A comprehensive survey and future trend of simulation study on FMS scheduling

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Since the late 1970s when the first collection of papers on scheduling of flexible manufacturing systems (FMSs) has been published, it has been one of the most popular topics for researchers. A number of approaches have been delivered to schedule FMSs including simulation techniques and analytical methods, whereas the former is the most widely used tool for modeling FMSs. The objective of this paper is to review scheduling study on FMSs and analyse future trend that employed simulation techniques as the analyzing tool. Scheduling methodologies are categorized into, namely traditional simulation techniques with single criterion scheduling approaches, traditional simulation techniques with multi-criteria scheduling approaches, and artificial intelligence (AI) approaches in FMSs. It is concluded that AI approaches will be dominating in future study.

Keywords: Flexible manufacturing systems, scheduling, simulation, multi-criteria, artificial intelligence (AI)

1. Introduction

Thanks to advanced and fast developing computer technologies, flexible manufacturing systems (FMSs) have received increasing attention in the last 10–20 years and have emerged in the last decade as one of the important keys to organizational success. FMSs are the result of the growth in demand for product quantity on one side and the concern for product quality on the other side. 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 (Sarin and Chen, 1987). In this connection, FMSs require more management to function efficiently and effectively.

FMSs have been defined in a number of ways, like Byrckett et al. (1988) defined an FMS as a manufacturing system in which groups of numerically controlled machines (machine centers) and a material handling system (MHS) work together under computer control. O’Keefe and Kasirajan (1992) described FMS as a group of workstations connected together by a MHS producing or assembling a number of different part types under the central control of a computer. Other definitions were based on the capability or performance of the system. For example, Kaltwasser et al. (1986) stated that 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.

Like definitions of FMS, different types of FMS were classified by various authors. Browne et al. (1984) classified FMSs into four types: flexible machining 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 (1985) extended the classification scheme to include the type of MHS as a further descriptor. Their
classification scheme was based on the flow pattern of parts through the system and emphasizes routing flexibility. Kusiak (1985) discussed FMS in its broadest sense to include fabrication, machining and assembly, and briefly gave a 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 (1993) classified FMSs into four types: a single flexible machine, a flexible manufacturing cell, a multi-machine FMS, and a multi-cell FMS. In addition, the relationships and boundaries between these four types of FMS were discussed. The approach emphasized 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 (1994) 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.

Traditionally, scheduling problems had been solved by analytical methods. These methods often provided optimal solutions for small scheduling problems under simplified assumptions. One of the most commonly used methods in recent years for solving scheduling problems is computer simulation. Simulation models can provide a thorough understanding of the dynamic behavior of a system as well as assisting the evaluation of various system operational strategies (Chan and Koh, 1994). It is a highly flexible tool that can be used effectively for analyzing complex systems. It enables us to model the complex manufacturing systems in detail, whereby the strategies to operate these systems efficiently can be applied in a more realistic environment. It can also handle stochastic problems, for which analytical models have often proved to be inferior or intractable without major simplifications. Simulation is most widely known as a design tool, but in recent years, an increasing number of researchers have been using it to develop various strategies for the operation and the control of manufacturing. Application of simulation technology for real-time scheduling has also been a very popular research topic (Tunali, 1997).

Simulation is a descriptive modeling technique that is used to evaluate schedules through computer-based experiments. This type of modeling is a bridge to the artificial intelligence (AI) approach. 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 (Carey and Johnson, 1979), where a large number of possibilities in which job operations can be sequenced. Therefore, dynamic scheduling does not lend itself to a satisfactory mathematical analysis and solution, especially for a complex manufacturing system like an FMS of realistic scale. 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 system’s data are at hand and under computer control, more sophisticated procedures can be designed and implemented.

Scheduling of FMSs have been extensively researched over the last three decades and it continues to attract the interests of both academic and industrial sectors. Ramasesh (1990) provided a state-of-the-art survey of the simulation-based research on dynamic job shop scheduling with a distinct emphasis on two aspects. First, simulation modeling and experimental considerations were focused. Second, findings on the job-shop performance criteria of interest were discussed. This excellent review covers simulation studies for job shops from years 1960 to 1987.

The theoretical research has focused on the development of mathematical models and optimal or sub-optimal algorithms (Baker, 1974; Bellman et al., 1982; French, 1982). This has been done using integer, mixed integer, and linear programming (Lashkari et al., 1987; Maheshwari et al., 1991). The theoretical results have not been widely used in industry due to the highly computational complexity. Mathematical programming models, which are based on simplified assumptions for the system under study, are the specificity of individual manufacturing
enterprises and processes. These models also need a high degree of accuracy in the data used. The experimental research has been primarily concerned with dispatching rules and heuristic procedures that efficiently solves the scheduling problems. 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 (Chan and Pak, 1986; Fry et al., 1990). This solution may or may not be the optimal solution, but can be derived with less computational effort than optimization approaches (Spano et al., 1993).

In short-term scheduling, as opposed to medium-term scheduling that is implemented through MRP systems, dispatching rules are widely used. For example, first-in-first-out (FIFO) rule selects the part that first entered the input/output buffer at/from a machine as the next part to be serviced. Dispatching rules are extensively employed in discrete event simulation models (ElMaraghy, 1981; ElMaraghy and Ravi, 1992; Goyal et al., 1995; Kannan and Ghosh, 1993; Kazerooni et al., 1995, 1996a, b, 1997a, b; Montazeri and Van Wassenhove, 1990; O’Keefe and Kasirajan, 1992; Oral and Malouin, 1973; Sarper, 1994; Tang et al., 1993, 1995).

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: designing, production planning, scheduling, and controlling. With the advance of automation technology, its decision supporting systems, production planning, scheduling and control, have gained importance (Kusiak and Ahn, 1992). In considering these four stages of planning in FMSs, scheduling still plays a crucial role.

There have been extensive studies on scheduling manufacturing systems. These studies can be divided into three basic approaches (Kusiak and Ahn, 1992):

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

Similarly, Spano et al. (1993) divided the scheduling research into two major approaches:

1. Traditional approach.
2. AI-based approach.

In this paper, this scheme is used to classify the scheduling researches. The objective of this paper is to review simulation study on FMSs scheduling, based on traditional approaches and AI approaches, and then to provide an analysis of the future trend of FMS scheduling. Base on the statistic in this paper, readers can find the most frequently employed type of scheduling problem and performance measures in past researches. Some examples of the performance measures are flowtime, makespan, utilization, etc. The following sections are contributed to review the three scheduling approaches, namely simulation of traditional FMS scheduling studies in single criterion and multi-criteria environment in Section 2, and AI approaches in FMSs in Section 3. In a single criterion scheduling problem, only one performance measure is evaluated against various scheduling rules. The objective is usually to maximize or minimize the selected criterion. However, it is not restricted to evaluating only one performance measure under the same model in a research. Nevertheless, different criteria usually contradict by themselves. For example, minimize flowtime and minimize makespan will properly draw a different solution. Therefore, multi-criteria decision-making is employed in a multi-criteria environment such that different criteria are considered at the same time in order to find the pseudo optimal solution, rather than finding the best solution for particular criterion. Section 4 provides conclusions and some suggestions for further research and development.

2. Review of traditional FMS scheduling studies

An FMS is an extremely complex, large-scale system consisting of many interconnected components of hardware and software. The scheduling problems in FMS relate to the execution of production orders and include raw part input sequencing, machine, and vehicle scheduling, monitoring system performance and taking the necessary corrective actions. Dispatching algorithms are widely used for scheduling in industrial practice. The algorithms are based on various dispatching rules that prioritize the products for assignment to machines and AGVs. Machine scheduling rules normally do not consider the availability of AGVs when the priorities of products are set. Similarly, AGV scheduling rules do not usually take into account the availability of
machines for products to be assembled. However, the procedures for scheduling the assembly operations on machines, and the scheduling of transportation operations on vehicles in an FMS, are closely interrelated. The dispatching algorithms for machine and vehicle scheduling will take into account the various interactions between machines and AGVs, and using the current information on assembly process and the system status. Some of this information is product related, such as processing and transportation times, precedence relations among operations, product assembly routes, etc. In the following subsections, a review of published papers will be presented. Basically, the scheduling problems can be classified, as mentioned above, as follows:

1. Parts dispatching problems—to select a part from a queue.
3. AGV scheduling problems—to select AGV for transportation or the routing of AGV.
4. Operation (process) selection problems—to select the next operation of a part to be processed.
5. Others—since FMS is a very complex system.

The number of variables inside an FMS is uncountable. Anything can be a research problem like number of AGVs, number of work-in-process, etc.

2.1. Single criterion scheduling problems

Scheduling of FMSs has been one of the most attractive areas of investigation for both researchers and practitioners in an industrial context, and the literature of FMSs is abundant with papers on scheduling. Several review articles were published which synthesize the literature on different phases of FMSs. For example, Stecke and Solberg (1981) 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 10 machines with two carts to transport parts. They concluded that scheduling rules have 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. It means that there was no single scheduling rule that outperforms the others for all performance measures. Spano et al. (1993) reviewed the work done on the design of FMSs in the areas of facilities design, MHS design, control system design, and scheduling. Rachamadugu and Stecke (1994) 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 subjected to disturbance. They also discussed the choice of appropriate scheduling criteria.

Basnet and Mize (1994) reviewed the literature concerning the operations aspect of FMS. They described scheduling methodology under six different categories: mathematical programming, multi-criteria decision-making, heuristic oriented, control theoretic, simulation, and AI. They concluded that discrete-event simulation technique has a great potential to make major contributions to FMS operation and stressed that simulation can be used to model FMSs quite comprehensively.

Gupta et al. (1990) 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 developed list of dispatching rules and performance criteria from the surveyed literature.

Buzacott and Yao (1986) presented a comprehensive review of the analytical models developed for the design and scheduling of FMS. They strongly advocated analytical methods as giving better insight into the system performance than simulation models. This point of view was adopted since, most likely, simulation techniques had not been matured up at that time. In the 1980s, there was less attention in the use of simulation in manufacturing applications (Rahnejat 1986), mainly because of the lack of model building expertise. Rahnejat (1986) emphasized 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.

Table 1 is the summary of the publications on
Table 1. Single criterion approach in FMS scheduling problems

<table>
<thead>
<tr>
<th>Year of publication</th>
<th>Authors</th>
<th>Type of scheduling problem (note)</th>
<th>Number of performance measures</th>
<th>Performance measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981</td>
<td>ElMaraghy</td>
<td>√</td>
<td>6</td>
<td>Station utilization, production rate and average throughput time for each part type, simulation time, total number of parts produced, and total processing time</td>
</tr>
<tr>
<td>1983</td>
<td>Hoffmann and Scudder</td>
<td>√</td>
<td>6</td>
<td>Mean flowtime, average tardiness, average lateness, average work-in-process dollars, average profit in all queues, and average dollars of value added for work waiting to be processed</td>
</tr>
<tr>
<td>1984</td>
<td>Dar-El and Sarin, Lin and Lu</td>
<td>√</td>
<td>2</td>
<td>Machine utilization, and minimum job tardiness</td>
</tr>
<tr>
<td>1985</td>
<td>Wilhelm and Shin, Scudder and Hoffmann, Chang et al., Chan and Pak, Abdin, Schriber and Stecke, Denzler and Boe, Co et al., Chryssoulouris et al., Choi and Malstrom</td>
<td>√</td>
<td>6</td>
<td>Same as Hoffmann and Scudder, 1983</td>
</tr>
<tr>
<td>1986</td>
<td>Chan and Pak, Abdin</td>
<td>√</td>
<td>3</td>
<td>Cost of tardiness, makespan, and average lead time</td>
</tr>
<tr>
<td>1987</td>
<td>Schriber and Stecke, Denzler and Boe</td>
<td>√</td>
<td>2</td>
<td>Machine utilization, and production rate</td>
</tr>
<tr>
<td>1988</td>
<td>Co et al., Chryssoulouris et al., Choi and Malstrom</td>
<td>√</td>
<td>2</td>
<td>Machine utilization, and production rate</td>
</tr>
<tr>
<td>1990</td>
<td>Slomp and Gaalman, Montazeri and Van Wassenhove</td>
<td>√</td>
<td>8</td>
<td>Mean flowtime, number of task orders completed, average WIP, and mean tardiness</td>
</tr>
<tr>
<td>1991</td>
<td>Ishii and Talavage</td>
<td>√</td>
<td>1</td>
<td>Makespan per part, and mean flowtime</td>
</tr>
</tbody>
</table>

Actual and relative system effectiveness, 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, total and average production lateness

Average and variance of waiting time per part, average and variance of machine utilization, average buffer utilization, average shuttle utilization, average carrier utilization, and makespan

Mean flowtime, mean tardiness, and number of tardy jobs

Average flow time, and adjusted production rate (similar to makespan)

Workload
<table>
<thead>
<tr>
<th>Year of publication</th>
<th>Authors</th>
<th>Type of scheduling problem (note)</th>
<th>Number of performance measures</th>
<th>Performance measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>Hutchison et al.</td>
<td>√</td>
<td>1</td>
<td>Makespan</td>
</tr>
<tr>
<td></td>
<td>Sabuncuoglu and Hommertzheim (1992a)</td>
<td>√</td>
<td>1</td>
<td>Mean flowtime criterion</td>
</tr>
<tr>
<td></td>
<td>Sabuncuoglu and Hommertzheim (1992b)</td>
<td>√</td>
<td>1</td>
<td>Mean flowtime criterion</td>
</tr>
<tr>
<td></td>
<td>O’Keefe and Kasirajan</td>
<td>√</td>
<td>1</td>
<td>Weighted flowtime</td>
</tr>
<tr>
<td></td>
<td>Rohleder and Scudder</td>
<td>√</td>
<td>8</td>
<td>Mean system inventory, NPV, mean tardiness, percentage of tardy jobs, average starting time of operations, number of jobs in process, number of jobs finished but not shipped, and average total jobs in system</td>
</tr>
<tr>
<td>1993</td>
<td>Rachamadugu et al.</td>
<td>√</td>
<td>3</td>
<td>Mean flowtime, average tardiness, and proportion of tardy jobs</td>
</tr>
<tr>
<td></td>
<td>Kannan and Ghosh</td>
<td>√</td>
<td>4</td>
<td>Mean flowtime, mean tardiness, standard deviation of flowtime, and standard deviation of tardiness</td>
</tr>
<tr>
<td></td>
<td>Linn and Xie</td>
<td>√</td>
<td>1</td>
<td>Delivery performance</td>
</tr>
<tr>
<td>1994</td>
<td>Gyampah</td>
<td>√</td>
<td>5</td>
<td>Mean flow-time, mean tardiness, percent of orders tardy, machine utilization, and robot utilization</td>
</tr>
<tr>
<td></td>
<td>Sarper</td>
<td>√</td>
<td>2</td>
<td>Mean lateness, and maximum lateness</td>
</tr>
<tr>
<td></td>
<td>Kim and Bobrowski</td>
<td>√</td>
<td>5</td>
<td>Set-up related measures, due-date related measures, flowtime related measures, shop utilization, and cost measures</td>
</tr>
<tr>
<td>1995</td>
<td>Tang et al.</td>
<td>√</td>
<td>7</td>
<td>Flow time, total completed parts, number of tardy jobs, average WIP, maximum number of jigs/fixtures, machine utilization, and AGV utilization</td>
</tr>
<tr>
<td></td>
<td>Selladuri et al.</td>
<td>√</td>
<td>3</td>
<td>Average flowtime, average tardiness, and number of late jobs</td>
</tr>
<tr>
<td></td>
<td>Goyal et al.</td>
<td>√</td>
<td>4</td>
<td>Average workstation utilization, average buffer utilization, average throughput, and average lateness</td>
</tr>
<tr>
<td>1997</td>
<td>Capirhan and Wadhwa</td>
<td>√</td>
<td>1</td>
<td>Makespan</td>
</tr>
<tr>
<td></td>
<td>Holthaus and Ziegler</td>
<td>√</td>
<td>5</td>
<td>Mean flowtime, maximum flowtime, percentage of tardy jobs, mean tardiness, and maximum tardiness</td>
</tr>
<tr>
<td>1998</td>
<td>Sabuncuoglu</td>
<td>√</td>
<td>1</td>
<td>Mean flowtime</td>
</tr>
<tr>
<td>1999</td>
<td>Mahmoodi et al.</td>
<td>√</td>
<td>3</td>
<td>Average flow time, average percentage tardy, and average tardiness</td>
</tr>
<tr>
<td>2000</td>
<td>Jayamohan and Rajendran</td>
<td>√</td>
<td>7</td>
<td>Mean flowtime, maximum flowtime, variance of flowtime, mean tardiness, maximum tardiness, variance of tardiness, and percentage of tardy jobs</td>
</tr>
<tr>
<td></td>
<td>Subramaniam et al.</td>
<td>√</td>
<td>2</td>
<td>Mean operational cost, and mean tardiness</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>28</td>
<td>8</td>
<td>Mean flowtime</td>
</tr>
</tbody>
</table>

Notes:
scheduling problems in single criterion environment. As shown in Table 1, 28 out of the 40 (that is 70%) of published papers dealt with part dispatching scheduling problems. Very few of them considered machine selection, AGV scheduling, and operation (process) selection problems. On the other hand, 23 researches (more than 50%) employed less than four performance measures. This is probably due to the fact that in a single criterion environment, the more performance measures (e.g. flow time, utilization, throughput, etc.), the more complex the system to be considered. Table 1 also shows that the investigation on FMS scheduling problems in the single criterion environment was most popular from the late 1980s to the early 1990s. However, one of the shortcomings of these researches is that no single rule can be found as the best rule in different models. In fact, some factors are contradictory. For example, minimizing flow time may result in low machine utilization. In fact, this may be the major factor which drives researchers into using multi-criteria decision-making techniques and AI techniques in order to get a more ‘‘balanced’’ solution, instead of obtaining the optimal solution on only a particular aspect.

2.2. Multi-criteria scheduling approaches

Because of rapid change in demand, FMSs are working with different customer orders, and each of them aims at different criteria. Therefore, operating an FMS is in fact a multiple criteria activity. Some authors employed these criteria in their modeling. For example, Lee and Jung (1989) developed a formulation for part selection and allocation problems 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 utilization, and minimization of throughput time of parts. This kind of goal programming could be used by decision-makers to satisfy their goals and their prioritization. However, two shortcomings of this kind of modeling are observed. First, information on the dynamic working of an FMS cannot be provided; second, effect of the waiting times on the system performance cannot be taken into account. Furthermore, the biggest disadvantage of this method is that it is computationally costly and is expensive to be used for practice.

Gupta et al. (1991) 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 some issues as below:

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.

The major advantages of multi-criteria decision-making technique is that it does not need holistic judgements, thus, it can accommodate the multi-dimensionality of value and allow the decision makers to evaluate several alternatives with different impacts. It also coincides with one practice of modern decision makers, who prefer to be presented with a range of feasible alternatives rather than one best solution. The aim is to select alternative(s) on the basis of their preference order. The preference order is constructed based on the alternatives’ values on the attributes considered. Usually, a function, which is a mathematical representation of the attributes, is constructed to evaluate alternatives by considering different attributes. The implications of the results can provide valuable insights and decision opportunities for major decision-making. The function is usually written in the form as follows:

\[ U_i(x_1, x_2, \ldots, x_m) = k_1u_{i1}(x_1) + k_2u_{i2}(x_2) + \cdots + k_mu_{im}(x_m), \]

\[ i = 1, 2, \ldots, n \]

where \( U_i(x_1, x_2, \ldots, x_m) \) is the function of \( m \) attributes of \( i \)th alternative, \( x_i \) are attributes under consideration, \( k_j \) is weighing of \( j \)th attribute such that summation of \( k_j \) is equal to 1, and \( u_{ij} \) is the effect of \( i \)th alternative related to \( j \)th attribute, that is, \( x_j \). The solution is usually either the maximum or minimum value of this function.

Table 2 summarizes the contributions on multi-criteria scheduling problems in FMS. Again, part dispatching scheduling problem was the most frequently encountered. However, one point which should be highlighted is that the number of performance measures is generally higher than that in a single criterion environment. Seventy percent of
Table 2. Multi-criteria approach in FMS scheduling problems

<table>
<thead>
<tr>
<th>Year of publication</th>
<th>Authors</th>
<th>Type of scheduling problem (note)</th>
<th>Number of performance measures</th>
<th>Performance measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>Shanker and Tzen</td>
<td>√</td>
<td>2</td>
<td>Machine utilization, and CPU time</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Average flowtime, WIP, number of jobs completed, and mean tardiness</td>
</tr>
<tr>
<td>1988</td>
<td>Chryssoupolis et al.</td>
<td>√</td>
<td>4</td>
<td>Makespan, mean flow time, mean tardiness, maximum tardiness, and system utilization</td>
</tr>
<tr>
<td>1990</td>
<td>Ro and Kim</td>
<td>√ √ √ √ √ √</td>
<td>5</td>
<td>Mean flowtime, mean tardiness, weighted mean flow time, weighted mean tardiness, and combination of them</td>
</tr>
<tr>
<td>1994</td>
<td>Ishii and Talavage</td>
<td>√</td>
<td>5</td>
<td>Machine utilization, due-date allowance, tardiness penalty rate, interest rate, and cost rate for holding inventory</td>
</tr>
<tr>
<td></td>
<td>Yang and Sum</td>
<td>√</td>
<td></td>
<td>Makespan, and mean flowtime</td>
</tr>
<tr>
<td>1995</td>
<td>Maheshwari and Khator</td>
<td>√</td>
<td>2</td>
<td>Makespan and mean flowtime</td>
</tr>
<tr>
<td>1996</td>
<td>Frazier</td>
<td>√</td>
<td>2</td>
<td>Makespan and mean flowtime</td>
</tr>
<tr>
<td></td>
<td>Klein and Kim</td>
<td>√</td>
<td>6</td>
<td>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</td>
</tr>
<tr>
<td>1999</td>
<td>Tung et al.</td>
<td>√</td>
<td>4</td>
<td>Profit, due dates, inventory cost, and finished-good inventory cost</td>
</tr>
<tr>
<td>2001</td>
<td>Chan and Chan</td>
<td>√</td>
<td>3</td>
<td>Mean flowtime, mean earliness, and mean tardiness</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>9 Ḿ 1 3 1 1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
(1) Part dispatching problems.
(2) Machine selection problems.
(3) AGV scheduling problems.
(4) Operation (Process) selection problems
(5) Others.

The listed papers employed more than three performance measures. In fact, the result is trivial since multi-criteria scheduling problems can, in theory, involve an infinite number of attributes. It can also be observed from Table 2 that this type of research was popular in the 1990s. This is because the rapid development in computer technology lead to fast processing time when dealing with the calculation in multi-criteria decision-making process, which is impossible to deal with by human power. However, the rapid developing technology also aids simulation study by using AI techniques, which will be covered in the following section.

3. Review of AI scheduling approaches

In a production system, the scheduling problem is to synchronize resources (connected by MHS), 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
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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 workstation and AGVs. For example, Chen et al. (1999) presented a framework of intelligent scheduling and control of rail-guided vehicles. Wallace (2001) applied AI technique to design an agent based AGV controller in order to control the flow of AGVs. Chan and Jiang (2001) even used AI technique for business process reengineering with flexible manufacturing technologies such as FMS.

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 (e.g., arrival of new parts or modification of previous priority queue size of resources, and so on). Therefore, it is not desirable and economical in 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, to 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 modeling can help to imitate human expertise to schedule manufacturing systems (Baid and Nagarur, 1994). ElMaraghy and Ravi (1992) reviewed some applications of knowledge-based simulation systems in the domain of FMSs, and also discussed their potentials for the development of new, powerful, and intelligent simulation environments for modeling and evaluating FMSs. Grabot and Geneste (1994) 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 solution to satisfy the performance of several criteria. Karwowski and Evans (1986) illustrated 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. Schnur (1987) 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 AI knowledge based expert systems was discussed as well. However, the application of AI in dispatching of parts was not demonstrated. In recent years, genetic algorithm (GA) and neural network received significant attention by many researchers because of its special evolutionary mechanism. They have also been used to solve FMS scheduling problems.

Basically, AI techniques can be classified in the following subsections.

3.1. Fuzzy logic

The theory of fuzzy sets is aimed at the development of a body of concepts and techniques for dealing with sources of uncertainty or imprecision that are non-statistical in nature. Fuzzy set theory, which was introduced by Zadeh (1965), plays a significant role in this kind of decision-making environment. The approximate reasoning of fuzzy set theory can properly represent linguistic terms (Zadeh, 1975). To deal quantitatively with imprecision and uncertainty, all the assessment data are specified into fuzzy numbers in a membership function. Hence, a fuzzy multi-criteria decision-making (MCDM) method is applied to integrate various linguistic assessments and weights in order to solve scheduling problems. Guilfrida and Nagi (1998) reported that fuzzy set theory can be applied in various production management research like job shop scheduling, quality management, project scheduling, facility location layout, aggregate planning, production and inventory planning, and forecasting. Giachetti (1998) used fuzzy sets theory to solve a multi-attribute decision model of a material and manufacturing process problem.

3.2. Expert system

Expert systems have grown dramatically in the past decade and represents the most successful demonstration of the capabilities of AI. Expert systems are the first truly commercial application of work done in the AI field and have received considerable publicity. For example, Rao et al. (1999) discussed how expert systems could be used in new product development. Reflecting human expertise, much of the information in the knowledge base of a typical expert system is imprecise, incomplete, or not totally reliable. For this reason, the answer to a question or the advice rendered by an expert system is usually qualified with a
“certainty factor”. It gives the user an indication of the degree of confidence that the system has in its conclusion. To arrive at the certainty factor, the existing expert systems employ what are essentially probability-based methods. A fuzzy expert system is an expert system that uses a collection of fuzzy membership functions and rules, instead of Boolean logic, to reason about data. The rules in a fuzzy expert system are usually expressed as follows:

If “x is low and y is high” then “z is medium”

where x and y are input variables (a name for known data values), z is an output variable (a name for a data value to be computed), low is a membership function (fuzzy subset) defined on x, high is a membership function defined on y, and medium is a membership function defined on z. The antecedent (the rule’s premise) describes to what degree the rule applies, while the conclusion (the rule’s consequent) assigns a membership function to each of one or more output variables. Most tools for working with fuzzy expert systems allow more than one conclusion per rule. The set of rules in a fuzzy expert system is known as the rule base or knowledge base. A closely related application is the use of fuzzy expert systems in simulations and models that are intended to aid decision-making.

3.3. Genetic algorithm (GA)

GA is a permutation approach that systematically permutes an initial pool of randomly generated solution based on pre-defined attributes to return the best solution. According to Chryssolouris and Subramaniam (2001) definition, GA has four dimensions, namely the problem investigated, the individual (schedule) representation, the crossover operator, and the mutation operator.

3.4. Neural network

In some sense, neural network is used to emulate the operation of the human brain. Unlike conventional AI techniques such as expert systems that were able to explain their reasoning by rule-following, knowledge-based approach, neural network rules were abandoned and explanations seemed impossible. Unfortunately, neural networks are not identical copies of the human brain but there is still a high potential to be researched if properly used. Burke and Ignizio (1997) reviewed neural network in engineering applications and attempted to correct the myths and misconceptions that have surrounded neural networks in recent years.

3.5. Other approaches

Apart from the four methods mentioned above, there are still many AI techniques available, for example, a knowledge-based system. These techniques usually have a “learning” capability from past experience and use a database to update it. The system can make decision based on the past experience from the database by following a set of preset rules. In fact, the aim is to emulate the decision-making process of human scheduler. For example, Zha et al. (1998) defined a knowledge-based Petri net approach to adjust, automatically, the deviations between the theoretical planning parameters and the process parameters of real assembly operations. Zha et al. (1999) then designed a knowledge-based approach and made use of it for product design for assembly. In these papers, they discussed how a knowledge-based system can be built.

Table 3 lists related publications and how they related to different AI techniques. Fuzzy approach was the most frequent employed method for problem solving. On the other hand, expert systems have not been researched since 1994, despite its early successes in related areas. It can be observed that other fields, such as GA and neural network, have been potential research areas in recent years. In fact, the related research works have been very active since the 1990s. Again, part dispatching is the most popular problem among the publications as 15 out of the 21 researches involved parts dispatching scheduling problems.

4. Conclusions and suggestions for future research

This paper has reviewed a number of reported researches that contribute to the scheduling study of FMS by simulation, from single criterion general studies to multi-criteria approaches, and to AI approaches. It was found that most authors researched on part dispatching scheduling problems and the trend is consistent for all the three categories under revision. In general, the papers under review are lacking a robust framework for evaluation of scheduling rules. Most of the authors evaluated the results based on an individual performance measure and failed to
### Table 3. AI approach in FMS scheduling problems

<table>
<thead>
<tr>
<th>Year of publication</th>
<th>Authors</th>
<th>Type of scheduling problem (note 1)</th>
<th>Type of AI techniques (note 2)</th>
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<td>1988</td>
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<td>Nakasuka and Yoshida</td>
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<td>1995</td>
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### Notes

1. Part dispatching problems.
3. AGV scheduling problems.
4. Operation (process) selection problems.
5. Others.
6. Fuzzy.
7. Expert system.
10. Others.

A single rule or a single combination of scheduling rules as overall the best one.

It was found that most of the authors investigated scheduling of FMS with only a few decision points. The majority of the authors considered single decision points only in their studies. Although modeling an FMS with multiple decision points is much more complex than one with a single decision point, the former is closer to reality and worth considering, although most of the FMSs under consideration were not realistic. For example, machine breakdown, rush job, etc., were not modeled. Some authors considered only time-processing-based rules and ignored due-date base rules. Rule based upon other attributes, for example, cost, tend to be less popular and only a few authors had reported them. On the other hand, AI approaches become the trend of the related study. It is not a surprise because both simulation and AI techniques are individually regarded as flexible tools for modeling and analysis. In addition, AI techniques possess the learning ability, which is the weakness of traditional scheduling rules. In this connection, if they could be combined as an integrated tool, which would be a very powerful tool capable of handling a larger variety of unpredictable situations of FMS scheduling problems.
Since different AI approaches would have various learning capabilities, it would be valuable if future researches can develop hybrid AI techniques, which combine the strengths of the existing techniques, for analyzing scheduling problems in FMS. A hybrid approach is already analyzed in some researches in other areas. For example, Cavalieri and Gaiardelli (1998) used hybrid genetic algorithms to solve a multiple-objective scheduling problem in a flow-shop environment. Kubota and Fukuda (1999) applied fuzzy theory to represent incomplete information about the machining time and used genetic algorithm to solve the fuzzy scheduling problem in a self-organizing manufacturing system. Mesghourni et al. (1999) showed the coupling of three approaches, namely genetic algorithms, constraint logic programming, and multi-criteria decision-making, to solve job-shop scheduling problem. Mok et al. (2000) developed an intelligent hybrid system called HSIM, which integrated case-based reasoning, hybrid neural network, and GA, to determine a set of initial process parameters for injection molding. Huang et al. (2001) presented an automated approach for knowledge acquisition by combining neural networks’ learning ability and fuzzy logics’ structured knowledge representation. The automated approach is then applied to the design and manufacturing of a micromachined atomizer for a gas turbine engine. Luo et al. (2001) employed a hybrid method, which combined GAs, linear programming, and ordinal optimization, and applied it to production planning and scheduling problem. Therefore, it is worth applying hybrid AI techniques to attempt to solve scheduling problem in FMSs, which are complex in real world problems.

References


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