period
Flow-time related	36	[4], [23], [25], [27], [28], [32], [36], [44], [46–48], [50–56], [58–63], [66–69], [71], [73–77] [79], [80]	1979–2000
Tardiness or tardy job related	19	[23], [27], [28], [36], [47–49], [59], [60], [62], [70], [71], [73–75], [77], [79–81]	1983–2000
Utilisation related (including system, machine, station, etc.)	17	[25], [27], [32], [36], [44], [46], [49–52], [54–57], [60], [73], [74]	1979–1995
Cost related	6	[23], [47], [48], [70], [74], [81]	1983–2000
Inventory related	6	[25], [36], [54], [59], [60], [70]	1981–1995
Others	12	[25], [32], [34], [36], [50], [51], [59], [60], [64], [70], [72], [74]	1981–1995

Stecke and Solberg [45] carried out a simulation study of an FMS at the Caterpillar Tractor Company to show the impact of several machine sequencing rules on the performance of the FMS, under different loading objectives. The model contained ten machines with two carts to transport parts. They concluded that scheduling rules have a significant effect on the performance of the FMS and some rules that were known to be superior in a conventional job shop performed poorly in the FMS. They also demonstrated that the set of best-performing scheduling rules varied with the performance measures. Thus, there was no single scheduling rule that outperforms the others for all performance measures.

ElMaraghy [25] developed a general discrete-event FMS simulator. The package was programmed in FORTRAN and was capable of simulating different configurations. Four dispatching rules were employed including SPT, FOPR, FIFO, and RANDOM. Six performance measures, which are station utilisation, production rate and average throughput time for each part type, simulation time, total number of parts produced, and total processing time, were used in this study. The effect of transporter speed and capacity on production rate and station utilisation were discussed. It was concluded that the SPT rule was the best rule, as it resulted in higher production, higher utilisation, shorter throughput time, and less congestion in the system. Neither due-date assignments nor due-date-based measures of performance were employed in the simulation model.

Bell and Bilalis [46] investigated a real FMS consisting of three machines using a digital simulation. Only one decision point was considered in the simulation model. They explored the effect of three dispatching rules (SIO, LIO, and FIFO) on machine utilisation and throughput times. Due-date-based rule and related measure of performance were not considered in their work.

Hoffmann and Scudder [47] investigated the influence of dispatching rules which directly involved costs, on the time-oriented and cost-oriented measures using a simulation model with one decision point. The simulation model used in their study was written in FORTRAN using GASP-IV simulation language. The model consisted of nine machines that were categorised into three classes of processing cost. Eight different priority rules were examined in this study, including four time-oriented rules and four cost-oriented rules. Time-oriented rules consisted of SPT, EDD, MNSTUP, and CR; and cost-oriented rules consisted of MXPROF that selected the most profitable job in the queue, DOLSHP that selected the job having the highest selling price, IPDOL that tried to minimise in-process cost and selected a job with the highest current value, and VALADD that selected a job with the greatest value added in previous operations. Six performance measures were employed to assess the performance of the proposed rules. These are categorised into two groups: three time-measures and three cost-measures. Mean flow-time, average tardiness, and average lateness were time-measures, whereas average work-in-process dollars, average profit in all queues, and average dollars of value added for work waiting to be processed, were cost-measures. They found that SPT minimised average flow-time and mean lateness, CR minimised mean lateness. IPDOL and VALADD minimised mean dollars in process, and MXPROF and DOLSHP dominated the other rules on the measure of average profit in the queue. They did not conclude which rule is, overall, the best one with respect to all performance measures. Scudder and Hoffmann [48] employed the same model to explore the effectiveness of more composite time/cost priority-rules on both time and cost performance measures. The model contained nine workstations, and only one decision point was considered. The due-date of jobs was assigned using TWK policy and thirteen priority scheduling rules were tested in this study. Two of them, SPT and CR, were pure time-oriented rules and another two rules, MXPROF and VALADD, were pure cost-oriented rules. Two rules, which were SPTTRN and MXPRFTRN, were truncated SPT and MXPROF at a maximum of 75 h waiting in the current queue, respectively. The remaining rules, MXPCRT, VLADCRT, VLADRAT, CRRATP, CRRATV, PRF/OPT, and PRF/TOPT, were composite, utilising time and cost information in various ways. Ties were broken in all cases using the SPT rule. Two utilisation levels were tested (80% and 90%), each with five different cases:

1. SPT compared to SPTTRN.
2. MXPROF compared to MXPRFTRN and MXPCRT.
3. VALADD compared to VLADCRT.
4. VLADRATCRRAT compared to CRRATP and CRRATV.
5. PRF/OPT compared to PRF/TOPT.

The only ordinary rule was SPT and the authors did not try to compare the above rules with some other ordinary due-date-based rules such as EDD or SLRO. The same performance measures as in the previous study were used, and the authors concluded that VLADRAT was the best rule over all utilisation levels, but did not mention how they reached this conclusion.

Dar-El and Sarin [49] used a digital simulation consisting of two decision points to study a real FMS with six machines. The effect of two dispatching rules and one heuristic algorithm on machine utilisation and minimum job tardiness were compared. Alternative routeings and part type due dates were investigated. Due-date information was used only for releasing the parts into the system, not for scheduling.

Lin and Lu [50] studied a simulation method, with two decision points, that allowed parts having alternative routes into the system. The impact of various methods of parts entering the system and the scheduling rules on four performance measures were investigated. The performance measures were mean flow-time, mean waiting time, ratio of maximum to minimum average queue length, and machine utilisation variance. To put parts into the system, two heuristic methods were used, one based on balancing workload and the other based on balancing workload plus the minimum number of tardy parts, in addition to EDD and FIFO. Scheduling rules used in the model were WINQ, SPT, and FIFO. WINQ led to a better result for mean flow-time. Although the due-date-based dispatching rule was not employed, one due-dated-based performance measure was examined in the model.

Wilhelm and Shin [51] described a study which investigated the influence that alternative operations might have on the performance of FMSs. Four process selection rules (NA, AP, AND, APD) were evaluated, which can be applied to a loop-type FMS with only an infinite common buffer. A SIMSCRIPT model was developed to evaluate the performance of proposed rules. The system contained four machining centres, a load/unload station, a set of AGVs, and three part types. The performance measures were makespan, system utilisation, utilisation of individual machines, flow-time, maximum spaces required in the common storage, and maximum number of vehicles required. It was concluded that there was no single process selection rule which was superior to the others. The main shortcoming of this work is that only one decision point was used in the model.

Kimemia and Gershwin [52] compared the LIFO rule with their developed algorithm on the system utilisation and production rate, using a simulation model that consisted of two workstations. The question that arises here is why the authors selected only the LIFO rule to compare with the algorithm results.

Chang et al. [53] reported a two-step method for scheduling parts using simulation. The suggested procedure was compared with some dispatching rules including SPT, LPT, FCFS, MWKR, and LWKR. The performance measure for this comparison was mean flow-time. The simulation model consisted of four machines and three parts. One disadvantage of the proposed method was its high computational time which made it unsuitable for a real-time scheduling.

Chan and Pak [23] studied a hypothetical FMS consisting of four machines and one loading/unloading station. They explored the effect of three heuristic dispatching rules on the cost of tardiness, makespan, and average lead time using a digital simulation developed in FORTRAN. The influence of rules was tested in both static and dynamic conditions for a finite plan horizon. In both conditions the developed heuristics were compared with one due-date-based rule (SLACK) and one processing-time-based rule (SIO). They considered alternative operations for parts, but did not use any operation selection rule in their simulation model.

Abdin [54] studied a scheduling problem of a job-shop type FMS with machine breakdown and considered three levels of decision making (decision point), that is, selection of machine tool, selection of transport device, and selection of parts from input buffers. An alternative machine was considered only when the buffer of the original machine was full. The FMS was modelled by a discrete-event simulation using SLAM II. The model consisted of one loading/unloading station, four multi-purpose CNC machines, and two carts. The SPT rule was the only dispatching rule used to select a part from the input buffer. The SDS rule determined which transport device to select if some were available. Five performance measures were employed consisting of machine utilisation, WIP, system throughput, mean flow-time, and makespan. The author found that schedules with alternative machine tools were better than schedules without alternative machine tools, and concluded that FMSs without alternative machine tools resemble transfer line systems. No effort had been made to combine the scheduling rules and apply them to the three decision points.

Schriber and Stecke [55] provided a simulation study of an FMS that investigated the effect of various modellings. They demonstrated successfully the validity of the theoretical results and tested the sensitivity of parameters such as the number of AGVs, the number of buffers, and the level of WIP. They used SPT as a dispatching rule, and two major performance measures were machine utilisation and production rate. Schriber and Stecke [56] further extended their previous study and provided a comparison of FIFO and SPT scheduling rules, but they did not extend the number of performance measures.

Denzler and Boe [57] used simulation to study a dedicated FMS by using actual data of routeing and operation times. The model was comprised of 16 CNC machines and pallet loading for the investigation of part-dispatching rules. The influence of the number of pallets and different scheduling rules on machine utilisation was demonstrated, which was the only performance measure used in the model. Results indicated that FMS performance was significantly affected by the choice of scheduling rules.

Co et al. [58] investigated the influence of queue length on five sequencing rules, which were FCFS, SPT, LWKR, TWK, and NXQL. A computer simulation model was developed to evaluate the performance of the alternative sequencing rules listed above, under various system configurations. The simulation model was written in SIMAN and contained n part types and m single server stations. Each part type followed a fixed routeing sequence, which defined the number of operations required to complete each job, the sequence of machines to visit, and the related processing times. The only performance measure reported was mean flow-time. The authors confirmed that the influence of the sequencing rules on the performance of the system, even in the case of short queue length, should not be ignored. No due-date-based rules and related performance measures were used in the simulation model.

Chryssolouris et al. [59] compared the system performance of a manufacturing system with different dispatching rules using a simulation model with only one decision point. Four dispatching rules and four performance measures were employed. The performance measures included mean flow-time, number of task orders completed, average WIP, and mean tardiness. They did not conclude which rule dominated the others for all performance measures.

Choi and Malstrom [60] described the use of a simulator to evaluate work scheduling rules in an FMS. An FMS was modelled using actual data. The model consisted of a miniature closed-loop system with eight NC machines, five robots, one washing station, and I/O queues. The combinations of seven part selection rules with four machine centre selection rules were investigated. Part selection rules were RANDOM, FSFS, EDD, SPT, SLACK, S/PT, and VALUE. Machine selection rules were RANDOM, FMFS, NINQ, and WINQ. Scheduling rules were evaluated using the following performance measures: actual and relative system effectivity, total and average travelling time, actual production output, achievement rate, total and average manufacturing throughput time, total and average waiting time, imminent operation work content, and total and average production lateness. The authors concluded that the SLACK/WINQ and SPT/WINQ scheduling rules dominated the other major decision rules for the due-date- and flow-time-based criteria.

Slomp and Gaalman [61] proposed three scheduling procedures. All procedures executed four functions, but the sequences of execution were different. The first function scheduled workstations and used the earliest possible moment rule. The second function scheduled transport devices and used the earliest moment rule and, in the case of a tie, the least moving time was used. The third one scheduled operators and used the earliest moment rule and, in the case of a tie, the operator who needed the least walking time was chosen. The last function scheduled operations and employed four dispatching rules consisting of SPT, SPT.TOT, SPT/TOT, and EFTA. The simulation model of a case study was used including two workstations, one loading station, and one unloading station. There was one input buffer with a capacity of two jobs in front of each workstation. Only two performance measures, makespan per part and mean flow-time, were used in the model. In addition to the case study, several simulation tests were carried out to demonstrate the behaviour of the procedures developed. In each simulation, scheduling started with an empty system, but the author did not mention how the initial bias (i.e. the transient state) of the results was eliminated. Results showed that the EFTA rule performed worse than SPT/TOT regarding both measures of performance. The main shortcoming is that due dates were completely ignored in this model.

Montazeri and Van Wassenhove [32] stressed the need for simulation prior to setting up the FMS. The characteristics of a general-purpose, user-oriented discrete-event simulation for FMS were discussed. Following a brief review of the literature on scheduling rules, they analysed the performance of 14 dispatching rules using the developed simulation model to mimic the operation of a real-life FMS. They studied SIO, SPT, SRPT, LRPT, SMT, LDT, FRO, LIO, LPT, SDT, LMT, MRO, FIFO, and FASFO scheduling rules in a simulation model consisting of five machine centres and three loading/unloading stations, and one WIP buffer with 11 positions. The criteria chosen for evaluating scheduling rules were average and variance of waiting time per part, average and variance of machine utilisation, average buffer utilisation, average shuttle utilisation, average carrier utilisation, and makespan. Four decision points were used in the model including select next part to be processed by the machine, select next part to be moved in the system, select next part to be reclamped by the worker, and select next part to be loaded on the carrier from the facility. All decision points were assigned the same priority rule in every run. The authors confirmed that a combination of a time-based rule like SMT and a due-date-based rule like SLACK merits further research. However, they did not conclude which rule is the best regarding all performance measures.

Kim [62] studied a manufacturing system in which alternative operations were considered. The author tested four different methods to define the precedence relationships. Dispatching rules considered in this study included SPT, Slack, S/RMOP, S/RMWK, MDD, MOD, COVERT, and ACT. Only three performance measures were used, i.e. mean flow-time, mean tardiness, and number of tardy jobs. The author concluded that the MDD rule outperformed all other rules. However, the results showed that the MDD rule did not perform well under one specific precedence method mentioned above.

Hutchison and Khumavala [63] compared seven real-time and two off-line scheduling schemes for a random FMS with a dynamic environment. Results indicated that full advantage could be taken of these flexible systems if off-line schemes were applied. The study was conducted in two phases. The first phase compared the two off-line scheduling schemes using 100 randomly generated static test problems to determine the deterioration in performance that would result from decomposing the problem. The second phase compared the decomposed off-line scheme against the seven real-time scheduling schemes using simulation. The scheduling rules for the second phase included SPT, LWKR, MOPR, SPT/TOT, MWKR, LOPR, and LPT. Only two performance measures were employed, namely, average flow-time, and adjusted production rate that was similar to makespan. They concluded that SPT was the best real-time scheduling rule for the adjusted production rate, and the MWKR rule was the best rule for the average flow-time. However, only processing-number and time-oriented-based rules and performance measures were used and no due-date information was employed in the model.

Ishii and Talavage [64] proposed a transient-based algorithm for determining the length of the simulation window. This algorithm defined a short-term scheduling interval based on the system's transient state that was evaluated by a measure similar to the workload in the FMS. As opposed to the Wu and Wysk [65] approach, which is explained in Section 4.3, the size of the scheduling interval was considered as a variable in the Ishii and Talavage [64] approach. The achievements are similar to those of Wu and Wysk [65] work.

Hutchison et al. [66] strongly advocated the use of off-line scheduling rather than real-time scheduling. The influences of scheduling schemes and the degree of routeing flexibility on random job shop FMS in a static environment were investigated. Three schemes were tested, which include two off-line and one real-time under different routeing flexibility. In the third scheme, they used a dispatching rule, SPT, coupled with a look-ahead policy to establish a schedule in a real-time mode. The SPT rule was used as a queue dispatching rule, and also to determine when parts were released into the system. The only performance measure was makespan. The results showed that the real-time scheme had an average makespan of 34.40% larger than the first off-line scheme, and 30.83% larger then the second off-line scheme. These differences became larger when the routeing flexibility increased. They did not mention why they did not use more performance measures or why they did not test off-line schemes with more dispatching rules.

Sabuncuoglu and Hommertzheim [67,68] studied the problems of scheduling machines and AGVs using an FMS simulation model in a single criterion environment. The influences of machine and AGV scheduling rules on the mean flow-time criterion were investigated. Machine scheduling rules were SPT.TOT, SPT/TOT, LPT.TOT, LPT/TOT, LWKR, MWKR, FOPR, MOPR, FCFS, FAFS, and RANDOM. AGV scheduling rules were FCFS, LOQS, STD, LQS, MWKR, and FOPR. The FMS consisted of six machine centres with limited input buffers, one inspection station, one washing centre, one loading, and one unloading station. Two AGVs were employed to transport parts through the system. The FMS was modelled using the SIMAN discrete simulation language and animated in CINEMA. The scheduling rules were tested with three factors, i.e. different utilisation levels, different queue capacities, and different AGV speeds. The results indicated that scheduling AGVs was as important as scheduling machines. The due-date of parts was not considered in the simulation model, and consequently no due-date-based rule or measure of performance was employed. Sabuncuoglu [69] then extended the studies under new experimental conditions. The same FMS was employed, but the objective was to measure the sensitivity of the rules to changes in processing time distributions, various levels of breakdown rates, and types of AGV priority scheme. Although similar results were obtained to those of the previous work [67,68], Sabuncuoglu concluded that scheduling of material handling systems is as important as the machining subsystem.

O'Keefe and Kasirajan [4] investigated the interaction between nine dispatching rules and four next station selection rules in a relatively large dedicated FMS with a simulation model using the RENSAM package. The FMS was modelled with constant operation times and no machine breakdowns or AGV failures. The model contained 16 workstations with local buffers, nine load/unload stations, three AGVs, and six part types. Dispatching rules used in the model were FIFO, SIO, LIO, FRO, MRO, SIO/TOT, LIO/TOT, SLACK, and SIO^x. Next station selection rules consisted of NS, WINQ, NINQ, and LUS. The only performance measure was weighted flow-time. The smallest value of weighted flow-time they found was related to SIO/TOT combined with WINQ. The best next station selection rule was WINQ and the worst was LUS. The main shortcoming of this study was its single criterion environment. Although due-date had been considered and two due-date-based rules were applied, no due-date-based performance was measured.

Rohleder and Scudder [70] made a simulation model, with only one decision point, to investigate the influence of ten scheduling rules on the net present value (NPV) in a JIT production system. Scheduling rules were OPCR, ODD, OPSLK, CR, EDD, MOD, TSLK, MDD, SPT, and LWKR. Performance measures were mean system inventory, NPV, mean tardiness, percentage of tardy jobs, average starting time of operations, number of jobs in process (WIP), number of jobs finished but not shipped (NFGS), and average total jobs in system (WIP + NFGS). Due-date of jobs was assigned using TWK. The model was run with three due-date tightness ($K = 3$, 6, and 9). The results showed that different scheduling rules had different influences on performance measures. For example, job-based allowance rules dominated the mean system inventory.

Rachamadugu et al. [71] studied the influence of sequencing flexibility on the performance of rules used, to schedule operations in manufacturing systems, using a simulation model consisting of ten machines. The performance of ten scheduling rules was examined including FIQ, FIS, SPT, EDD, MDD, CR, EODD, MODD, OCR, and MSUC. The performance measures were mean flow-time, average tardiness, and proportion of tardy jobs. The results showed that the performances of all rules were improved, while levels of sequencing flexibility were increased. It was demonstrated that the performance differences between the scheduling rules diminished significantly at high flexibility levels.

Kannan and Ghosh [28] described three new truncation procedures, along with two existing ones, which truncated jobs based on their critical ratio, operation slack, and change in queue rank. Their simulation model consisted of ten machines. In addition to the above five truncation procedures, four dispatching rules were used to dispatch the truncated jobs in the priority queue. Dispatching rules applied were SPT, FCFS, MSLK, and MODD. The performance measures of this study were mean flow-time, mean tardiness, standard deviations of flow-time, and tardiness. The authors concluded that the performance of the SPT rule could be improved using truncation procedures and the selection of the truncated rule was dependent on the selected performance measure.

Linn and Xie [72] investigated the influence of job sequencing rules on delivery performance of an automated storage/retrieval system base on simulation modelling. They also examined the interaction of the sequencing rules with other control variables such as production load level, product mix, and delivery due time estimate. The simulation model was written in GPSS/H and FORTARN and the sequencing rules were FCFS, SDDT-F, and SDDT-L.

Gyampah [73] evaluated the part type selection procedures for different tool allocation approaches. Three tool allocation approaches, three production scheduling rules, and three levels of part mix were assessed using a simulation model of an FMS coded in SLAM II. Three tool allocation approaches were batching, flexible tooling, and resident tooling. The part type selection rules were LNT, SNT, and EDD. Performance measures in this study consisted of mean flow-time, mean tardiness, percentage of orders tardy, machine utilisation, and robot utilisation.

Sarper [34] examined two criteria against four dispatching rules under three system utilisation levels and five due-date assignment levels. Criteria used in the paper were MAL and MXAL, and dispatching rules were MDD, SPT, EDD, and FIFO. The results showed that the MDD rule was the best one to minimise MAL. When MAXL was considered as a criterion, the Sarper did not conclude which rule dominated the others. In effect, there was no single rule that led to the best result for all system utilisation levels and for all due-date tightness.

Kim and Bobrowski [74] used simulation to investigate the job-shop scheduling problems and tested the scheduling rules. A simulation model, with only one decision point, was developed using SLAM II which consisted of nine machines. Scheduling rules were CR, SIMSET, JCR, and SPT. The performance measures were set-up related measures, due-date related measures, flow-time related measures, shop utilisation, and cost measures. The model was run for two levels of due-date tightness. They did not conclude from simulation results which rule was the best overall.

Tang et al. [36] proposed a framework for a two-phase model of planning and scheduling. The planning phase was involved with part type and tool assignment in which a linear integer programming was used. In the scheduling phase, decisions were made at six decision points and various dispatching rules were evaluated using a simulation model. The model consisted of ten part types, 12 tool types, and five machine centres. Two AGVs were assigned for transporting parts among machines and between load/unload stations and machines. There were six decision points in the model including AGVs selection by parts, routeings selection, parts selection by machines at input buffers, next operation selection by parts at output buffer, parts selection by AGVs, and AGV destination selection. Decision rules used at each decision point mentioned above were as follows:

1. SDS, RAN, CYC, and FCFS.
2. SDM, SFTAO, and FWJM.
3. SPT, FCFS, and SRPT.
4. LST, SPT, and CGO.
5. SPT, SRPT, and SRCS.
6. WFFS, WLAS, and WFLUS.

The scheduling model was implemented in a SIMAN simulation program and the dispatching rules were coded in FORTRAN. Seven performance measures (flow-time, total completed parts, number of tardy jobs, average WIP, maximum number of jig/fixture, machine utilisation, and AGV utilisation), under three separate algorithms were employed to evaluate the scheduling rules. Algorithm 1 used a look-ahead approach, algorithm 2 used the rules found to be effective from previous studies [35], and algorithm 3 used simple rules at each decision point. Tang et al. found that the look-ahead approach outperformed the other approaches for flow-time and number of tardy parts. They did not conclude which combination of scheduling rules was the best one overall.

Goyal et al. [27] investigated the effect of various scheduling rules applied to two decision points, i.e. selection of jobs to enter to the system (loading), and selection of jobs to be processed by the machine (dispatching). Seven scheduling rules and four performance measures (average workstation utilisation, average buffer utilisation, average throughput, and average lateness) were employed to determine the most effective production schedule for an FMS. However, results indicated that the best combination of rules for each performance measure was different.

Selladurai et al. [75] developed, in the “C” language, a visual interactive computer graphics simulation software for analysing dynamic scheduling of an FMS. The FMS consisted of a load/unload station and eight machines with equal capacity. A local buffer was presented in front of each machining centre. Dispatching rules being analysed were SPT, LPT, EDD, SIO, SLACK, and SLACK/LRO. Performances of each rule on average flow-time, average tardiness, and number of late jobs were reported, but only the average flow-time was considered as the major performance criterion, and the authors concluded that SIO was an optimal scheduling rule for the system.

Caprihan and Wadhwa [76] studied the impact of the routeing flexibility of an FMS. The FMS, which was modelled by SIMAN IV simulation language with user written C code, consisted of six machines, one load station, and one unload station. Four factors, which were routeing flexibility, number of pallets, dispatching rule, and sequencing rule, were considered. Makespan was the only performance measure employed. They used Taguchi's experimental design framework to gain quick insights into the behaviour of the four factors within the FMS environments. However, they concluded that routeing flexibility should not be taken for granted as a direction for performance improvement.

Holthhaus and Ziegler [77] presented a new coordination scheduling approach, which was analysed using a simulation model consisting of 256 machines and only one decision point. Four local dispatching rules, i.e. FIFO, SPT, MOD, and S/OPN, and two global rules, i.e. NINQ and COVERT, were used in the model. In the new approach, a look-ahead policy, namely look-ahead job demanding (LAJD), was used to schedule the jobs of each machine, say machine m, based on look-ahead information introduced by Itoh et al. [78]. LAJD considered not only the state of a given machine, but also the states of all machines which preceded machine m. Whenever there was the risk of running idle for one or more of the machines, LAJD was activated in conjunction with one of the above-mentioned traditional rules. For a specific machine, the risk of running idle was measured by the run-out time of the current total-work-content (i.e. the remaining processing time of the waiting-for-processing jobs and the currently processing job). LAJD was not activated when the work-content was high. They tested the developed procedure on five performance measures, that is, mean flow-time, maximum flow-time, percentage of tardy jobs, mean tardiness, and maximum tardiness. Although the results showed that the look-ahead policy outperformed all traditional rules, there was no single combination of LAJD and a traditional rule outperforming all other combinations. They did not conclude which combination was the best one overall.

Mahmoodi et al. [79] examined the effects of a new combination scheduling rule on the performance of a random FMS and compared it with three existing rules, which were SPT, SI^x, and SPT/TOT. The new rule was CR-SPT which calculated the critical ratio, which was due date minus the current time, divided by the estimated remaining processing time. They attempted to use this rule to compensate for SPT's shortcomings considering part due dates. The FMS was written in the SIMAN simulation language. The system consisted of three machine types, eight machines, three load/unload stations, 16 AGVs, an infinite central WIP buffer, a transfer station, and a computer-controlled network. Performance measures were average flow-time, average percentage tardy, and average tardiness. Results showed that CR-SPT did not perform the best when compared with the other rules. It was the poorest rule with respect to average flow-time.

Jayamohan and Rajendran [80] analysed two different approaches for scheduling flexible flow shops. The two approaches were:

1. Use of different dispatching rules at different stages of the flow shop.
2. Use of the same dispatching rules at all the stages of the flow shop.

The model under evaluation had three work centres, and each work centre consisted of two machines. Performance measures were mean flow-time, maximum flow-time, variance of flow-time, mean tardiness, maximum tardiness, variance of tardiness, and percentage of tardy jobs. Scheduling rules used at different stages were SPT, ATC, RR, MOD, COVERT, PT (process time) + WINQ (work in next queue) + SL (slack), PT + WINQ + AT (arrival time), PT + WINQ + SL + AT, SPT then EDD then SPT, and SPT then SPT then EDD. Jayamohan and Rajendran concluded that the use of various simple rules at different stages of manufacturing systems might not always be good. They advocated the use of single dispatching rules, especially those incorporating the both process time and due date, at every stage of the system.

Subramaniam et al. [81] proposed three machine selection rules, namely LAC, LAP, and LACP, in a dynamic job shop. The proposed rules were applied together with four common dispatching rules, which were RAN, FIFO, EDD, and SPT. The effectiveness of the new rules was evaluated through a simulation study. The system under consideration consisted of three machines. Mean operational cost and mean tardiness were employed as the performance measures. Results showed that LAC and LAP rules performed well for the mean cost and mean tardiness, respectively. The authors concluded that the use of the machine selection rules significantly improved the scheduling performance of dispatching rules.

3. Multi-Criteria Scheduling Approaches

3.1 Introduction

Because of rapid change in demand, FMSs are working with different orders, each of which aims at some criteria. Therefore, operating an FMS is, in fact, a multiple criteria activity. Some authors employed these criteria in their modelling. For example, Lee and Jung [82] developed a formulation for part selection and allocation using goal programming (the basic concept of goal programming involves incorporating all goals into a single model). Their model considered the goal of meeting production requirements, balancing of machine utilisation, and minimisation of throughput time of parts. This kind of goal programming could be used by decision-makers to satisfy their goals and their prioritisation. Two shortcomings of this kind of modelling are that information on the dynamic working of an FMS cannot be provided and the effect of the waiting times on the system performance cannot be taken into account. The greatest disadvantage of this sort of programming is that it is computationally costly and is expensive in practice.

3.2 Statistics on Scheduling Problems and Performance Measures

3.2.1 Scheduling Problems

Table 3 shows the distribution of scheduling problems that are involved under this category. As for the general FMS scheduling studies, the parts dispatching was a popular item, which attracted the attention of many authors.

3.2.2 Performance Measures

Both flow-time and tardiness related measures were employed most frequently as the performance measures. This is shown in Table 4.

Table 3. Scheduling problem in multi-criteria scheduling approaches.

Scheduling problem	Number of publications	Reference number of publications	Period
Parts dispatching	8	[59], [83], [85–89], [91]	1985–1999
Machine selection	1	[84]	1990
AGV scheduling	3	[84], [88], [90]	1990–1996

Table 4. Performance measures used in multi-criteria approaches.

Performance measures	Number of publications	Reference number of publications	Period
Flow-time related	5	[59], [84], [86], [88], [90]	1988–1996
Tardiness or tardy job related	5	[59], [84], [86], [87], [91]	1988–1999
Utilisation related (including system, machine, station, etc.)	3	[83], [84], [87]	1985–1994
Cost related	2	[87], [91]	1994 and 1999
Inventory related	1	[59]	1988
Others	4	[59], [83], [87], [90]	1985–1996

3.3 Review of Related Publications

Shanker and Tzen [83] found that random FMSs require balanced workloads to operate effectively. They studied a scheduling problem in an FMS that was considered to be a composite of two independent tasks: loading and sequencing. Formulations were presented for the loading problem with two objectives:

1. Minimisation of the system workload unbalance.
2. Minimisation of the system unbalance and the number of late jobs.

For both objectives, heuristic methods were developed and the system performance was compared with exact mixed integer programming solutions. A simulation model using GPSS V was also developed to determine the system performance and influence of loading policies on dispatching rules employed to sequence the jobs. Only one of the proposed loading procedures was compared with the FCFS rule and another one was not used in the simulation model. The model consisted of four machines, and parts entered into the system in batches of 5 to 15. Due dates of parts were assigned using the TWK policy. Performance measures were CPU time and machine utilisation. The dispatching rules used in the simulation model were FIFO, SPT, LPT, and MOPR. Shanker and Tzen reported that the SPT rule performed the best on average. Although due dates were assigned to the incoming parts, no due-date-based dispatching rules or measures of performance were used in the model. It is unclear why the authors considered due dates for parts.

Chryssolouris et al. [59] tested a modular system that treated a production scheduling problem as a multi-criteria decision-making issue using a simulation model. The developed method attempted to model the decision-making process, at the work centre level, as a multi-criteria decision problem. The simulation model consisted of two different work centre configurations (i.e. one work centre, and five work centres) and compared the rule-based method with four dispatching rules, which were LCFS, FCFS, SPT, and LPT. The employed performance measures were average flow-time, WIP, number of jobs completed, and mean tardiness. The results showed that for one work centre, the SPT rule performed well, and in the case of five work centres, the rule outperformed all other dispatching rules.

Ro and Kim [84] considered the FMS scheduling problem as a process of two loading and four dispatching subproblems. A hypothetical FMS was composed of four CNC machining centres, each of which had a finite buffer space, a load/unload station, and two AGVs. Two loading subproblems were stated as follows:

1. Part type selection during initial entry (the EDD rule was used for the simulation experiments as a part type selection rule during initial entry).
2. Part type selection during general entry (the part having the highest ratio of remaining requirement to their original requirement would be selected first).

Four dispatching subproblems were stated as follows:

1. Part-to-machine allocation rule (the SPT rule was used for the simulation experiments as a part-to-machine selection rule).
2. Process or machine centre selection rule (ARD, ARP, ARPD, NAR, and WINQ rules were used as process selection rule).
3. AGV dispatching rule (a heuristic rule was used to select a free AGV).
4. AGV route selection rule (a bi-directional guide path was used).

Ro and Kim proposed three process selection rules for evaluation. The performance of these rules was then compared with WINQ and NAR rules. The developed rules assumed that a number of alternative machines were available when an unexpected event, such as machine breakdown, ccurred and thus, tried to take advantage of the inherent routeing flexibility of FMSs. The performance of developed rules was evaluated by building a simulation model of the FMS using SLAM II and FORTRAN. The model consisted of four CNC machines with a finite buffer space for each one. The simulation results indicated that, first, the ARD led to the best result in four performance measures except for system utilisation. Secondly, ARD, ARPD, and WINQ produced significantly better results than ARP and NAR in every performance measure. The authors demonstrated the effectiveness of the proposed rules for multiple performance measures including makespan, mean flow time, mean tardiness, maximum tardiness, and system utilisation.

Gupta et al. [85] explored the applicability of multi-criteria approaches to the production scheduling problems of an FMS, and reviewed the pertinent literature on scheduling of FMS involving multiple objectives, and discussed:

1. FMS scheduling problems within the context of a general decision-making process.
2. An overview of multi-criteria decision-making approaches and its feasibility to FMS scheduling problems.
3. The literature of FMS scheduling involving multiple objectives.
4. The major findings.

Ishii and Talavage [86] demonstrated a mixed dispatching rule (MDR) approach, in contrast to a single dispatching rule (SDR) approach, for assigning different dispatching rules to FMS machines, which considered one decision point only. The developed approach proposed different dispatching rules for different machines. In addition, a search algorithm that selected appropriate mixed dispatching rules using predictions based on discrete-event simulation, was developed for this approach. The effectiveness of the mixed dispatching rule and the efficiency of the search algorithm relative to an exhaustive search were shown using an FMS. It was reported that it was up to 15.9% better than the conventional approach, and 4% better on average. The best combination of dispatching rules that they found were NINQ, SPT, SLACK, and FIFO. The system performances were based on mean flow-time, mean tardiness, weighted mean flow-time, weighted mean tardiness, and combinations of them. The FMS example was modelled using SLAM II.

Yang and Sum [87] selected total cost as a better overall measure of satisfying a set of different performance measures. A penalty was applied to both early and tardy jobs. A simulation model using SLAM II was employed to examine the cost performance of various dispatching rules. The total cost and its cost components were reported as the costs incurred per simulated year. Dispatching rules were SPT, SWPT, CR, CRTC, WCRTC, and VLADRAT. Dispatching rules were investigated under several environmental factors including machine utilisation (low and high), due-date allowance (loose and tight), tardiness penalty rate (low and high), and interest rate and cost rate for holding inventory (low and high). Only one decision point was considered in the simulation model.

Maheshwari and Khator [88] demonstrated that machine loading and control strategies, buffer size, number of pallets, etc., could be evaluated simultaneously. Several issues were stated as follows:

In which sequence should the parts be launched into the system?

What priority should be assigned to the parts at the machining centre?

What priority should be assigned to the parts for transportation?

What dispatching rules should be adopted for material handling vehicles?

For a machine-loading model, an integer programming was used to determine part assignment and tool allocation with material handling considerations. Four objectives were used as a loading strategy including minimisation of operational cost, minimisation of operational time, balancing of machines, and minimisation of the sum of penalty and operational cost. A discrete-event simulation model was used for the control level. The model was developed using SIMAN and consisted of four workstations, one load/unload station, one staging area, and two AGVs to transport the parts between machines. Part releasing rules consisted of LPR, LNV, and STPT RAN. Dispatching rules applied at the input buffer were SPT, SRPT, SPT/TPT, and FIFO. Vehicle dispatching rules were MWIQ, MRV, MRQS, and FIFO. As a result, Maheshwari and Khator considered one loading and three control decision points, and two other parameters considered were buffer size and number of pallets. Two performance measures were used, e.g. makespan and mean flow-time. It was concluded that when makespan was considered, a combination of LPR, MWIQ, SPT/TPT, five buffer spaces, and ten pallets worked best. When considering mean flow-time, a combination of LPR, MWIQ (or FIFO), SPT/TPT, three buffer spaces, and six pallets, outperformed the others. When both performance measures were considered, the combination of LPR, MWIQ, SPT/TPT, four buffer spaces, and eight pallets was best. Machine workload balancing strategy outperformed the other three loading strategies for both performance measures. They did not mention what procedure was used to arrive at such a conclusion. No due-date-based rule or performance measure was used in the model.

Frazier [89] investigated the effect of one-stage and two-stage scheduling rules on different performance measures in a cellular manufacturing system. Fourteen scheduling rules and eight performance measures were used in the study. The simulation model was developed in SLAMII with FORTRAN subroutines incorporated, and represented a production cell with six machines with separate queues for each part family. Two decision points were employed: the first one was switching between queues of part families or selecting the next part family queue, and the second one was selecting jobs in each part family queue. It was concluded that the MJ/SPT rule was ranked the best when all performance measures were considered. The main shortcoming was that all performance measures were considered to be of the same importance.

Klein and Kim [90] demonstrated how a multi-attribute decision-making method could be used for dispatching a vehicle. Using simulation models, the characteristics of decision rules for dispatching AGVs were shown. Single-attribute dispatching rules consisted of LWT, STT/D, and MQS; and multi-attribute dispatching rules consisted of SAWM, YAGER, MMM, and MAWM methods. Performance measures considered include average and maximum waiting time of a unit load in the output buffer, average and maximum queue length of the output buffer, job completion time, and total travel time of empty vehicles. However, no due-date-based performance measure was considered. The simulation model was tested for one, two, and three AGVs. Results showed that multi-attribute dispatching rules outperformed the single-attribute ones.

Tung et al. [91] presented a hierarchical approach to scheduling FMSs with multiple performance objectives. The FMS consisted of a shop controller, a multiple-task sequencing controller with several AGVs, four CNC machines, one robot, an input buffer, an output buffer, and an inner buffer for storing parts. The scheduling problem was solved at two levels: the shop level, and the manufacturing system level. The shop level controller employed a combined priority index to rank shop production orders for meeting scheduling objectives. The FMS controller provided feedback to the shop controller with a set of suggested detailed schedules and projected order completion times. The shop controller then evaluated each candidate schedule using a multiple-objective function and selected the best schedule for execution. The proposed method was compared with SPT and EDD rules on four specific performance objectives, which were maximise profit, meet due dates, minimise the WIP inventory cost, and minimise finished-good inventory cost. Results indicated that the proposed scheduling method outperformed the two traditional scheduling rules. However, Tung et al. concluded that no single rule was universally the best.

4. Review of AI Scheduling Approaches

4.1 Introduction

In a production system, the scheduling problem is to synchronise resources (connected by material transport system), and material flow, to produce a variety of parts in a certain period of time. Scheduling rules are used to select the next part to be processed from a set of parts awaiting service. These rules can also be used to introduce workpieces into the system, to route parts in the system, and to assign parts to facilities such as workstations and AGVs. Some constraints also have to be considered such as:

The schedule has to satisfy one or more system objectives, such as minimisation of mean flowtime or/and mean tardiness.

Buffer sizes are limited.

Number of transporters are limited, etc.

Because of the complexity of the system, it is not very useful to find an optimal solution in an industrial context since changes often occur rapidly (for example, arrival of new parts or modification of previous priority queue size of resources, and so on). Therefore, it is not desirable or economical when designing an optimal scheduler, but rather developing a flexible scheduling tool to assist the operator to monitor the system and make decisions. In fact, some operations can be replaced with an automatic scheduler tool. The developed tool has to be easy to use, and react to changes in real-time. Consequently, it has to be expressed in terms of parameters that have to be chosen in accordance with the system objectives, which depend on the production situation. In the complex environment of an FMS, proper expertise and experience are needed for decision making. Artificial intelligence, together with simulation modelling can help to imitate human expertise to schedule manufacturing systems [92]. ElMaraghy and Ravi [26] reviewed some applications of knowledge-based simulation systems in the domain of FMSs, and also discussed their potential for the development of new, powerful and intelligent simulation environments for modelling and evaluating FMSs. Grabot and Geneste [93] stated that workshop management is a multi-criteria problem and proposed a way to use fuzzy logic in order to build aggregated rules and obtain a compromise between the satisfaction of several criteria.

Table 5. Scheduling problem in AI scheduling approaches.

Scheduling problem	Number of publications	Reference number of publications	Period
Parts dispatching	16	[65], [92], [95–98], [100], [101], [103], [106–110], [112], [113]	1987–2000
Machine selection	3	[97], [99], [105]	1989–1997
AGV scheduling	3	[104], [105], [111]	1996–1999

4.2 Statistics on Scheduling Problems and Methodologies

4.2.1 Scheduling Problems

Table 5 showed the scheduling problems found in this category. Parts dispatching was the most popular scheduling problem for research. This result is consistent with the one found in general FMS scheduling studies and multi-criteria approaches.

4.2.2 Methodologies

Table 6 summarised the AI scheduling methodologies that were used in the reported research in this section. A fuzzy approach and an expert system were the most frequently employed methods. However, expert systems have not been investigated since 1994. Other fields, such as generic algorithms and neural networks, are potential research areas.

4.3 Review of Related Publications

Karwowski and Evans [94] illustrated the potential applications of fuzzy methodologies to various areas of production management, including new product development, facilities planning, human product management, production scheduling, and inventory control.

Table 6. Methodologies in AI scheduling approaches.

Methodologies	Number of publications	Reference number of publications	Period
Fuzzy	7	[94], [97], [98], [101], [104], [105], [112]	1986–1999
Expert system	5	[65], [95], [96], [99], [102]	1987–1994
Generic algorithm	3	[106], [107], [113]	1997–2000
Neural network	4	[103], [109–111]	1995–1999
Others	3	[92], [100], [108]	1992–1998

Schnur [95] discussed the use of "what if" analysis as a decision support tool for manufacturing systems. The application of simulation in the decision-making process by managers, using artificially intelligent knowledge-based expert systems, was discussed as well. However, the application of artificial intelligence in the dispatching of parts was not demonstrated.

Wu and Wysk [65,96] described a multi-pass real-time scheduling algorithm, in which discrete simulation in combination with an expert system and straightforward part dispatching rules in a dynamic fashion, was employed. The algorithm used a constant short time window for each scheduling interval. The logic of the algorithm was as follows. A dispatching rule that performed the best, according to the selected performance criteria, was applied in successive short-term scheduling intervals. A learning module in the expert system learnt from previous decisions and then generated the candidate set based on the current shop floor status. A simulation model was constructed according to the collected data. A series of simulation runs were carried out starting from the current state using each of the candidate dispatching rules for the next short planning horizon (Δt) introduced by the user. The rule that had the best-simulated performance in the time period was used to generate a series of commands to the real-time control system of the FMS. The evaluation/application process was then carried on repeatedly, based on a relatively short time frame. As a result of this process, a continual alternating of different dispatching rules would be carried out automatically (for example, in time period one, SPT was selected; in time period two, WINQ was selected; in time period three, FIFO rule was selected, etc.). Consequently, in the long run, this process resulted in a combination of different dispatching rules based on their performance in each short time period. The use of different dispatching rules at different times was designed to overcome the weakness of any single rule. It was reported that an improvement of 2.3% to 29.30% was achieved under three different simulation windows ($=\Delta t$) and measures of performance. However, Wu and Wysk did not consider any alternative routeings or operations, nor AGVs dispatching rules.

Hintz and Zimmermann [97] developed a simulation model for the purpose of a multi-objective study. They proposed a fuzzy linear programming model to provide a master schedule. For the parts release scheduling and machine scheduling, a multi-criteria decision-making approach using a knowledge-based machine was developed. The simulation model consisted of several workstations, tooling, transportation and storage facilities, pallets, and fixture units. The decision of the knowledge-based machine scheduling was compared with some priority rules. The comparison showed that the knowledge-based system outperformed the priority rules.

Watanabe [98] developed a new algorithm using fuzzy logic to determine the priority of parts in computer integrated manufacturing systems for producing many kinds of products in small volumes. The author believed that some customers require short due dates and do not mind paying high costs, whereas some do not mind the lateness of due dates. In this connection, the quickness (how fast a part should be produced) requirements and the profit of production indices were studied. In addition, priority of a part in a queue was determined by two fuzzy rules:

1. If "the slack time is short" and "the profit index is high", then "the priority of the job is high".
2. If "the slack time is long" and "the profit index is low", then "the priority of the job is low".

The fuzzy propositions "slack time is short or high", "profit index is high or low", and "priority is high or low", were defined by membership functions. The results of the constructed simulation model showed that profit was significantly improved by using the proposed method in comparison with the SLACK rule, flow-time was increased by 20% but no other performance measure was used. Watanabe did not compare the efficiency of the proposed method with some other dispatching rules, such as SPT, and no transportation and alternative routeings were considered.

Chandra and Talavage [99] proposed an intelligent dispatching rule called EXPERT using an expert system. They conducted a simulation model using the RUNSHOP program to demonstrate the effectiveness of the proposed rule. The system contained ten machines with one general queue. A part, upon completion of an operation, was not routed to a specific machine, but rather was sent to the general queue. Thus, a machine had a global option to select parts which, in turn, might be processed on alternative machines. When a machine became idle and a loading decision was required, RUNSHOP called a subroutine, which updated all status variables required for intelligent reasoning to select a job for the idle machine. Selection of the job depended on the current objective that could be either maximising work progress rate or minimising the number of tardy jobs. The effectiveness of the proposed rule was compared with some traditional rules including SPT, EDD, LSPO, and LRS. Performance measures were number of completed jobs, number of tardy jobs, total work, average tardiness per completed job, and average shop lead time factor that was equal to the ratio of total flow-time to the total actual processing time expended on the job. Simulation results showed that the proposed method outperformed all dispatching rules listed above except when the shop lead time factor was considered. The main shortcoming of the model is that only one decision point was investigated.

Nakasuka and Yoshida [100] proposed a new learning algorithm for acquiring sufficient knowledge, which enables the prediction of the best rule to be used under the current line status. In this algorithm, a binary decision tree was automatically generated using empirical data obtained by iterative production line simulations, and it decided, in real time, which rule to be used at decision points during the actual production operations. Simulation results of its application to the dispatching problem were discussed with regard to its scheduling performance and learning capability.

O'Keefe and Rao [101] reported an investigation into part input sequencing methods for a flexible flow system. Two new dynamic methods were developed, i.e. look-ahead simulation, and a fuzzy heuristic rule base. These two new methods were then compared with three simple static sequencing rules and one dynamic rule. The system consisted of ten machines, nine load/unload stations, and AGVs to transport the parts. Parts were dispatched within the system by using the FIFO rule. Performance measures used in the simulation model included production rate, flow-time, makespan, and machine utilisation. The system was modelled on a Sun workstation using a discrete-event simulation language written in LISP. The fuzzy rules were also written in LISP as a subroutine and called within the simulation model. An example of fuzzy rule used was stated as follows:

If "the utilisation ratio is less than low", *and* "the part-processing ratio is more than moderately high" *then* "force the part".

Unfortunately, owing to the confidentiality of the work, the authors did not disclose details. It was concluded that the look-ahead procedure led to better results than fuzzy rules. They did not mention whether they had tested different fuzzy rules or fuzzy functions, used in the rule base, for further improvement.

Kovàcs et al. [102] described the application of expert systems to assist quality control and to help the control of FMSs via simulation. They believed that a close-to-optimal operation of complex, real-time, and stochastic systems such as FMSs could not be achieved by the application of traditional programming. They strongly advocated the use of expert system and artificial intelligence techniques in conjunction with sophisticated modelling and simulation. Their simulation model consisted of four machines, two robots, one input store, one output store, and one AGV to manufacture four different part types of workpieces. SIMAN/CINEMA was used as a simulation package with the advice of expert systems.

Baid and Nagarur [92] strongly advocated the use of simulation techniques and described an intelligent simulation modelling for a manufacturing system, considering a three-level interdependent planning hierarchy. The developed intelligent simulation system incorporated three basic modules, namely, an intelligent front end, a simulator, and an intelligent back end. The intelligent front-end module consisted of a simulation model generator. The model generator created a SIMAN model and experimental framework for the simulation of manufacturing systems. An intelligent back end was employed to analyse the output of the simulation. The simulation model reported in this study contained four workstations, one automated storage/retrieval system (AS/RS), one vehicle in AR/RS, AGVs for handling of parts, and one loading/unloading station. One user interactive rule was provided which gave a choice to the user, to order the jobs personally using some chosen criteria such as due-dates, if necessary. Three traditional dispatching rules, FIFO, LIFO, SLACK, were modelled. The intelligent decision support system developed by Baid and Nagarur was not able to interpret the results, and also failed to select a combination of scheduling rules as the best one for all performance measures.

Wang et al. [103] presented a system-attribute-oriented knowledge-based scheduling system (SAOSS). The SAOSS employed an inductive learning method to induce decision rules for scheduling by converting corresponding decision trees into hidden layers of a self-generated neural network. The FMS under consideration was composed of two machines, a machining centre, five tools, four fixtures, and two industrial robots for loading/unloading parts. Six part dispatching rules, which were SPT, LRPT, SRRTIOM, EDD, MRTRAUO, and FCFS, were compared with the proposed SAOSS. Performance measures employed were mean flow-time and mean tardiness. Results indicated that the SAOSS was superior to other dispatching rules in both performance measures.

Wen et al. [104] proposed a dynamic routeing method using a fuzzy part-family formation approach, combined with a certainty factor procedure, to suggest the best route in a multi-cell FMS. In order to take into account the quantitative estimate of the relationship between machines and parts, a fuzzy clustering algorithm was suggested. The clustering algorithm was based on the distance from the clustering centre, a smaller distance associated with a higher degree of membership. The fuzzy clustering approach not only revealed the specific part family that a part belongs to, but also the degree of membership of a part associated with each part family. In summary, the fuzzy clustering algorithm provided extra information that was not available in conventional algorithms. The following rules were some examples of the routeing decision process:

If "part type 1 enters cell-1 for processing" *then* "the degree of difficulty is 0.4".

If "part type 1 enters cell-2 for processing" *then* "the degree of difficulty is 0.96".

A simulation model was constructed to compare the performance of the proposed dynamic routeing method with the performance of the fixed routeing method. The model was developed using SLAM II, which consisted of two machine cells, 22 part types, and two AGVs (each machine cell had one AGV). The dispatching rule used in the model was FCFS. Three performance measures were employed consisting of mean flow-time, mean tardiness, and absolute lateness. The performance measures were obtained under three different levels of the system utilisation.

Chan et al. [105] developed a fuzzy approach for operation and routeing selection in an FMS via simulation. The FMS consisted of six workstations, a finite input and output buffer at each station, a load/unload station, and three AGVs. The authors used a fuzzy approach to study operation selection first. It was compared with five operation selection rules, which were RAN, SNQ, LULIB, CYC, and WINQ. Performance measures employed were net profit, makespan, average lead time, average tardiness, average lateness, average machine utilisation, average WIP at the input buffer, and average delay at the local buffer. Results showed that the proposed method performed better than the other rules on the performance measures other than makespan, and average WIP at input buffer. The authors then applied the fuzzy approach to routeing selection. It was compared with three rules, which were SNQ, WINQ, and SPT. Performance measures were average and maximum flow-time, average and maximum tardiness, average and maximum lateness, number of tardy jobs, number of completed jobs, and net profit. Results showed that the fuzzy approach outperformed the other selection rules on all the performance measures. The authors concluded that the proposed method showed a good improvement in some performance measures.

In recent years, genetic algorithms (GAs) have received significant attention because of their special evolutionary mechanism. GAs have also been used to solve FMS scheduling problems. Fang and Xi [106] studied a hybrid of GAs and dispatching rules for solving the job shop scheduling problem with sequence-dependent set-up time and due-date constraints. They concluded that the proposed strategy is more suitable for a dynamic job shop environment than the static scheduling strategy.

Jawahar et al. [107] proposed a GA to derive an optimal combination of priority dispatching rules. The performance was compared for makespan criteria and computational time of an FMS. The proposed algorithm was compared with four dispatching rules, which were SPT, LPT MINSLK, and EDT. It was shown that computational time obtained from the GA approach was less than that from the other methods but, for most of the time, it did not provide the optimal solution. Jawahar et al. [108] then carried out work on two knowledge-based scheduling schemes (work cell attribute oriented dynamic schedulers "WCAODSs") to minimise the makespan performance criterion. Results were compared with GA-based methodology and the results indicated that there was no significant variation in the solution output. The same FMS was employed both times, consisting of 2 to 10 work cells, which was either a machining centre or an assembly machine or an inspection station. An AGV was used to transfer materials, pallet, and fixtures between work cells.

Min et al. [109] developed an FMS scheduler, which applied a neural network to present fast but good decision rules, to maximise the desired values of the objectives. The scheduler generated the next decision rules, which were based on the current decision rules, system status, and performance measures. The FMS consisted of four machine centres, a washing machine, 39 work-in-process (WIP) storage racks, and a crane for material handling. Nine performance criteria were considered, namely, mean tardiness, maximum tardiness, mean flow-time, average machine utilisation, average crane utilisation, average total processing time, slack, average jobs in the system, and average WIP in the rack. The model was developed using SLAM II. Results showed the comparison of mean tardiness, maximum tardiness, mean flow-time, and slack between the values obtained from the proposed neural network, and the values obtained from selection of next decision rules randomly. However, Min et al. concluded that the methodology had difficulty to achieve all the objectives simultaneously. Kim et al. [110] employed the same configuration to study an integrated approach of inductive learning and neural networks for developing a multi-objective FMS scheduler. Results showed that the proposed approach gave better results than the neural network approach that was developed by Min et al. [109].

Chen et al. [111] presented an intelligent manufacturing scheduling and control with specific applications to the load/unload operation of an AGV system in a real FMS. The FMS had two enter/exit areas, four load/unload stations, one storage rack for WIP inventory, and two AGVs. A neural network provided the material handling control strategy. Data obtained by simulating various scenarios were used to train the artificial neural network. The trained neural network generated appropriate output for a particular input. The control strategy was simulated and compared with a static system that using LOPNR rule for load/unload stations, and SPT for AGV. The performance measures employed were flow-time, throughput, time in load/unload station, time wait for load/unload station, WIP rack, and AGV queue size. Results showed that the proposed control system was superior to the static system as it led to shorter flow-time, higher system throughput, and less WIP inventory.

Yu et al. [112] proposed a fuzzy inference-based scheduling decision approach for FMS with multiple objectives, which consisted of different and dynamic preference levels. The preference levels were dynamic because the priority given to different objectives might change depending on the conditions of the production environment, such as an abnormally large number of customer orders. The changes in production environment were sensed by environmental variables and these changes were input in a fuzzy inference mechanism, which output the current preference levels of all objectives. A multiple criteria scheduling decision was then made, using the partitioned combination of the preference levels. A simulation example was used to demonstrate the proposed approach. The FMS consisted of three machines and five different products with routeing flexibility. Two objectives were considered, i.e. mean flow-time, and absolute slack, the latter was used to penalise both tardiness and earliness in a just-in-time system. The system was simulated in the "C" language. The proposed fuzzy inference-based scheduling rule was compared with two traditional dispatching rules, which were earliest finishing time (EFT) and shortest absolute slack (SAS). Results indicated that the proposed fuzzy rule produced the best result for all performance measures, except mean flow-time for a light workload situation. It was concluded that the proposed fuzzy rule had a very robust performance under a heavy workload.

Qi et al. [113] described the use of parallel multi-population GAs to deal with the dynamic nature of job-shop scheduling. A modified genetic technique was adopted by using a specially formulated genetic operator to provide an efficient optimisation search. The proposed algorithm was programmed using MATLAB. Four performance measures, number of tardy jobs, total tardiness, mean flow-time, and makespan were monitored for comparison. The proposed algorithm was compared with five conventional scheduling rules, which were EDD, FCFS, LSF, SPT, and LWR. Results indicated that the performance measures were improved by using the proposed GA. However, the system configuration under evaluation was not mentioned clearly.

5. Conclusions and Suggestions for Future Work

This paper has reviewed a number of papers about the scheduling study of FMS by simulation, from general studies to multi-criteria approaches, and to AI approaches. From Tables 1, 3, and 5, it was found that most authors considered the parts dispatching scheduling problem and the trend is consistent for all three categories under review. In addition, as illustrated in Tables 2 and 4, flow-time and tardiness related measures are the most frequently applied performance measures to reflect system status. This is, in fact, a representation of a decision maker's objectives in reality, who would like to allocate the greatest effort to shorten lead time and produce goods on schedule.

Off-line simulation of an existing or imaginary system is very popular in the published work. The majority of the papers dealt with this methodology. However, a physical model or simulator, like [60] and [65], for a real-time model is worth considering in future work.

We may see a future trend of study in AI approaches. Both simulation and AI techniques are regarded individually as flexible tools for modelling and analysis. In addition, AI techniques possess learning ability, which is lacking in traditional scheduling rules. In this connection, if they were combined as an integrated tool, this could be a very powerful tool capable of handling a larger variety and unpredictable situations of FMS scheduling problems. However, it seems that no one has attempted to use hybrid AI techniques for analysing scheduling problems in FMS. Since different AI approaches would have different learning capabilities, work in this area would be valuable.

References

1. J. M. Mellichamp, O. J. Kwon and A. F. A. Wahab, "FMS designer: an expert system for flexible manufacturing system design", International Journal of Production Research, 28(11), pp. 2013–2024, 1990.
2. P. J. O'Grady, Controlling Automated Manufacturing Systems, Chapman and Hall/Kogan Page, London, 1987.
3. D. L. Byrkett, M. H. Ozden and J. M. Patton, "Integrating flexible manufacturing systems with traditional manufacturing, planning, and control", Journal of Production and Inventory Management, 29, pp. 15–21, 1988.
4. R. M. O'Keefe and T. Kasirajan, "Interaction between dispatching and next station selection rules in a dedicated flexible manufacturing system", International Journal of Production Research, 30(8), pp. 1753–1772, 1992.
5. J. Kaltwasser, A. Hercht and R. Lang, "Hierarchical control of flexible manufacturing systems", IFAC Information Control Problems in Manufacturing Technology, Suzdal, USSR, pp. 37–44, 1986.
6. S. C. Sarin and C. S. Chen, "The machine loading and toll allocation problem in a flexible manufacturing system", International Journal of Production Research, 25, pp. 1081–1094, 1987.
7. P. J. O'Grady and U. Menon, "A concise review of flexible manufacturing systems and FMS literature", Computers in Industry, 7, pp. 155–167, 1986.
8. J. Browne, D. Dubois, K. Rathmill, S. Sethi and K. E. Stecke, "Classification of flexible manufacturing systems", FMS Magazine, 2(2), pp. 114–117, 1984.
9. K. E. Stecke and J. Browne, "Variation in flexible manufacturing systems according to the relevant types of automated materials handling", Material Flow, 2, pp. 179–185, 1985.
10. A. Kusiak, "Flexible manufacturing systems: a structural approach", International Journal of Production Research, 23, pp. 1057–1073, 1985.
11. B. L. MacCarthy and J. Liu, "A new classification scheme for flexible manufacturing systems", International Journal of Production Research, 31(2), pp. 299–309, 1993.
12. R. Rachamadugu and K. E. Stecke, "Classification and review of FMS scheduling procedures", Production Planning and Control, 5(1), pp. 2–20, 1994.
13. A. Kusiak and J. Ahn, "Intelligent scheduling of automated machining systems", International Journal of Computer Integrated Manufacturing Systems, 5(1), pp. 3–14, 1992.
14. R. J. Clossen and E. M. Malstrom, "Effective capacity planning for automated factories requires workable simulation tools and responsive shop floor control", Industrial Engineering, 15, pp. 73–79, 1982.
15. M. R. Spano, P. J. O'Grady and R. E. Young, "The design of flexible manufacturing systems", Computers in Industry, 21, pp. 185–198, 1993.
16. R. Ramasesh, "Dynamic job shop scheduling: a survey of simulation research", Omega International Journal of Management Science, 18(1), pp. 43–57, 1990.
17. K. R. Baker, Introduction to Sequencing and Scheduling, Wiley, New York, 1974.
18. R. E. Bellman, A. O. Esogbue and I. Nabeshima, Mathematical Aspects of Scheduling and Applications, Pergamon, UK, 1982.
19. S. French, Sequencing and Scheduling: An Introduction to the Mathematics of the Job-Shop, Wiley, New York, 1982.
20. B. Pourbabai, "A production planning and scheduling model for flexible manufacturing", Proceedings of the 2nd ORSA/TIMS Conference on FMS, Elsevier, Amsterdam, 1986.
21. R. S. Lashkari, S. P. Dutta and A. M. Padhye, "A new formulation of operation allocation problem in flexible manufacturing systems: mathematical modeling and computational experience", International Journal of Production Research, 25(9), pp. 1267–1283, 1987.
22. S. K. Maheshwari, L. C. Leung and W. A. Miller, "An FMS planning procedure with material handling consideration", International Journal of Industrial Engineering, pp. 421–430, 1991.
23. F. T. S. Chan and H. A. Pak, "Heuristical job allocation in a flexible manufacturing system", International Journal of Advanced Manufacturing Technology, 1, pp. 69–90, 1986.
24. T. D. Fry, R. D. Armstrong and L. D. Rosen, "Single machine scheduling to minimize mean absolute lateness: a heuristic solution", International Journal of Computers and Operations Research, 17(1), pp. 105–112, 1990.
25. H. A. ElMaraghy, "Simulation and graphical animation of advanced manufacturing systems", Journal of Manufacturing Systems, 1, pp. 53–63, 1981.
26. H. A. ElMaraghy and T. Ravi, "Modern tools for the design, modeling and evaluation of flexible manufacturing systems", International Journal of Robotics and Computer-Integrated Manufacturing, 9(4–5), pp. 335–340, 1992.
27. S. K. Goyal, K. Mehta, R. Kodali and S. G. Deshmukh, "Simulation for analysis of scheduling rules for a flexible manufacturing system", International Journal of Integrated Manufacturing Systems, 6(5), pp. 21–26, 1995.
28. V. R. Kannan and S. Ghosh, "An evaluation of the interaction between dispatching rules and truncation procedures in job-shop scheduling", International Journal of Production Research, 31(7), pp. 1637–1654, 1993.
29. A. Kazerooni, F. T. S. Chan and K. Abhary, "Simulation of flexible manufacturing systems via fuzzy control scheduling", Proceedings of the Sixth International Conference on Manufacturing Engineering, Melbourne, Australia, pp. 95–99, 29 November–1 December 1995.
30. A. Kazerooni, F. T. S. Chan and K. Abhary, "An intelligent fuzzy decision support system for scheduling of FMS", Proceedings of the International Conference on CAD/CAM, Robotics, and Factories of the Future, London, pp. 400–410, 14–16 August 1996.
31. A. Kazerooni, F. T. S. Chan, K. Abhary and R. W. L. Ip, "Simulation of scheduling rules in a flexible manufacturing system using fuzzy logic", Proceedings of the Ninth International Conference on Industrial and Engineering Application of Artificial Intelligence and Expert System, IEA-AIE96, Japan, pp. 491–500, 4–7 June 1996.
32. M. Montazeri and L. N. Van Wassenhove, "Analysis of scheduling rules for an FMS", International Journal of Production Research, 28(4), pp. 785–802, 1990.
33. M. Oral and J. L. Malouin, "Evaluation of the shortest processing time scheduling rule with transaction process", AIIE Transactions, 5(4), pp. 357–365, 1973.

34. H. Sarper, "Evaluation of simple dispatching rules for dynamic single-machine earliness/tardiness", Production Planning and Control, 5(2), pp. 185–192, 1994.
35. L. L. Tang, Y. Yih and C. Y. Liu, "A study on decision rules of scheduling model in an FMS", Computers in Industry, 22, pp. 1–13, 1993.
36. L. L. Tang, Y. Yih and C. Y. Liu, "A framework for part type selection and scheduling in FMS environments", International Journal of Computer Integrated Manufacturing, 8(2), pp. 102–115, 1995.
37. A. Kazerooni, F. T. S. Chan and K. Abhary, "A fuzzy integrated decision support system for scheduling of FMSs", International Journal of Computer Integrated Manufacturing Systems, 10(1), pp. 27–34, 1997.
38. A. Kazerooni, F. T. S. Chan and K. Abhary, "Real-time operation selection in an FMS using simulation – A fuzzy approach", Production Planning and Control, 8(8), pp. 771–779, 1997.
39. M. R. Carey and D. S. Johnson, Computers and Intractability: A Guide to Theory of NP-Completeness, Freeman, New York, 1979.
40. C. Basnet and J. H. Mize, "Scheduling and control of flexible manufacturing systems: a critical review", International Journal of Computer Integrated Manufacturing, 7(6), pp. 340–355, 1994.
41. Y. P. Gupta, M. C. Gupta and C. R. Bector, "A review of scheduling rules in flexible manufacturing systems", International Journal of Computer Integrated Manufacturing, 2(6), pp. 356–377, 1990.
42. J. A. Buzacott and D. D. Yao, "Flexible manufacturing systems: a review of analytical models", Management Science, 32, pp. 890–905, 1986.
43. H. Rahnejat, "Simulation aids design for flexible automation", International Journal of Advanced Manufacturing Technology, 1(2), pp. 91–108, 1986.
44. S. Nof, M. Barash and J. Solberg, "Operational control of item flow in versatile manufacturing systems", International Journal of Production Research, 17(5), pp. 479–489, 1979.
45. K. E. Stecke and J. Solberg, "Loading and control policies for flexible manufacturing systems", International Journal of Production Research, 19(5), pp. 481–490, 1981.
46. R. Bell and N. Bilalis, "Loading and control strategies for an MS for rotational parts", First International on FMS, pp. 77–87, 1982.
47. T. R. Hoffmann and D. G. Scudder, "Priority scheduling with cost considerations", International Journal of Production Research, 21(6), pp. 881–889, 1983.
48. D. G. Scudder and T. R. Hoffmann, "Composite cost-based rules for priority scheduling in a randomly routed job shop", International Journal of Production Research, 23(6), pp. 1185–1195, 1985.
49. E. Dar-El and S. Sarin, "Scheduling parts in FMS to achieve maximum machine utilization", Proceedings of the First ORSA/TIMS Conference on FMS, pp. 300–306, 1984.
50. L. S. Lin and C. Y. J. Lu, "The scheduling problem in random flexible manufacturing systems", Proceedings of the First ORSA/TIMS Conference on FMS, pp. 278–283, 1984.
51. W. E. Wilhelm and H. M. Shin, "Effectiveness of alternate operations in a flexible manufacturing system", International Journal of Production Research, 23(1), pp. 65–79, 1985.
52. J. Kimemia and S. Gershwin, "Flow optimization in flexible manufacturing systems", International Journal of Production Research, 23, pp. 81–96, 1985.
53. Y. L. Chang, R. S. Sullivan, U. Bagchi and J. R. Wilson, "Experimental investigation of real-time scheduling in flexible manufacturing systems", Annals of Operations Research, 3, pp. 355–377, 1985.
54. M. F. Abdin, "Solution of scheduling problems of job shop type FMS with alternative machine tools", Computers and Industrial Engineering, 11, pp. 241–145, 1986.
55. T. J. Schriber and K. E. Stecke, "Machine utilizations and production rates achieved by using balanced aggregate FMS production ratios in a simulated setting", Proceedings of the Second ORSA/TIMS Conference on FMS, Elsevier, Amsterdam, 1986.
56. T. J. Schriber and K. E. Stecke, "Using mathematical programming and simulation to study FMS machine utilizations", Proceedings of the 1987 Winter Simulation Conference, 1987.
57. D. R. Denzler and W. J. Boe, "Experimental investigation of flexible manufacturing system scheduling rules", International Journal of Production Research, 25(7), pp. 979–994, 1987.
58. H. C. Co, T. J. Jaw and S. K. Chen, "Sequencing in flexible manufacturing system and other short queue-length systems", Journal of Manufacturing Systems, 7(1), pp. 1–9, 1988.
59. G. Chryssolouris, K. Wright, J. Pierce and W. Cobb, "Manufacturing systems operation: dispatch rules versus intelligent control", International Journal of Robotics and Computer Integrated Manufacturing, 4(3), pp. 531–544, 1988.
60. R. H. Choi and E. M. Malstrom, "Evaluation of traditional work scheduling rules in a flexible manufacturing system with a physical simulator", Journal of Manufacturing Systems, 7(1), pp. 33–45, 1988.
61. J. Slomp and G. J. C. Gaalman, "Quasi on-line scheduling procedures for flexible manufacturing systems", International Journal of Production Research, 26, pp. 585–598, 1988.
62. Y. D. Kim, "A comparison of dispatching rules for job shops with multiple identical jobs and alternative routeings", International Journal of Production Research, 28(5), pp. 953–962, 1990.
63. J. Hutchison and B. Khumavala, "Scheduling random flexible manufacturing systems with dynamic environments", Journal of Operations Management, 9(3), pp. 335–351, 1990.
64. N. Ishii and J. J. Talavage, "A transient-basaed real-time scheduling algorithm in FMS", International Journal of Production Research, 29(12), pp. 2501–2520, 1991.
65. S. Y. D. Wu and R. A. Wysk, "An application of discrete-event simulation to on-line control and scheduling in flexible manufacturing", International Journal of Production Research, 27(9), pp. 1603–1623, 1989.
66. J. Hutchison, K. Leong, D. Snyder and P. Ward, "Scheduling approaches for random job shop flexible manufacturing systems", International Journal of Production Research, 29(5), pp. 1053–1067, 1991.
67. I. Sabuncuoglu and D. L. Hommertzheim, "Dynamic dispatching algorithm for scheduling machines and automated guided vehicles in a flexible manufacturing system", International Journal of Production Research, 30(5), pp. 1059–1079, 1992.
68. I. Sabuncuoglu and D. L. Hommertzheim, "Experimental investigation of FMS machine and AGV scheduling rules against the mean flow-time criterion", International Journal of Production Research, 30(7), pp. 1617–1635, 1992.
69. I. Sabuncuoglu, "A study of scheduling rules of flexible manufacturing systems: a simulation approach", International Journal of Production Research, 36(2), pp. 527–546, 1998.
70. T. R. Rohleder and G. D. Scudder, "Scheduling rule selection for the forbiden early shipment environment: a comparison of economic objectives", International Journal of Production Research, 30(1), pp. 129–140, 1992.
71. R. Rachamadugu, U. Nandkeolyar and T. Schriber, "Scheduling with sequencing flexibility", Decision Sciences, 24(2), pp. 315–342, 1993.
72. R. J. Linn and X. Xie, "A simulation analysis of sequencing rules for ASRS in a pull-based assembly facility", International Journal of Production Research, 31(10), pp. 2355–2367, 1993.
73. K. A. Gyampah, "A comparative study of FMS tool allocation and part type selection approaches for a varying part type mix", International Journal of Flexible Manufacturing Systems, 6, pp. 179–207, 1994.
74. S. C. Kim, and P. M. Bobrowski, "Impact of sequence-dependent setup time on job shop scheduling performance", International Journal of Production Research, 32(7), pp. 1503–1520, 1994.
75. V. Selladurai, P. Aravindan and R. Satheesan, "Development of a computer simulator for dynamic scheduling of FMS to achieve optimal performance", International Journal of Advanced Manufacturing Technology, 12, pp. 145–152, 1986.
76. R. Caprihan and S. Wadhwa, "Impact of routing flexibility on the performance of an FMS – a simulation study", International Journal of Flexible Manufacturing Systems, 9, pp. 273–298, 1997.

77. O. Holthhaus and H. Ziegler, "Improving job shop performance by coordinating dispatching rules", Internal Journal of Production Research, 35(2), pp. 539–549, 1997.
78. K. Itoh, D. Huang and T. Enkawa, "Twofold look-ahead search for multi-criterion job shop scheduling", International Journal of Production Research, 31 pp. 2215–2234, 1993.
79. F. Mahmoodi, C. T. Mosier and J. R. Morgan, "The effects of scheduling rules and routing flexibility on the performance of a random flexible manufacturing system", International Journal of Flexible Manufacturing Systems, 11, pp. 271–289, 1999.
80. M. S. Jayamohan and C. Rajendran, "A comparative analysis of two different approaches to scheduling in flexible flow shops", Production Planning and Control, 11(6), pp. 572–580, 2000.
81. V. Subramaniam, G. K. Lee, T. Ramesh, G. S. Hong and Y. S. Wong, "Machine selection rules in a dynamic job shop", International Journal of Advanced Manufacturing Technology, 16, pp. 902–908, 2000.
82. S. M. Lee and H. J. Jung, "A multi-objective production planning model in a flexible manufacturing environment", International Journal of Production Research, 27(11), pp. 1981–1992, 1989.
83. K. Shanker and Y. J. Tzen, "A loading and dispatching problem in a random flexible manufacturing system", International Journal of Production Research, 23(3), pp. 579–595, 1985.
84. I. K. Ro and J. I. Kim, "Multi-criteria operational control rules in flexible manufacturing systems (FMSs)", International Journal of Production Research, 28(1), pp. 47–63, 1990.
85. Y. P. Gupta, G. W. Evans and M. C. Gupta, "A review of multi-criterion approaches to FMS scheduling problems", International Journal of Production Economics, 22(1), pp. 13–31, 1991.
86. N. Ishii and J. J. Talavage, "A mixed dispatching rule approach in FMS scheduling", International Journal of Flexible Manufacturing Systems, 6, pp. 69–87, 1994.
87. K. K. Yang and C. C. Sum, "A comparison of job dispatching rules using a total cost criterion", International Journal of Production Research, 32(4), pp. 807–820, 1994.
88. S. K. Maheshwari, and S. K. Khator, "Simultaneous evaluation and selection of strategies for loading and controlling machines and material handling systems in FMS", International Journal of Computer Integrated Manufacturing, 8(5), pp. 340–356, 1995.
89. G. V. Frazier, "An evaluation of group scheduling heuristic in a flow-line manufacturing cell", International Journal of Production Research, 34(4), pp. 959–976, 1996.
90. C. M. Klein and J. Kim, "AGV dispatching", International Journal of Production Research, 34(1), pp. 95–110, 1996.
91. L. F. Tung, L. Lin and N. Rakesh, "Multiple-objective scheduling for the hierarchical control of flexible manufacturing systems", International Journal of Flexible Manufacturing Systems, 11, pp. 379–409, 1999.
92. N. K. Baid and N. N. Nagarur, "An integrated decision support system for FMS: using intelligent simulation", International Journal of Production Research, 32(4), pp. 951–965, 1994.
93. B. Grabot and L. Geneste, "Dispatching rules in scheduling: a fuzzy approach", International Journal of Production Research, 32(4), pp. 903–915, 1994.
94. W. Karwowski and G. W. Evans, "Fuzzy concepts in production management research: a review", International Journal of Production Research, 24(1), pp. 129–147, 1986.
95. J. A. Schnur, "Simulation through simulation", CIM Review, 3(2), pp. 3–5, 1987.
96. S. Y. D. Wu and R. A. Wysk, "Multi-pass expert control system – a control/scheduling structure for flexible manufacturing cells", Journal of Manufacturing Systems, 7(2), pp. 107–120, 1988.
97. G. W. Hintz and H. J. Zimmermann, "A method to control flexible manufacturing systems", European Journal of Operational Research, 41, pp. 321–334, 1989.
98. T. Watanabe, "Job shop scheduling using fuzzy logic in a computer integrated manufacturing environment", Proceedings of the 5th International Conference on System Research, Information and Cybernetics, Baden-Baden, Germany, pp. 1–7, 6–12 August 1990.
99. J. Chandra and J. J. Talavage, "Intelligent dispatching for flexible manufacturing", International Journal of Production Research, 29(11), pp. 2259–2278, 1991.
100. S. Nakasuka and T. Yoshida, "Dynamic scheduling system utilizing machine learning as a knowledge acquisition tool", International Journal of Production Research, 30(2), pp. 411–431, 1992.
101. R. M. O'Keefe and R. Rao, "Part input into a flexible input flow system: an evaluation of look-ahead simulation and a fuzzy rule base", International Journal of Flexible Manufacturing Systems, 4, pp. 113–127, 1992.
102. G. L. Kovàcs, I. Mezgàr, S. Kopàcsi, D. Gavalcovà and J. Nacsa, "Application of artificial intelligence to problems in advanced manufacturing systems", International Journal of Computer Integrated Manufacturing Systems, 7(3), pp. 153–160, 1994.
103. L. C. Wang, H. M. Chen and C. M. Liu, "Intelligent scheduling of FMSs with inductive learning capability using neural networks", International Journal of Flexible Manufacturing Systems, 7, pp. 147–175, 1995.
104. H. J. Wen, C. H. Smith and E. D. Minr, "Formation and dynamic routeing of part families among flexible manufacturing cells", International Journal of Production Research, 34(8), pp. 2229–2245, 1996.
105. F. T. S. Chan, A. Kazerooni and K. Abhary, "A fuzzy approach to operation selection", Engineering Applications of Artificial Intelligence, 10(4), pp. 345–356, 1997.
106. J. Fang and Y. Xi, "A rolling horizon job ship rescheduling strategy in the dynamic environment", International Journal of Advanced Manufacturing Technology, 13, pp. 227–232, 1997.
107. N. Jawahar, P. Aravindan and S. G. Ponnambalam, "A genetic algorithm for scheduling flexible manufacturing", International Journal of Advanced Manufacturing Technology, 14, pp. 588–607, 1998.
108. N. Jawahar, P. Aravindan and S. G. Ponnambalam, "Knowledge-based workcell attribute oriented dynamic schedulers for flexible manufacturing systems", International Journal of Advanced Manufacturing Technology, 14, pp. 514–538, 1998.
109. H. S. Min, Y. Yih and C. O. Kim, "A competitive neural network approach to multi-objective FMS scheduling", International Journal of Production Research, 36(7), pp. 1749–1765, 1998.
110. C. O. Kim, H. S. Min and Y. Yih, "Integration of inductive learning and neural networks for multi-objective FMS scheduling", International Journal of Production Research, 36, pp. 2497–2509, 1998.
111. F. F. Chen, J. Huang and M. A. Centeno, "Intelligent scheduling and control of rail-guided vehicles and load/unload operations in a flexible manufacturing system", Journal of Intelligent Manufacturing, 10, pp. 405–421, 1999.
112. L. Yu, H. M. Shih and T. Sekiguchi, "Fuzzy inference-based multiple criteria FMS scheduling", International Journal of Production Research, 37(4), pp. 2315–2333, 1999.
113. J. G. Qi, G. R. Burns and D. K. Harrison, "The application of parallel multipopulation genetic algorithms to dynamic job-shop scheduling", International Journal of Advanced Manufacturing Technology, 16, pp. 609–615, 2000.

Acronyms

ACT	apparent tardiness time
AP	alternative operations planned
APD	alternative operations planned and directed dynamically
ARD	alternative route dynamic
ARP	alternative route planned
ARPD	alternative route planned and dynamic
ATC	apparent tardiness cost
CGO	continue go on
COVERT	cost over time
CR	critical ratio
CRRATP	CRRAT is used unless jobs are in the queue which provide a profit of $100 or more; if so, MXPROF is used among these jobs

CRRATV	CRRAT is used unless jobs are in the queue which have had $300 or more of value added; if so, VALADD is used among the jobs
CR-SPT	critical ratio divided by the estimated remaining processing time
CRTC	critical ratio tardiness cost
CYC	cyclic
DOLSHP	selected the job having the highest selling price
EDD	earliest due date
EDT	earliest due time
EFT	earliest finishing time
EFTA	earliest finished time with alternatives considered
EODD	earliest operation due date
FAFS	first arrived first served
FASFO	first at shop, first out
FCFS	first-come-first-service
FIFO	first-in-first-out
FIQ	first in queue
FIS	first in system
FMFS	first machine, first served
FOPR	fewest operations remaining
FRO	fewest remaining operations
FWJM	fewest waiting job for machine
IPDOL	job with highest current value
JCR	job of smallest critical ratio
LAC	lowest average cost
LACP	least aggregate cost and processing time
LAJD	look-ahead job demanding
LAP	least average processing time
LCFS	last-come-first-service
LDT	largest divided time
LIFO	last-in-first-out
LIO	longest imminent operation
LIO/TOT	ratio of LIO to TOT, where TOT is total operation time
LMT	largest multiplied time
LNT	largest number of tools first
LNV	least number of visits
LOPNR	least operation remaining
LOPR	least operation remaining
LOQS	largest output queue size
LPR	least production ratio
LPT	longest imminent processing time
LQS	largest queue size
LRO	least remaining operations
LRPT	longest remaining processing time
LRS	least relative slack
LSF	least slack first
LSPO	least slack per operation
LST	least station time
LULIB	lowest utilisation in the load input buffer
LUS	lowest utilised station
LWKR	least work remaining
LWR	least work remaining
LWT	longest waiting time
MAWM	modified additive weighting method
MDD	modified due date cost over time
MDR	mixed dispatching rule
MINSLK	minimum slack
MMM	max–max method
MNSTUP	minimum set-up time
MOD	modified operation due date
MODD	modified operation due date
MOPR	maximum operations remaining
MQS	maximum queue size
MRO	maximum remaining operations
MRQS	minimum remaining outgoing queue space
MRTRAUO	minimum remaining time allowance per unprocessed operations
MRV	minimum remaining visits
MSLK	minimum job slack
MSUC	maximum success ratio
MWIQ	minimum work in queue time
MWKR	maximum work remaining
MXPCRT	CRRAT is used if any job in the current queue is critical, that is CRRAT <= 1.0. If no jobs are critical, MXPROF is used
MXPRFTRN	truncated of MXPROF
MXPROF	maximum profitable job
NA	no alternative operations
NAR	no alternative route
NFGS	number of jobs finished but not shipped
NINQ	a machine centre was selected that had the lowest number of parts in the queue at the time a part was fetched
NINQ	number of jobs in the queue
NS	next station
NXQL	next queue length
OCR	operation critical ratio
ODD	operation due date
OPCR	operation critical ratio
OPSLK	operation slack per remaining operation
PRF/OPT	ratio of profitability of a job to its current operation set-up and run time
PRF/TOPT	ratio of profitability of a job to its total remaining set-up and run time
RAN	random selection
RANDOM	random selection
RR	Roghu and Rajendran
S/OPN	slack per number of operations remaining
S/PT	a storage area was selected whose first part had the smallest ratio of slack time divided by the remaining processing time
S/RMOP	slack per remaining operation
S/RMWK	slack per remaining work
SAS	shortest absolute slack
SAWM	simple additive weighting method
SDDT-F	shortest-delivery-due-time plus FCFS
SDDT-L	shortest-delivery-due-time plus least-work-remaining
SDM	shortest distance to machine
SDR	single dispatching rule
SDS	shortest distance to station
SDT	smallest divided time
SFTAO	shortest flow time at operation
SIMSET	similar set-up
SI^{x}	truncated SIO
SIO	shortest imminent operation
SIO^{x}	truncated SIO
SLAC	minimum slack rule
SLRO	slack ratio
SMT	smallest multiplied time
SNQ	sequential
SNT	smallest number of tools first
SPT	shortest imminent processing time
SPT.TOT	product of SPT and TOT, where TOT is total operation time
SPT/TOT	ratio of SPT to TOT, where TOT is total operation time
SPT/TPT	ratio of SPT to TPT, where TPT is total processing time
SPTTRN	truncated of SPT
SRCS	shortest remaining buffer capacity on station
SRPT	shortest remaining processing time
SRRTIOM	shortest ratio of remaining processing time to imminent processing time
STD	shortest travelled distance
STPT	shortest total processing time
STT/D	shortest travel time/distance
SWPT	shortest weighted processing time
TPT	total processing time
TSLK	total slack per remaining operation
TWK	total work content
VALADD	highest value added job in the previous operations
VALDRAT	value added ratio

VALUE	a storage area was selected whose first part had the highest dollar value. Dollar values were functions of raw material cost and completed work
VLADCRT	CRRAT is used if any job in the current queue is critical, that is CRRAT is $<= 1.0$. If no jobs are critical, VALADD is used
VLADRAT	ratio of value added to a job to the total value which will be added at completion
WCRTC	weighted critical ratio tardiness cost
WFFS	waiting for the first completed station
WFLUS	waiting at the first completed or loading/unloading station
WINQ	a machine centre was selected that had the least work in queue in terms of process time
WINQ	work in next queue
WIP	work in progress
WLAS	waiting at the last arrival station
YAGER	Yager's multi-attribute decision-making method