JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Application of operational research models and techniques in flexible manufacturing systems: a review

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Abstract

This paper offers the outline of Flexible Manufacturing Systems (FMSs) and flexibilities. It would be difficult to efficiently implement an FMS without solving its design problems. These problems, as well as a number of operations problems, are discussed. A planning and scheduling framework is developed. Based on this framework, the relevant FMS literature is discussed. Most of the tools and techniques applicable for solving FMS problems are listed. Recommendations for future research are also presented.

Keywords: Flexible manufacturing systems flexibilities FMS literature, framework, applicable, scheduling

1. Introduction

A Flexible Manufacturing System (FMS) is typically defined as a set of machine tools linked by a material handling system, all controlled by a computer system. The first FMS was installed in England in 1968 (see Dempsey, 1983). Since then hundreds of these systems have been developed in many different countries. It appears that Japan is leading this international competition in terms of a number of actually used and sold elsewhere FMSs. Although the idea of an FMS has been created almost twenty years ago, they started to be of significant interest to the research community some growing a solution. All through run-time, the system begins with imaging, then movements directly to automatic picture analysis and records extraction.[1]

Although the idea of an FMS has been created almost twenty years ago, they started to be of significant interest to the research community some five years ago. This interest can be measured by the number of books, edited books, conference proceedings and research papers published. One of the first books has been published by Ranky (1983). Raouf and Ahmad (1985) edited the first book covering the operational research and production aspects of FMSs. Two edited books on operational and design aspects of FMSs are being currently prepared by the author (see Kusiak, 1986a, and Kusiak, 1986b). IFS Publishing Ltd. and NorthHolland Publishing Co. have annually published proceedings of the International Conference on FMSs since 1982. The first conference on operational research problems generated by this new technology was held in Ann Arbor in 1984 (see ORSA/TIMS, 1984). To accommodate a rapidly increasing number of research papers, many special issues of the existing journals have been published (see for example Kusiak, 1985a) and a number of new manufacturing journals have been established (see for example Heginbotham, 1985). Interesting survey papers have been written by Buzacott and Yao (1982) and Kalkunte et al (1986). In Section 2 of this paper five classes of FMSs and relevant flexibilities are defined. Design problems are listed in Section 3. Only three from the listed eight design problems have been approached by operational researchers and those are discussed. In Section 4 an FMS planning and scheduling framework is defined. Based on this framework, three of the operational problems are expanded in Sections 5 to 7. Section 5 covers the resource grouping problem. Disaggregate planning approaches are discussed in Section 6. In Section 7, the machine scheduling problem, the AGV scheduling problem and the order picking problem are discussed. The summary of basic tools and techniques applicable for solving the FMS problem are presented in Section 8. Conclusions and suggestions for further research are discussed in Section 9.[2][3][4]

2. FMS structure

Many researchers consider an FMS as a rather simple, isolated system. In this paper a broad view on FMS is presented. Many of the currently developed and forthcoming systems may consist of the following three basic subsystems (Kusiak, 1985):

(1) fabrication;

(2) machining;

(3) assembly.

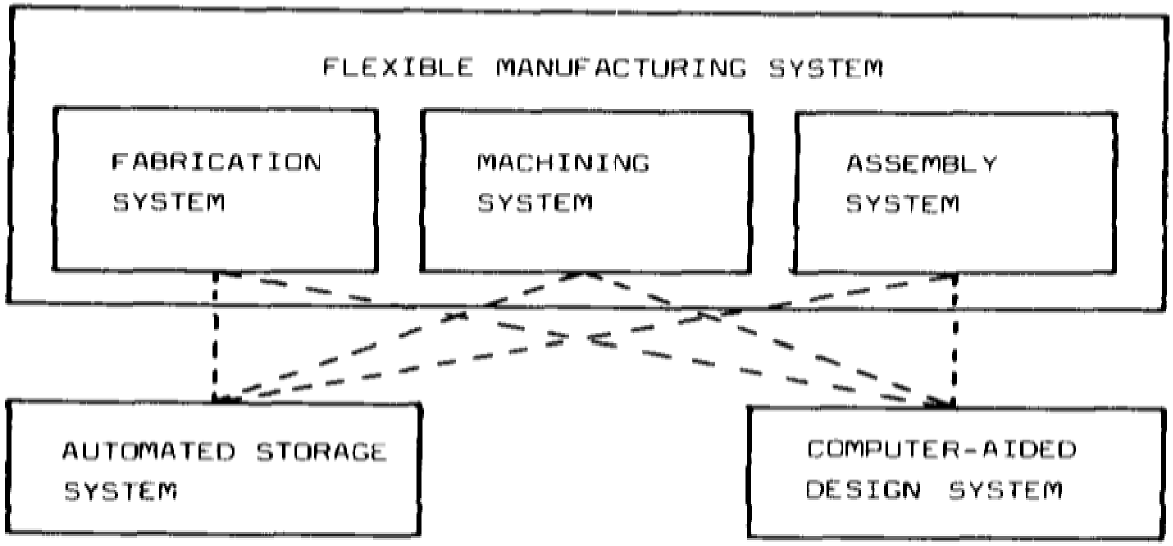

Fig. 1. Relationship among flexible manufacturing system, automated storage system and computer-aided design system [5]

Each of these subsystems may be integrated with a Computer-Aided Design (CAD) system and a storage system (in many cases an Automated Storage/Retrieval System, AS/RS). The FMS and the storage system are integrated by a material handling system (for example, an Automated Guided Vehicle System, AGVS) and an information system. The linkage between FMS and CAD system is typically in a form of information system. [6][7] Figure 1 shows the relationship among the discussed subsystems. It should be emphasized that the term 'flexible manufacturing system' does not imply 'unmanned or totally automated manufacturing system'. One expects an FMS to be some degree automated system and this is due to the progress made in the development of its technological components (for example: machines, robots, storage systems). The degree of automation tends to spread evenly among the FMS technological components, however, one can find examples of systems which consist of such components with a different degree of automation. Based on the number of technological components and their arrangement FMSs can be divided into the following five classes (Kusiak, 1985):

(1) Flexible Manufacturing Module (FMM);

(2) Flexible Manufacturing Cell (FMC);

(3) Flexible Manufacturing Group (FMG);

(4) Flexible Production System (FPS);

(5) Flexible Manufacturing Line (FMU)

A sample flexible production system is presented in Figure 2. It incorporates an FMM, an FMC, FMGs, and an FML all linked by an AGVS. [8][9][10]

The above classes of FMSs can be characterized by four types of flexibilities (Kusiak, 1985):

(1) FMM flexibility;

(2) materials handling system flexibility;

(3) computer system flexibility;

(4) organizational system flexibility encompassing:

(a) job flexibility;

(b) scheduling flexibility;

(c) short-term flexibility;

(d) long-term flexibility.

It would be appropriate to quantify these flexibilities. Some other views on the flexibility issue are presented in Dupont-Gatelmand (1982), Zelenovic (1982), Gustavsson (1984) and Stecke and Browne (1985). In order to make an FMS operational, there are a number of problems involved. They can be grouped into two classes (Kusiak, 1985):

(1) design problems;

(2) operational problems

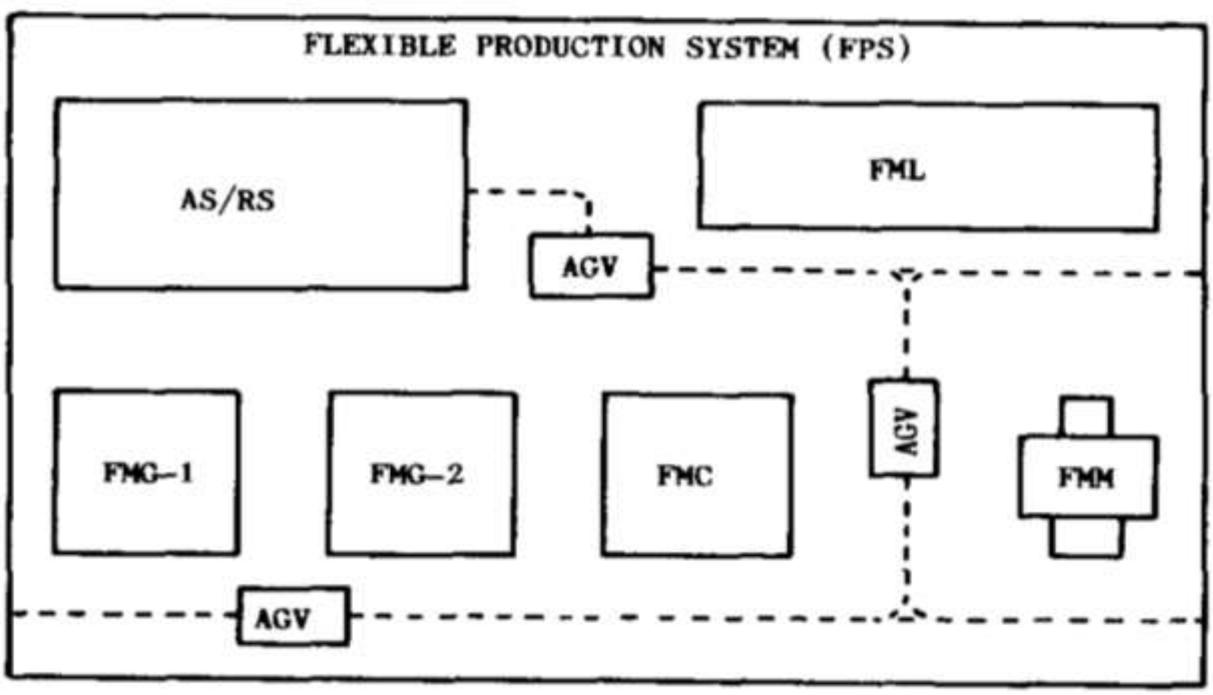

Fig 2: A flexible production system [11]

3. Design problems

The design class of FMS problems concerns the following subproblems: (1) economic justification; (2) selection of parts to be manufactured in an FMS. This issue arises due to the technological limitation restricting the shape of parts to be manufactured; (3) selection of machine tools; (4) selection of a storage system (in-process and/or central storage systems);

(5) selection of a material handling system; (6) selection of fixtures and pallets; (7) selection of computer software and hardware; (8) layout and integration of machine tools, storage system, materials handling system and computer system. To date only some of the above problems have been addressed in the operational research literature. The approaches applied to solve these problems are discussed below. Browne et al. (1984) and Whitney and Suri (1984) present frameworks for FMS design. systems and smart digicam integration in system imaginative and prescient systems have greater information on discrete as opposed to included system imaginative and prescient. [12][13]14][15]

The success of the machine vision machine is likewise dependent on the form of the parts being evaluated, irrespective of whether a discrete or included gadget is used. The higher the consistency of part placement and orientation, the better the device's overall performance may be.

3.1 FMS economic justification

Leimkuhler (1981) applied the traditional engineering economic approach to justify installing an FMS. This approach requires detailed information regarding parts to be manufactured and necessary machines. Hundy (1984) and Primrose and Leonard (1984) presented a qualitative approach to the FMS justification problem. Burstein and Talbi (1984) reviewed characteristics of the classification. [16]

3.2 Selection of parts

This problem arises in FMSs due to the following two issues: (1) design of existing machine tools and other technological components restricts shapes of parts to be manufactured in an FMS; (2) FMS performance. The first issue was addressed by Steinhilper (1984). He discussed the geometrical, technological and organizational criteria to be considered while selecting parts. The second issue was studied by Buzacott and Shanthikumar (1980). They applied a queueing network approach to discuss the impact of selected parts on FMS performance. [17] [18]

3.3 Selection of a storage system

This problem is very complex and involves a large number of design issues. The current operational research literature is concerned only with one part of this problem, namely the work-in-process and central storage capacities. Buzacott and Shanthikumar (1980) analyzed queueing network models for systems with work-in-process storage, central storage and a combination of both. [19] [20]

4. Operational problems

Due to the high capital involvement in FMSs, a high rate of their utilization is necessary to ensure a short return on investment. The sufficient rate of FMSs utilization can be assured by an appropriate planning, scheduling, control and monitoring strategies. Due to the relevance to the scope of interest of operational researchers, in this paper, the planning and scheduling methodologies are emphasized. In order to better understand the existing approaches to FMS planning and scheduling a new planning and scheduling framework is presented. This framework may be applicable to many instances among the discussed five classes of FMSs [21] [22] [23] [24]

Planning and scheduling framework

The presented framework incorporates optimization into the FMS planning and scheduling decision problems. An attempt is made to reduce the size of these problems either through aggregation or decomposition. Such an approach may assure solution of these problems in a practically acceptable time. Readers not familiar with the aggregation may refer to Liesegang (1984) who provides a theoretical basis for the general aggregation problem. Figure 3 shows the four-level planning and scheduling framework. The aggregate planning (level 4 in Figure 3) is, to some degree, similar to the aggregate model of Bitran et al. (1981, 1982). To reduce the problem size, the products should be grouped into product types. It is necessary, however, to modify the Bitran's et al. (1981, 1982) model to make it applicable to FMSs. The modification may concern both the objective function and the constraints. First of all, the workforce factor can be eliminated from this aggregate model. A typical objective function in an FMS aggregate model would include the sum of inventory costs, production costs and production capacities• It should be stressed that a production capacity can be a parameter in the aggregated FMS planning model• In the classical systems the production capacity was varied typically by hiring and firing policies. In FMSs, it is possible to vary the production capacity rather by changing the technological parameters; i.e. machining speed or feed rate. It should be remembered that this also influences the production costs. Resource grouping (level 3 in Figure 3) is a very important issue in the FMSs and is discussed mainly in the parts context in Kusiak (1985d). [25] [26] [27] [28] [29]

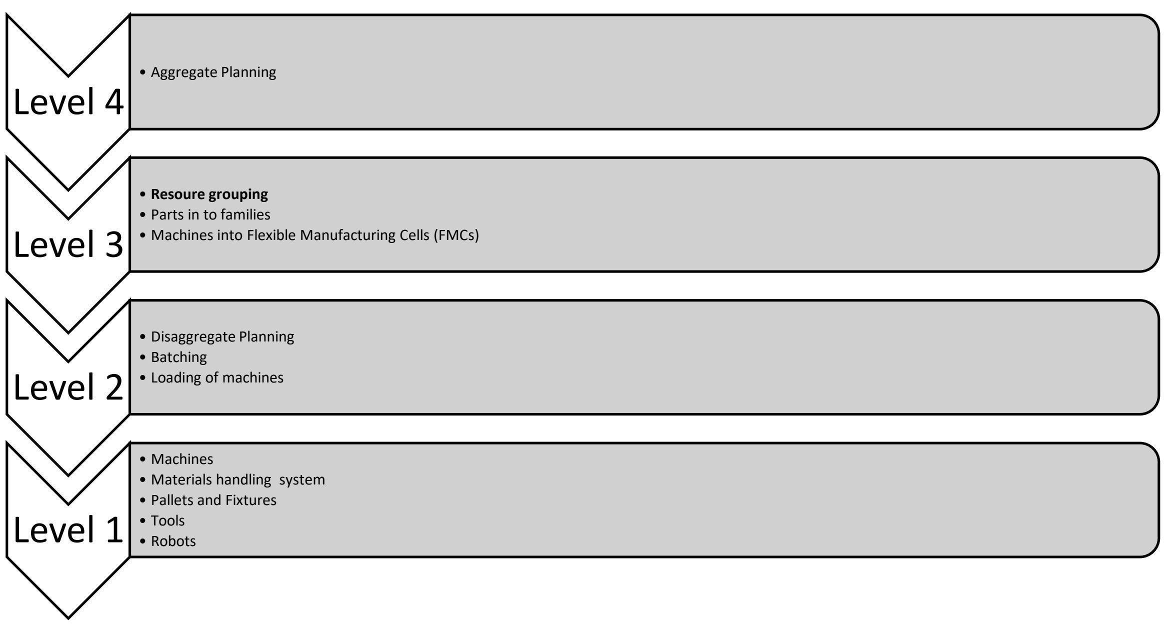

Figure 3. FMS planning and scheduling methodology [30]

Grouping parts and machines enables decomposition of the overall planning problems into subproblems• As indicated in Kusiak (1985d), grouping machines into Flexible Manufacturing Cells (FMCs) is considered as a logical grouping as opposed to the physical cellular concept in the classical Group Technology (GT) systems• In an FMS, the modularity and flexibility of the materials handling system enables grouping machines according to the current planning needs• Grouping machines in FMSs becomes a software issue, rather than the hardware layout problem in the GT manufacturing concept• In the planning and scheduling methodology proposed in this paper, the part families concept is different than in the classical GT systems.[31] [32] We should look at generation of part families as an aggregation process• At level 3 in Figure 3 parts can be aggregated subject to similarity of requirements on - tools, - fixtures, - pallets, - robot grippers, - machines. Here a number of different models could be formulated. However, the exact consideration would be beyond the scope of this paper. It should be stressed that this methodology assumes a relatively large number of part families. At level 2, families are optimally loaded onto FMCs. The objective function could have different forms. As an example, the minimization of production costs or travel costs could be considered. The constraint is such that a model could, for example, limit the number of part families loaded onto one FMC, limit the number of tools, pallets, etc. [33] [34] At this level, after the FMC loading problem has been solved, it may be necessary to split parts into batches. This, however, depends on the length of the planning period at level 1 and order sizes. The short planning period and the small size of orders may result in small batch sizes. If this would not occur, the batching model related to the aggregated model of Bitran et al. (1981) can be formulated for part families. After the FMCs have been loaded with part families, another optimization problem arises within each FMC. There is always some flexibility is assigning operations to machines. The problem of loading of machines with operations (level 2 in Figure 3) can be modeled in a number of ways. Loading problems of this nature have been formulated in Kimemia and Gerschwin (1980), Kusiak (1983), and Stecke (1983a). Alternate FMS planning and scheduling methodologies are presented in Nof et al. (1979), Hildebrant (1980), Kimemia and Gerschwin (1983), and Stecke (1983), Suri and Whitney (1984) and Kusiak (1985c). In the existing FMS literature only, models related to levels 1-3 have been exploited and those will be discussed in the next three sections. [35] [36] [37]

5. Resource grouping (Level 3)

This problem has been for the first time discussed in Kusiak (1983a, 1984) and then extended in Kusiak et al. (1985f). It was modelled as a clustering problem. Both integer programming and graph theory approach are presented in Kusiak (1983a) and Kusiak et al. (1985f), respectively. [39]

6. Disaggregate planning (level 2)

The machine loading problem has brought attention to many researchers. Stecke and Solberg (1981) presented five different loading policies for an existing FMS. An impact of these policies on machine scheduling (level 1) is discussed. Detailed nonlinear integer programming formulations of this problem are presented in Stecke (1983a). The discussed models include a set of constraints related to a limited space of a tool magazine. Kusiak (1983) introduced an additional set of tool life and part assignment constraints. Ammons et al (1984) developed a loading model which minimizes a number of operation-to-machine assignments while balancing the workload. The developed model is solved with three variants of the objective function. Chakravarty and Shtub (1984) linked the concept of grouping parts and machines (level 3) with the loading model [40] [65]

7. Scheduling (level 1)

There are two problems which have been covered by the operational research literature: (1) machine scheduling problem; (2) materials handling system scheduling problem, in particular: (a) Automated Guided Vehicle (AGV) scheduling problem; (b) stacker crane scheduling problem (a variation of this problem is known in the operational research literature as the order picking problem) The final say is all the machine vision system research has been around working, maintenance and industrial applications but none have focused on making it feasible or cheaper as the current technology is expensive and as a result is not accessible to many right now. [70] [76] [42]

7.1 Machine scheduling problem

Hitz (1979) developed a model for scheduling of flexible manufacturing line (FML). A solution generated by an implicit enumeration algorithm indicated superiority of the developed model compared to the classical approaches. The periodic release strategy proposed by Hitz (1979) has been exploited in Erschler et al. (1984). Chang and Sullivan (1984) presented a binary formulation of the FMS scheduling problem. To solve this problem they developed a two-phase suboptimal algorithm. Two stage scheduling approach to FMS is discussed in Dridi and Menaldi (1984). [56] [58] [59]

7.2 Scheduling of automated guided vehicles (A G Vs) problem

There has been little research done in the literature on the scheduling of AGVs. A vast majority of work has been published on the design and implementation of AGV hardware. Optimization papers have basically dealt with finding the optimum number of vehicles and some scheduling issues. Maxwell and Muckstadt (1982) optimized the number of empty AGV trips between machines subject to network flow constraints at each machine. The formulated model has been solved by an LP algorithm. They also discussed the vehicle interference issue and some of the AGV dispatching rules. Kuhn (1983) defined the traffic flow as a function of time, AGV velocity and route length. [60] [61] [62] This function was used to determine the number of AGVs. Muller (1983) presented a formula for a number of AGVs during the peak demand hour. Spur, Hirn and Seliger (1983) discussed a simulation approach to demonstrate the interaction between a number of AGVs, the vehicle speed, the number of pallets required, the buffer storage size, the vehicle waiting time and the part lead time. The First-In First-Out (FIFO) and the shortest processing time rules were used to schedule the vehicles. In a recent paper, Egbelu and Tanchoco (1984) presented a number of heuristic rules for the dispatching of AGVs. An integer programming approach to AGV scheduling problem is discussed in Cyrus and Kusiak (1984). To solve the developed large scale model, an efficient heuristic algorithm was developed. Villa and Rosetto (1985) and Yao (1985) presented interesting dynamic approaches to the optimization of material flow in FMSs. A simulation approach to the design of AGVS is discussed in Alshayeri et al. (1984). Survey papers by Kusiak (1985b) and Matson and White (1982) describe models and algorithms related to material handling systems. [66] [63] [71]

7.3 Order picking problem

Before the order picking problem in storage systems will be discussed, let us define some terms. A storage system (also an AS/RS) can be defined as a set of n storage locations. An aisle is a space in front of a set of storage locations where the stacker crane travels. The pick-up and delivery (P/D) point is the transfer point in and out of the storage system. A pallet refers to the volume stored in one location, although pallets may be of different weights owing to the different product types and quantities which they may contain. There exist several types of storage systems depending upon the level of automation and the corresponding number of storages, retrievals, or combination of both which the stacker crane can complete in one tour. Single-, dual- and multicommand systems can perform one, two and several storage or retrieval operations between successive visits to the P/D point, respectively, subject to the capacity limitations of the stacker crane expressed in terms of the number of addresses, weight or volume. Goetschalchx (1983) classified storage systems into three categories. A one-dimensional storage system is one in which travel time between any storage locations is determined by the distance in one dimension only, for example, a rack where height is not a factor affecting travel time. In a two-dimensional storage system, the travel time is determined by the distance along two axes, for example, a stacker crane operating with horizontal and vertical motion and confined to a single aisle. [48] [49] [45] A three-dimensional storage facility consists of a group of two-dimensional racks which are not independent, as in the case of a warehouse two or more stacker -ranges can travel in the same aisle through the use of transfer aisles. Batching policies involve the assignment of items to picking tours, while picking policies determine the sequence in which a number of items are picked in one tour. There are the following two order picking policies applicable to most of the currently available storage systems:

(1) one-dimensional order picking;

(2) two-dimensional order picking.

One-dimensional order-picking

In one-dimensional order-picking, storage and retrieval time is determined by the movement along one coordinate only. For single-command systems, Goetschalchx (1983) states that the picking time is fixed and independent from the sequence in which the items are picked. Let t_i be the time for the stacker crane to travel from the P/D point to item i, and N be the number of items to pick in a single order. The total single-command picking time is then

$$\sum_{i=1}^{N} 2t_{i.}$$

For dual-command trips in one-dimensional picking, the optimal picking sequence is obtained by successively pairing the two farthest unmatched locations, regardless of whether the trips involve two retrievals, two storages, or one storage and one retrieval. For multi-command systems, the optimal travel length is to travel from the P/D point to the farthest item, picking up all the items either on the way out or on the way back, giving a multi-command cycle time of $2t_N$.

Two-dimensional order-picking

In two-dimensional picking, Goetschalchx (1983) investigated the z-pick in which items have to be picked from both sides of a wide aisle, with the stacker crane alternating between each side of the aisle. Based on certain properties, the author reduced the z-pick problem to finding the shortest path in an acyclic graph, for a traversal picking policy. For a return picking policy, the optimal tour is to pick all the items on one side of the aisle before crossing and picking all the items on the other side. Graph theory was used to solve a two-dimensional order picking problem by Ratliff and Rosenthal (1983). It was assumed that the orderpicking vehicle picks only one order at a time and that an order does not exceed the vehicle's capacity in their model of a rectangular warehouse with crossovers only at the ends of the aisles. The algorithm is linear in the number of aisles, and the number of items in an order has little effect on the solution time. A fifty-aisle problem required one minute to solve on an Apple III using a code written in BASIC. A decomposition-based dynamic programming algorithm for solving a single-command system with due dates is presented in Kusiak et al. (1985e).

8. Basic tools and techniques applicable for solving FMS problems

Due to the complexity of FMSs a number of mathematical and methodological tools and techniques have been applied to model and solve the resulting FMS design and operational problems. These basic tools and techniques are: (1) mathematical programming; (2) simulation; (3) queueing networks; (4) Markov processes; (5) Petri nets; (6) artificial intelligence; (7) perturbation analysis. They are illustrated with sample references in

Table 1. A list of basic tools and techniques applied to FMSs and sample references

Tool or techniques	**Sample references**
Mathematical programming	Chang and Sullivan (1984), Kimemia and Gerschwin (1979), Kusiak (1983), Kusiak (1984), Kusiak (1985c), Stecke (1983).
Simulation	Akella et al. (1985), E1-Maraghy (1982), Mayer and Talavage (1976), Martin and Musselman (1984), Spur et al. (1983).
Queueing networks	Cavaille and Dubois (1982), Hildebrant (1980), Solberg (1980), Suri and Hildebrant (1984).
Markov processes	Alam and Gupta (1984).
Petri nets	Nahrahari and Viswandham (1984).
Artificial intelligence	Bourne and Fox (1984), Grosseschallau and Kusiak (1985).
Perturbation analysis	Suri (1981), Suri and Cao (1981), Suri and Dille (1984).

9. Conclusions

Most reviewed papers are seeking to resolve one or greater discrete issues which had been imposed with the aid of their preceding research. As a result, a couple of classes of papers can be located. Approaches showcase the principles and a short evidence of labor for a singular or advanced, small subarea of a research field.

In this paper a broad view on FMS problems has been presented. In the author's view, in order to make the design and operation of these new systems efficient, one has to consider not only the FMS itself but the interaction with the storage system and the CAD system. These three systems are closely interrelated. As an example, operation of the FMS depends on the quality of process plans provided by the CAD system. There are number of issues which should be a subject of future research programs:

(1) model and solve design problems, in particular, those which have not been covered at all in the operational research literature;

(2) develop planning and scheduling methodologies for each class of FMSs;

(3) exploit interaction between FMS and its environment;

(4) evaluate appropriateness to FMSs the currently used tools and techniques and design a more focused hybrid approach. Development of FMS technological components will undoubtedly generate many new research topics and the exciting FMS subject should attract many researchers in the future.

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