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A Review of Different Approaches to the FMS Loading Problem

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Abstract. Loading in flexible manufacturing systems (FMSs) is affected by the characteristics of the FMS under analysis, by the type of plant where the FMS is introduced, and by the production planning hierarchy where the loading module operates. We propose an analysis of the various aspects that influence the problem formulation, identifying the alternatives available in real systems and possible future evolutions. We then provide a survey of different approaches proposed in the literature to tackle the loading problem. Articles are classified according to the type of FMS analyzed, the objective function, and the constraints. Finally, based on our analysis, we suggest some problem issues which need to be addressed, and also directions for future research.

Key Words: FMS, loading survey

1. Introduction

Since the publication of the first articles on the short-term production-planning problems in flexible manufacturing systems (FMSs) proposed by Stecke and Solberg (1981) and Stecke (1983), much research has been devoted to the solution of these types of problems. In particular, among the levels of the production-planning hierarchy proposed by Stecke, the loading problem has received considerable attention. It seems important to organize past research, and to compare the state of the art research with the needs of the companies using FMSs. Some published articles provide frameworks to clarify the various approaches to the short-term production-planning problems in FMSs, point out unsolved problems, and provide directions for future research (Liu and MacCarthy, 1996; Rachamadugu and Stecke, 1994; Hedin, Malhotra, and Philipoom, 1994; Gray, Seidmann, and Stecke, 1993).

Few of the past contributions, however, focus on the loading problem. By narrowing the analysis to the loading problem, it is possible to be more specific and also consider aspects that are relevant only at the loading level. Also, it is possible to have a more detailed analysis of the literature than has appeared to date. Therefore, the analysis carried out in this article starts with an in-depth evaluation of various features that can affect the loading problem. Since some of these features have evolved over time, their impact on the loading problem has not been fully investigated in earlier research. Some future changes, as well as their impact on the loading problem, can already be foreseen.

2. Analysis of the loading problem

In this section, various elements that can affect the definition of a loading problem are analyzed. This analysis is carried out by grouping these elements into three main categories, namely,

- the characteristics of the FMS (Section 2.1);
- the characteristics of the plant where the FMS operates (Section 2.2);
- the interface of the loading module with the upper and lower level of the management hierarchy (Section 2.3).

Within each section, different topics are discussed in separate subsections. These are identified by labels to be used in other parts of the article to refer to the corresponding topics.

2.1. Characteristics of the flexible manufacturing system

The characteristics of the physical system introduce opportunities and constraints that must be taken into account when formulating a loading problem. In the following analysis, we identify the characteristics of each component of the physical system that may affect the problem formulation. One of our goals is also to understand how the components have evolved over time, and which new problems should be addressed. The analysis concentrates on the following components: machines, control system, tools and tool handling system, and parts, pallets, and fixtures.

2.1.1. Machines. (M1) A loading problem is strongly affected by the characteristics of the machines in the system. The first FMSs were composed of different machines with different capabilities. Slowly, this diversity was reduced and now many new FMSs have identical machines. This evolution is due to many factors:

- machining centers are more versatile than in the past, and therefore, they can perform almost all of the machining required. This new situation is due to increased precision, increased number of controlled axes, increased spindle power, and increased spindle speed;
- current FMSs are mostly dedicated to prismatic parts not requiring turning operations;
- due to the failure of some earlier FMSs, machine tool manufacturers tend to keep the systems simple and do not integrate different technologies (e.g., deburring, grinding, assembly, washing, inspection).

In the future, a multivendor solution may appear because of the standardization of the various interfaces, the introduction of open control architectures, and distributed control paradigms. Multivendor solutions may push again toward the integration of machines with different capabilities.

Given the evolution, it is important to differentiate between parallel machine FMSs and general FMSs because both systems can be found in real situations. These systems require different formulations of the loading problem.

(M2) As discussed in M1, FMSs composed of identical machines are frequently adopted. Moreover, even in a general system, identical machines of a given type are frequently present. Identical machines, when properly tooled, may be interchangeable. However, even identical machines are not exactly the same. Therefore, when a given part requires a high level of accuracy, it may happen that a machine or a set of machines is chosen, and is specially tuned to machine that part. From that time on, while some parts can be assigned to all of the identical machines, other parts have to be processed on these machines.

(M3) When tight position tolerances are present, it may be required that two or more operations are performed on the same machine. This is due to the fact that pallet repositioning introduces an error. This constraint is not normally important at a loading level because most of the loading modules do not allocate a single operation but allocate the whole part program or set of operations already grouped (also taking into account this constraint). In the future, however, when it may be possible to split part programs (see P3, P4, and P5 in the following Section 2.1.2), these considerations could become relevant.

2.1.2. Control system. The behavior of an FMS is affected by the characteristics of its control system. At present, the control system of most of the existing FMSs is based on a "supervisor" coordinating the behavior of the various devices (machines, transport system, etc.) and on a set of Computerized Numerical Controls (CNCs) and Programmable Logic Controllers (PLCs), each of which controls a specific device. The supervisor is proprietary software running on a central computer while CNC and PLC are based on proprietary hardware managed by proprietary software. Even if, in theory, the control system should result in highly flexible FMSs, in practice the lack of standardization results in a very rigid system (in which the different devices are seen as proprietary black boxes connected by means of software interfaces written in an ad hoc manner). This situation has many drawbacks:

- it is difficult to integrate hardware devices supplied by different companies into the same system;
- it is difficult to integrate the FMS with other systems operating in the same company;
- it is difficult to introduce a new control system or to change the control hierarchy even slightly;
- it is difficult to integrate new sensors in an existing control architecture.

Some attempts have been made to change this situation. In the late 1980s, for instance, the concept of a standard platform for automation was put forward by some companies like IBM with "DAE" and ITP with "Mainstream." This attempt failed because even if the "standard" platform provided a lot of software services for easy integration of different devices, it was a proprietary platform and was not accepted by FMS manufacturers. In the 1990s, many projects to make CNCs more open and easy to interface were started. In particular, OSACA (followed by HUMNOS) was developed in Europe, OMAC-TEAMAPI in the US, and OSEC in Japan. Even if the results are not yet fully applicable, these projects are paving the way for standard, open, and PC-based CNCs.

From the point of view of the supervisor, the introduction of an object orientation paradigm improved software reusability and gave an opportunity to split the supervisor into a number of small autonomous processes. The introduction of the concept of object bus (like the one proposed by CORBA), may allow spreading of various objects that constitute the supervisor among the various computers of the FMS (including the PC-based CNCs), and may allow decentralized control to take place.

Even if this evolution seems promising, at present control systems are still constrained by the problems outlined earlier. Some of these problems directly affect the way the loading problem is formulated. In particular, since the CNC is seen as a proprietary black box, the part programs are seen as indivisible wholes, even if a lot of different operations are performed inside a part program. The results of this situation are now listed.

(P1) All of the tools required to execute a part program are requested at the beginning of the part program; therefore even if the first tool required by a part program is available, the part program cannot start if one or more tools needed later are not present.

(P2) A tool required in a given part program is considered busy during the entire time the part program runs, even if the tool has already been used and will not be used again by that part program.

Conditions P1 and P2 imply that a tool is kept busy during the whole part program even if typically it will be used only for a small fraction of the total time (for instance in a typical part program lasting 8 minutes, a tool is normally used or manipulated for only about 30 seconds).

This aspect becomes particularly important when tool-sharing policies are adopted. Up to now in the literature, this problem has scarcely been addressed (see Section 4.2.2) even if it may become crucial in real situations where one may want to reduce the number of tool copies (in particular, of very expensive special tools) by using tool sharing.

Other aspects related to part programs and part program management deeply affect the way a loading problem can be stated. In particular, at present a part program is seen as an indivisible fixed sequence of given operations. This approach has the following consequences:

(P3) The whole part program must be performed on the same machine. No splitting of the part program among the machines is allowed.

(P4) The sequence of operations is given. The sequence is defined by the process planner taking into account both technological constraints and the fact that an operation sequence must be specified. In practice, even if the part program contains a sequence of operations, only a few of them are connected by precedence constraints. In theory, the same part could be obtained using many different sequences defined over the same set of operations.

(P5) No alternative operation can be considered. A given feature of a part can be obtained in various ways. One way could be to use a special tool that completes all of the machining in one operation, another could be to use a sequence of standard tools that does the same operations. For each standard tool there could be an alternative tool that performs the same task with different feed or cutting speed. Therefore, in principle, there are many alternatives for each operation and some of them could be made available so that a selection can be made at a management level.

At present, none of the alternatives suggested in P3, P4, and P5 is available in real systems. Therefore the problem of process selection is not normally considered within loading problems (see Liang, 1993, 1994; Hsu and De Matta, 1997). As soon as some degrees of freedom become available, which seems reasonable given the evolution of control systems and CNCs, the nature of the loading problem could change radically. Indeed, the options pointed out in P3, P4, and P5 would introduce new degrees of freedom and could modify the constraints associated with work assignment to the resources (machines, tools, fixtures) of the system.

2.1.3. Tools and tool handling systems. Tools are an important resource in FMSs and most of the loading models proposed in the literature pay particular attention to the management of tools. In our analysis, in addition to the tool itself, other issues such as the way tools are handled within the system are also considered. Regarding the tools, two considerations need to be addressed:

(T1) *Tool life issues.* Tools are subject to wear and often need to be reconditioned. Tool life depends on the workpiece material and on cutting conditions. It can be very long when cutting aluminum (on the order of hours of cutting), short for cast iron (on the order of 20 minutes of cutting), and very short for special materials (like those used in the aeronautical industry, such as titanium). Once the tool is worn, it needs replacement or reconditioning, processes which are performed in the tool room. Reconditioning lead time can be extremely variable because it depends on how frequently worn tools are brought to the tool room, the queue in the tool room, and the time actually taken by the reconditioning operation. Also, the tool room does not normally work during an unpersonned shift, while an FMS normally does. This way of operating the system introduces a hard constraint regarding the availability of tools in the unpersonned shift (see also E1).

(T2) *Number of tool copies.* Since tools are expensive, normally only few copies of a given tool type are available in the system. As a consequence, the loading method, in order to generate feasible plans, should take into account the availability of tool copies while assigning the load to the various machines (see also TH2).

Considerations T1 and T2 refer to the tools used in the system. Tools, however, are handled by numerous devices which in turn introduce constraints that may affect the loading decisions. In particular, regarding the components of the tool handling system, it is important to consider the impact of tool magazines and the tool transport system (if available) on the definition of the loading problem.

(TH1) *Tool magazine capacity.* Tool magazines have finite capacity. This puts constraints on the set of operations that can be assigned to a machine during a given period (see also TH2). Machine tool builders normally try to equip their machining centers with large tool magazines (50–60 tool slots is common) in order to reduce the impact of the capacity constraint. However, large tool magazines result in high seek time, and sometimes greater than the time required to perform an operation. This results in high spindle idle times between two different operations. This problem is becoming serious in newer machining centers due to:

- high cutting speed which reduces cutting times;
- high axes acceleration (of the order of 20 meters per square second) obtained with linear motors, that reduces the time devoted to rapid movement;
- very fast tool exchange (2.5 seconds cut to cut), which reduces the unproductive time of the spindle;
- small working range (cube 600 millimeters), which reduces the number of identical parts on the same pallet and therefore the number of identical operations performed by the same tool.

These elements together mean shorter operations and therefore more frequent tool exchanges. For instance, hole making or tapping operations can require a tool change every 10 seconds or less. To cope with this situation, some newer machining centers are equipped with small tool magazines (20 tool slots) with very short seek times. In this case, the constraints on tool magazine capacity can become the most important concern while solving a loading problem.

It should also be noted that tools differ in dimensions and therefore the space they occupy in the tool storage devices is not always the same. Perera and Carrie (1987) proposed to classify the tools in the following three classes:

- *Class I.* Tools that occupy only one tool slot and can be put in the magazine near both Class I and Class II tools;
- *Class II.* Tools that occupy only one tool slot in the magazine but can be put near Class I tools only (otherwise there is interference);
- *Class III.* Tools that occupy more than one tool slot (no tool can be put close to them).

Alternatively, in some type of tool magazines (like planar tool magazines), an area with wider spaces among the slots is reserved for big tools. These considerations show that at a loading level, the constraint on tool magazine capacity must be stated considering the physical device available.

(TH2) *Tool transport system.* Some FMSs are equipped with an automatic tool transport system that can exchange the tools with the tool magazines of the various machines and with a central tool store. If properly managed, this device can allow tool sharing among the machines, thus reducing the importance of the constraints on the number of tool copies and on the tool magazine capacity (see T2 and TH1). When a tool-sharing policy is adopted, a constraint on tool traffic must be introduced because the tool transport system is itself a physical device with finite capacity. Tool transport systems with speed on the order of 100 meters per minute and tool exchange time with the magazines of 10 seconds (to unload a tool and load a new one) are already available. A Brite project (MOD-FLEX-PROD BE96–3883) is producing a prototype of a tool transport system equipped with linear motors having peak speed of 200 meters per minute, acceleration of 5 meters per square second, and tool exchange time of 5 seconds.

2.1.4. Parts, pallets, and fixtures. For machining parts in FMSs, they must be correctly positioned, held, and transported within the system. Therefore parts need to interface with the various devices of the system. For this reason, they are mounted on fixtures which are mounted on pallets. Pallets and fixtures represent the interface between the FMS and the parts to be machined. While the pallet represents the interface with the FMS, and is normally standardized (see, for instance, ISO 8526/1), fixtures are the interface with the parts which differ in shape, material, and required operations. As a consequence, fixtures cannot be standardized and are dedicated to part types. The presence of this specifically dedicated device introduces important constraints at the loading level which is analyzed below.

(F1) *Part loading.* Normally parts are loaded manually on the correct fixtures because of the positioning precision required and because each part type must be handled differently. In the last few years, however, robotized load/unload has begun to be used especially in FMSs producing few part types. When automatic load/unload is present, the constraints introduced in the loading phase to take into account the unpersonned shift (see E1 in Section 2.2) are somewhat relaxed. This leads to a possible simplification of the problem.

(F2) *Fixture cycle time.* As already mentioned, parts can only be mounted on the correct fixture. After parts are loaded, the fixture is brought either to the central storage or to the input/output buffer of a machine (normally a pallet shuttle) to wait for machining to take place. After one or more stops at the various machines where the necessary operations are performed, the fixture can go to a washing station and then to an inspection station. Therefore, before going back to the load/unload station to load new raw parts, the fixture has to complete a time-consuming cycle. The length of this cycle affects the number of parts per unit time the FMS can produce with that fixture. Therefore, the throughput of the FMS for a given part type is limited not only by the capacity of the machines, but also by the number of available fixtures of the proper type. This constraint can be considered at different levels of the production planning hierarchy. However, if it is not considered at a higher level (in the part selection phase, for instance), it must be included in the formulation of the loading problem.

(F3) *Parts requiring more than one fixture.* Since a fixtured part is not completely accessible, it is normally necessary to change the position of the part in order to complete all the operations required. Normally, different placements of the part are obtained on the same fixture mounted on a pallet. It can sometimes happen, however, especially when numerous inclined operations are required, that a single fixture is not enough to complete the working cycle and therefore two or three fixtures in sequence are required. In this situation, the part, after having completed all the placements on one fixture, is unloaded and put aside until a new pallet with the proper fixture arrives. At this moment, the partially machined part is loaded on the new fixture to complete its working cycle. Obviously, there is a certain coupling between the different fixtures required for the same part. Also, the space available to hold the parts unloaded from the first fixture can be limited. This problem must be addressed partly at the loading level and partly at a lower level of the production planning hierarchy (at the dispatching level, for instance). At the loading level, it could be required that the two different fixtures are machined by the same machine to avoid synchronization problems at a lower level. The problem described is not very frequent but, when present, deeply affects the structure of the loading problem (De Vecchi, Parola, Tolio, and Semeraro, 1993).

(F4) *More than one part type on the same fixture.* When the quantities required for certain part types are very small (which is frequent if the part mix is wide), it can be useful to mount on a pallet a fixture able to hold different part types. (For instance, it is possible to use a "cube" mounted on a pallet and dedicate each face of the cube to different part types.) While normally it is reasonable at a loading level to allocate the load expressed in terms of the number of fixtures to be machined, in this case it is necessary to input parts. Even if, in principle, each part type of a given fixture could be machined by different machines, the loading module should try to avoid frequent pallet changes to reduce unproductive time. Therefore, when inputting parts on a machine, the fact that some part types will go on the same pallet must be taken into account.

2.2. Characteristics of the plant where the FMS operates

In Section 2.1 the characteristics of the FMS that directly or indirectly affect the loading problem have been considered. However, an FMS is normally introduced within a broader plant that is part of the whole firm which in turn cooperates with other firms. The characteristics of the socio-technical system where the FMS operates deeply affect the way the loading problem may be stated. Following are some of the issues related to the FMS environment.

(E1) *Characteristics of the shifts.* Even if FMSs have a high degree of automation, people are normally present to supervise the system, load/unload parts (see F1), introduce new fixtures and remove unnecessary ones, and remove worn tools and replace them with new ones. The behavior of the system is therefore affected by the availability of humans. Therefore it can happen, for instance, that fixture changes can be made only in particular shifts or even in particular periods within the shifts. This must be taken into account while solving a loading problem. The most critical problem, however, is that normally one of the shifts is unpersonned and therefore no load/unload or tool reconditioning can take place during that shift. This situation introduces heavy constraints on the loading phase and can totally change the nature of the problem when compared with the personned shifts.

(E2) *Tool room management.* Normally, the tool room serves all the machines of the plant and not just the FMS. The policies within the tool room may therefore take into account various needs and normally, at loading level, tool room behavior should be considered as a constraint. Therefore lead times to recondition a tool may be quite different from plant to plant and can introduce important constraints at the loading level.

(E3) *Preventive maintenance.* Normally, each machine of the FMS undergoes preventive maintenance following the instructions of the machine tool manufacturer. Therefore, following the schedule of the maintenance team of the plant, some machines or the whole FMS may be unavailable for particular periods of time. This introduces a constraint at the loading level on the capacity of the machines.

(E4) *Downstream assembly operations.* Parts produced in the FMS may be components of the same product assembled in a system downstream. In this case it is sometimes necessary to introduce, at the loading level, constraints regarding the ratio in which the various part types must be produced.

2.3. Production planning hierarchy

A loading model is a component of a production-planning hierarchy and must therefore fit within the whole architecture. The characteristics of the problem are therefore deeply affected by the characteristics of the higher and lower levels of the hierarchy. In particular, planning horizons, input data, output data, and production-planning goals reflect the philosophy of the whole hierarchy (Kuhn, 1995). Some of the characteristics of the higher and lower levels of the production-planning hierarchy affecting the loading module are discussed below.

2.3.1. Higher level. The characteristics of the higher level can be quite diverse. Indeed, depending on the type of firm and the market in which it operates, at this level it is possible to find MRP, MRP II, ERP modules as well as production-planning modules based on JIT or OPT or simple reorder point mechanisms. Also, it is possible that between these modules and the loading level a part type selection phase is introduced. In any case, the higher level will transmit some requests to the loading level that the loading module must try to satisfy. Some of the characteristics of these requests deeply affect the loading problem as described below.

(H1) *Requests are handled periodically or continuously.* Most of the models proposed in the literature assume periodic handling of requests. It can happen, however, especially for small firms supplying components to different companies, that dynamic behavior is required.

(H2) *Due dates/release dates.* Normally, due dates and release dates are managed by higher level modules and therefore at a loading level, all parts are assumed to be available at the beginning of the planning horizon and due at the end of that horizon. However, if due dates and release dates are not handled at the higher level, the nature of the whole loading problem changes.

(H3) *Priorities.* In many real applications all part types cannot be treated in the same way; for instance, some parts may be required by clients that are strategic for the firm, yet other part types may be very important because of contractual constraints. Therefore, in practice, it may be necessary at the loading level (or at the part type selection level) to take into account the different priorities of the parts especially if some constraints of the problem formulation have to be relaxed to guarantee feasibility. Even if priority mechanisms are used with caution, it is almost impossible to get rid of them especially in small firms that have to follow the desires of their customers.

2.3.2. Lower level. Below the loading level there can be several levels in the production-planning hierarchy. All these levels, being closer to the real system, are increasingly affected by the characteristics of the FMS. At the loading level, however, most of the details of these lower levels are not very important. In any case at least two issues must be considered.

(L1) *Unforeseen events.* Unforeseen events of little importance (e.g., breakage of a tool) are normally dealt with directly at the lower level. However, problems that may change the capacity of some resources of the system considerably will also have an impact at a loading level and normally require a new plan from the loading module or possibly the detection of infeasibility to be sent to a higher level. The new plan, after a disruption, must take into account not only the current productive capacity of the system, but also the distribution of the resources (especially tools) within the system at the time of the failure. Speed in the generation of the plan is generally a major issue in these situations.

(L2) *Limits of the lower levels.* Sometimes the levels below the loading module introduce constraints that are not related to the FMS itself but are due to the management software. For instance, a tool transport system may be available in the FMS but tool-sharing policies cannot be used because the scheduling software cannot handle this complexity. In such cases the tool transport system is normally only used to manage the flow of worn tools. Also, the problem related to part program splitting (see P1 and P5), to some extent, falls into this category.

3. Survey of the different problem formulations

Having defined in the previous Section 2 the characteristics of the loading problem, in this section, various formulations of the loading problem which have apperared in the literature are analyzed. The analysis concentrates on articles that formalize the loading problem as a mixed integer programming or as a 0–1 programming problem. However, some articles, not based on these methodologies, are also considered. Most of the articles on loading propose mixed integer or 0–1 programming formalization as a starting point, and then tend to modify slightly the model or propose heuristic techniques in order to overcome computational problems.

The goal of the analysis is to see how the issues discussed in Section 2 are actually formalized in the proposed models. At the same time, the analysis provides the basis for the evaluation of the areas for future research directions. In Section 3.1, a brief analysis of the evolution of the literature is first presented. Then the approaches which have appeared so far are grouped on the basis of some key assumptions that affect the whole problem formulation. Finally, a detailed oveview of the objective function and the constraints considered in the various formulations are presented.

3.1. Evolution of the loading problem literature

The loading problem proposed by Stecke (1983) is as follows:

> Allocate the operations and the required tools of the selected part types among the machine groups subject to technological and capacity constraints of the FMS.

The initial articles in this area were proposed by Stecke and Solberg (1981) and Stecke (1983). It is possible to identify an initial period in the literature which is strongly affected by these pioneering articles. Most of the contributions in this period tend to analyze the advantages and disadvantages of the models proposed by Stecke (1983) and to propose alternative solutions for various FMS types, sometimes concentrating on other aspects of the loading problem.

Rajagopalan (1986) formulated a mixed integer programming problem which solves the problems of part grouping and part and tool allocation at the same time, and eliminates some nonlinearities of the model given by Stecke. Berrada and Stecke (1986) pointed out that the linearization process used by Stecke (1983) may not always be viable. They proposed a new nonlinear mixed integer programming formulation.

Lashkari, Dutta, and Padhye (1987) added to the formulation of the operations allocation problem given by Stecke (1983) the aspects of refixturing and limitations on the number of avilable tools. The nonlinear model proposed in Lashkari et al. (1987) was subsequently reconsidered and simplified by Wilson (1989). He showed how the constraints regarding the number of available tools can be extended to consider other scarce resources as well.

After the initial period described above, a second generation of articles emerged. Authors tended to redefine the characteristics of the loading problem. Han, Yoon, and Hogg (1989) took as a reference system a flexible manufacturing system provided with tool transport devices (see also TH2). They proposed a loading model in which parts can be assigned to machines that do not have all the required tools. In this case tools can be taken from other machines by means of the tool transport device. The objective function adopted is the minimization of the tool traffic. In general, this second phase is more concerned with the problem of tool management, since several authors recognized that tools are expensive, and therefore possibly a scarce resource (De Werra and Widmer, 1991; De Vecchi et al., 1993; Amoako-Gyampah, Meredith, and Raturi, 1992; Amoako-Gyampah, 1994; Sodhi, Askin, and Sen, 1994; Song, Hwang, and Kim, 1995; Roh and Kim, 1997; Colosimo, Conti, Grieco, and Tolio, 1998).

Lee and Jung (1989) showed that the production phase of an FMS must take into account different objectives at the same time. They also pointed out that the previously proposed models were based on a single objective. Therefore, they introduced a multiple objective problem and tackled it by means of goal programming.

Another interesting tendency of this second phase of the literature was that it considered together different problems connected with the loading phase, sometimes proposing new hierarchies for the whole production planning problem. For instance, Chen and Askin (1990) and Kumar, Tewari, and Singh (1990) tried to find a joint solution to the grouping and loading problem. Sawik (1990) proposed a hierarchy for the production planning task based on part type selection, machine loading, part input sequencing, and operational scheduling. Chen and Chung (1991) considered loading and routing problems. Hsu and De Matta (1997) pointed out that feedback among the various models of the hierarchy is very important and proposed a model to evaluate the feasibility of a loading problem.

3.2. Types of loading problems

Some characteristics of the loading problem described in the first part of the article deeply affect the problem formulation. In practice, totally different problems can be obtained by varying some of the key assumptions. Therefore it seems important to analyze the literature by dividing various approaches on the basis of the type of problem they tackle. In Sections 3.2.1 and 3.2.2 a grouping of the papers is proposed based on the following categories: (a) parallel vs. general FMSs and (b) tool management strategy.

3.2.1. Parallel vs. general FMSs. As discussed in M1, FMSs can be either general or composed of identical machines (parallel machines). Even if the parallel machine FMSs

Table 1. Physical structure.

General systems	Parallel machine systems
Stecke and Solberg (1981), Stecke (1983), Shanker and Tzen (1985), Stecke (1986), Rajagopalan (1986), Berrada and Stecke (1986), Greene and Sadowski (1986), Stecke and Kim (1986), Lashkari et al. (1987), Sarin and Chen (1987), Ventura et al. (1988), Shanker and Srinivasulu (1989) Chung and Doong (1989), Lee and Jung (1989), Wilson (1989), Sawik (1990), Chen and Askin (1990), Ram et al. (1990), Kumar et al. (1990), Kumar et al. (1991), Mukhopadhyay et al. (1992), Liang and Taboun (1992), Kim and Yano (1993), Liang and Dutta (1993), Moreno and Ding (1993), Liang (1993), Liang (1994), Sodhi et al. (1994), Sodhi et al. (1994), Hsu and De Matta (1997), Atmani and Lashkari (1998).	Kusiak (1985), Ventura et al. (1988), Han et al. (1989), Shanker and Rajamarthandan (1989b), Bretthauer and Venkataramanan (1990), De Werra and Widmer (1991), Chen and Chung (1991), Amoako-Gyampah et al. (1992), Stecke (1992a), De Vecchi et al. (1993), Kirkavak and Dincer (1993), Amoako-Gyampah (1994), Grassi et al. (1995), Kuhn (1995), Song et al. (1995), Colosimo et al. (1998).

Note. Papers appearing in more than one cell deal with various system configurations.

could be simply seen as a special case of the general system, they are considered separately for two reasons:

- there are several FMSs with this structure (i.e., it is a relevant subgroup);
- it is possible to exploit the particular structure of the system and propose formulations not suited for the general case.

In Table 1, the articles considered in the present survey have been divided following the two categories described above. It can be seen that most of the articles have addressed the general case. One of the reasons could be the strong influence of the earlier works (based on general FMSs).

3.2.2. Tool management strategy. The nature of the loading problem is deeply affected by the strategy of managing the tools within the system. In particular, a distinction can be made among batching, flexible, and hybrid tool management. Among the three strategies listed, the batching strategy is the most common one. With this strategy, the configuration of each tool magazine is "frozen" for a given length of time; during this period each machine can only use the tools which are available on its tool magazine. After this period, the configuration of the tool magazine is changed and a new period starts. In some formulations, the end of each period is the same for all the machines, in others it may be different. Within this category we also include the strategy named "flexible" as defined by Stecke and Kim (1986).

An opposite approach is adopted within the flexible strategy. With this strategy tools are brought to the machines while the system is working, thus generating a continuous evolution of the configuration of the tool magazines. The tool flow depends totally on the needs of the machines which in turn are derived from the flow of parts.

The hybrid strategy can be found between the flexible and the batching strategy. With this strategy, even if tools can be brought to the machines while the system is working, some limitations are introduced. For instance, some "critical" tools may be assigned to the machines for given periods of time or tools may have a "preferred location" they should reach whenever possible.

The proposed classification resembles the one given by Amoako-Gyampah et al. (1992) although there are some differences in the way "flexible" and "hybrid" are defined. Another classification that has been frequently adopted is the one proposed by Carrie and Perera (1987) in which tool management strategies are divided into two classes, namely, tool dominant and part dominant. The former is similar to the batching strategy defined above and the latter is similar to the flexible strategy. An interesting classification is also given by Veeramani, Upton, and Barash (1992).

The adoption of one of these three strategies (batching, flexible, and hybrid) is not independent of the structure of the physical system. In practice, a flexible or hybrid strategy is favored by the presence of an automatic tool handling system (otherwise an operator should continuously move the tools following the needs of the machines). In adopting a flexible or hybrid strategy, one should also take into account the problems related with the control system described in P1, P2, and P3 because the control system could strongly reduce the potential advantage introduced by an automatic tool transport system.

In Table 2, the articles considered in the present survey are divided into the three categories described so far. It is noted that most of the articles concentrate on the batching approach even though in recent years some articles dealing with the hybrid and flexible approaches have appeared.

Table 2. Tool management policy.

Flexible	Lee and Jung (1989), Amoako-Gyampah et al. (1992), Katayama (1994), Roh and Kim (1997)
Hybrid	Han et al. (1989), Amoako-Gyampah et al. (1992), De Vecchi et al. (1993), Amoako-Gyampah (1994), Sodhi et al. (1994), Grassi et al. (1995), Song et al. (1995), Colosimo et al. (1998)
Batching	Stecke and Solberg (1981), Stecke (1983), Kusiak (1985), Shanker and Tzen (1985), Rajagopalan (1986), Berrada and Stecke (1986), Stecke (1986), Stecke and Kim (1986), Lashkari (1987), Sarin and Chen (1987), Ventura et al. (1988), Moreno and Ding (1989), Wilson (1989), Shanker and Srinivasulu (1989), Chung and Doong (1989), Shanker and Rajamarthandan (1989), Sawik (1990), Kumar et al. (1990), Chen and Askin (1990), Bretthauer and Venkataraman (1990), Col et al. (1990), Ram et al. (1990), Kumar et al. (1991), De Werra and Widmer (1991), Chen and Chung (1991), Stecke (1992a), Amoako-Gyampah et al. (1992), Mukhopadhyay (1993), et al. (1992), Liang and Taboun (1992), Kim and Yano (1993), Kirkavak and Dincer Liang and Dutta (1993), Moreno and Ding (1993), Liang (1993), Sodhi et al. (1994), Sodhi et al. (1994), Amoako-Gyampah (1994), Liang (1994), Katayama (1994), D'Alfonso and Ventura (1995), Kuhn (1995), Hsu and De Matta (1997), Atmani and Lashkari (1998)

Note. Papers appearing in more than one cell deal with various models.

3.3. Objectives and constraints

Having looked at the loading problems, it is useful to analyze the articles in greater detail. For this purpose, this section provides a detailed analysis of the objective functions and the constraints adopted by various authors in their formulations. The results of this analysis are provided in Table 3 (dealing with the objective functions adopted). Table 4 reports on the constraints included in the formulations. Sections 3.3.1 and 3.3.2 interpret these tables in some detail.

3.3.1. Objective functions. As can be seen in Table 3, in some papers more than one objective function is indicated. This normally means that different models are given in the same articles. In some articles however, combined objective functions are proposed.

Analysis of Table 3 shows that the objective functions listed belong to two different categories. Indeed, the first category (A, B, C, D) includes objective functions which are directly connected with the goals of the firm. In this group objective functions, such as cost minimization, flow time or work in process minimization, minimization of the number of late part types, and minimization of makespan, are considered.

The second category (V, W, X, Y, Z), however, includes all the objective functions which are not directly connected with the goals of the firm. This group includes objective functions, such as maximization of the workload balancing among the machining centers, minimization of the load of some particular subsystem (workpiece transport system, tool transport system, refixturing stations), and maximization of the number of alternative routings for the various parts. These surrogate objectives allow for an easy formulation and stand as proxy for the ultimate firm goals.

From Table 3, it can be seen that most of the articles that include objective functions of the first category adopt makespan minimization or cost minimization; very few articles use due date-related measures (e.g., minimization of the number of late part types). From the table it can be seen that most of the objective functions considered by the various authors fall into the second category.

3.3.2. Constraints. The constraints introduced in various formulations are listed in Table 4. They are grouped as assignment constraints, capacity constraints, and management constraints. In the assignment constraints, all constraints which limit the way the work can be assigned to the machines are considered (see also M2 and M3). Besides technological considerations, another reason for the introduction of an assignment constraint is the reduction of computational complexity. Indeed, by limiting the number of possible assignments, the search space can be limited to a great extent (consider, for instance, the constraints type "a_3" which enforces the fact that a part type can be assigned to only one machining center).

The second group of constraints, the "capacity" constraints, are introduced to take into account the fact that the FMS has finite capacity resources. Constraints such as the tool magazine capacity (the number of tool slots is finite, see also TH1), the limited number of pallets/fixtures (see also F2), and the limited number of tool copies for each tool type (see also T2) fall into this category. Also, constraints on the available machining time fall into this category because it is directly related to the amount of work that can be assigned to

Table 3. Objective functions.

	A[a]	B[b]	C[c]	D[d]	W[e]	X[f]	Y[g]	Z[h]
Stecke (1983)					1, 2	1	X	
Shanker and Tzen (1985)			1		2			
Kusiak (1985)	1							
Berrada and Stecke (1986)				X				
Rajagopalan (1986)				X				
Stecke (1986)					1	1	X	
Stecke and Kim (1986)					2			
Sarin and Chen (1987)	1							
Lashkari et al. (1987)						1, 3		
Ventura et al. (1988)				X				
Shanker and Srinivasulu (1989)				X				
Wilson (1989)						1		
Han et al. (1989)						2		
Lee and Jung (1989)		X			1			
Shanker and Rajamarthandan (1989)						1		
Moreno and Ding (1989)			1		2			
Chung and Doong (1989)				X				
Ram et al. (1990)	1							
Chen and Askin (1990)				X	1	1	X	
Kumar et al. (1990)					2	1		
Sawik (1990)				X				
Bretthauer and Venkataramanan (1990)							X	
Co et al. (1990)					1			
De Werra and Widmer (1991)				X				X
Chen and Chung (1991)							X	
Liang and Taboun (1992)	3							
Bernardo and Mohamed (1992)	2			X				
Mukhopadhyay et al. (1992)					2			
Stecke (1992a)					2			
De Vecchi et al. (1993)				X				
Kim and Yano (1993)				X				
Kirkavak and Dincer (1993)					1			
Liang (1993)	1			X				
Liang and Dutta (1993)	1			X				
Moreno and Ding (1993)			1		2			
Liang (1994)	1			X				
Sodhi, Askin, and Sen (1994)	2		2					

(*Continued on next page*.)

Table 3. (*Continued.*)

	A[a]	B[b]	C[c]	D[d]	W[e]	X[f]	Y[g]	Z[h]
Katayama (1994)				X				
Sodhi et al. (1994)				X	1	1	X	
D'Alfonso and Ventura (1995)						1		
Grassi et al. (1995)						2		
Kuhn (1995)				X				
Song et al. (1995)						2		
Hsu and De Matta (1997)	1							
Roh and Kim (1997)			2					
Atmani and Lashkari (1998)			1					
Colosimo et al. (1998)						2		

[a]A = cost related measures: (1) minimization of manufacturing costs; (2) minimization of inventory costs; (3) maximization of the total profit (difference between income and costs).
[b]B = minimization of flow time and minimization of WIP.
[c]C = due date related measures: (1) minimization of the number of tardy jobs; (2) minimization of the total (weighted) tardiness.
[d]D = minimization of makespan or maximization of system production rate or maximization of system saturation.
[e]W = optimal system balancing: (1) maximization of the differences of load among the MCs; (2) minimization of the total overload and underload of the MCs.
[f]X = minimization of the load of some particular subsystem: (1) workpiece transport system; (2) tool transport system; (3) refixturing stations.
[g]Y = maximization of the number of alternative routings.
[h]Z = minimization of the number of tool magazine configuration changes.

each machine. Similarly, type "y" constraints dealing with the limited tool life (see also T1) belong to this category because they limit the amount of work which can be assigned to a single tool.

Finally, the management constraints introduce management preferences and/or limitations due to other planning modules that are connected with the loading module. Constraints regarding workload balancing among the machines and those enforcing due date requirements (see also H2) fall into this category. Another type of constraint which could be included in this category, but has not been encountered in the articles analyzed, is the priority of part types (see also H3).

4. General comments and future research directions

In the first part of the article, the elements of the real world that can affect the formulation of the loading problem have been discussed, while in the second part, the different formulations of the loading problem proposed in the literature are presented. To complete the analysis, it is necessary to make a critical comparison between these two sets in order to identify the areas of possible improvements and future research directions.

Analysis of the literature on loading shows that very few articles deal with the same loading problem. Even if this situation is due to the large number of different key elements

Table 4. Constraints.

	a[a]	b[b]	c[c]	u[d]	v[e]	w[f]	x[g]	y[h]	z[i]	α[j]	β[k]
Stecke (1983)	2		X		X	X					
Shanker and Tzen (1985)	1		X		X	X				X	
Kusiak (1985)	2			X	X	X					
Berrada and Stecke (1986)	1		X		X	X					
Rajagopalan (1986)			X		X	X				X	
Stecke and Kim (1986)									X		
Sarin and Chen (1987)			X	X	X	X	X	X			
Lashkari et al. (1987)	1	X	X		X	X	X				
Ventura et al. (1988)	1		X		X	X	X			X	
Shanker and Srinivasulu (1989)			X	X	X	X					
Wilson (1989)	1	X	X		X	X	X				
Han et al. (1989)	3					X	X			X	
Lee and Jung (1989)			X	X					X		
Shanker and Rajamarthandan (1989)	1				X	X	X				
Chung and Doong (1989)			X		X	X			X		X
Ram et al. (1990)			X	X	X	X		X			
Chen and Askin (1990)	1		X	X	X	X					
Kumar et al. (1990)	2		X		X	X				X	
Sawik (1990),			X		X	X					
Bretthauer and Venkataramanan (1990)					X	X	X				
Co et al. (1990)			X		X	X				X	
De Werra and Widmer (1991)				X	X	X	X				
Chen and Chung (1991)					X	X	X				
Liang and Taboun (1992)	1		X	X							
Bernardo and Mohamed (1992)				X							
Stecke (1992a)	2				X	X				X	
De Vecchi et al. (1993)	3					X				X	
Kim and Yano (1993)			X	X	X	X					
Kirkavak and Dincer (1993)	1				X	X			X		
Liang and Dutta (1993)			X	X	X	X					
Liang (1993)			X	X	X	X					
Moreno and Ding (1993)	1		X		X	X					
Liang (1994)			X	X	X	X					
Sodhi et al. (1994)			X	X	X	X					
Sodhi et al. (1994)			X	X	X	X	X				
Katayama (1994)	1		X	X	X	X	X				
Katayama (1994)	1		X	X							

(*Continued on next page*.)

Table 4. (*Continued.*)

	a[a]	b[b]	c[c]	u[d]	v[e]	w[f]	x[g]	y[h]	z[i]	α[j]	β[k]
D'Alfonso and Ventura (1995)	1				X	X					
Grassi et al. (1995)	3			X		X	X			X	
Kuhn (1995)	1				X	X					
Song et al. (1995)	3					X	X			X	
Hsu and De Matta (1997)	1		X	X	X	X					
Roh and Kim (1997)						X	X				
Atmani and Lashkari (1998)	1		X	X	X	X		X			
Colosimo et al. (1998)			X				X	X		X	

[a] a = constraints regarding the work assignment: (1) all the operations of a given type must be assigned to the same machine/cell; (2) all the operations of a given type must be assigned to a limited number of machines/cells; (3) each part type can be assigned only to one MC.
[b] b = groups of operations must be assigned to the same MC.
[c] c = elimination of unfeasible couples tool and MC or operation and MC.
[d] u = limited machinining time available and limited production capacity.
[e] v = all the tools used by the MCs must be present on their tool magazine.
[f] w = tool magazine capacity.
[g] x = limited number of tool copies.
[h] y = limited tool life.
[i] z = limited number of pallets and fixtures.
[j] α = workload balancing among the MCs.
[k] β = due date of the part types.

identified in the first part of the article and is also reflected in the differences among the FMSs installed, nevertheless, the lack of reference problems does not always allow a comparison among the different approaches. Also, it results in the fragmentation of the research effort. This situation is made even more critical by the fact that few articles present detailed real or realistic test cases which can be adopted as test beds for subsequent research work. In order to contribute to the solution of this problem the authors have created web pages (http://tecnologie.mecc.polimi.it) which describe in detail a real FMS providing all the data required to test loading methods. Another case study with data is provided in Stecke (1992a). In the future other cases could be provided by different authors thus creating a library of test problems useful both for the comparison of different approaches and as a means to concentrate research on some relevant and typical problems.

We also observe the need to clarify the characteristics of the production planning hierarchy where the loading module operates. Few articles give a description of the characteristics of the upper and lower levels in the planning hierarchy, and how the loading module under analysis is integrated with them. For instance, some articles use an objective function that is not related to the goals of the firm. Even if this approach is perfectly sound since it is the whole production planning hierarchy which guarantees the achievement of the goals of the firm, it is, in any case, difficult to appreciate the reasons for the selection of a particular objective function at the loading level without a description of how the loading module fits into the whole hierarchy. For instance, very few articles deal with the problem of meeting due dates. This requires that the problem of meeting due dates be solved at a higher level (e.g., MRP). A description of how the loading module operates in connection with this higher level is therefore required to understand the logic of the whole approach.

Also, the interface with the lower level is rarely described. Hence the problem of how to deal with the information that the lower level sends to the loading module is frequently underestimated. In particular, all the problems related to unforeseen events which could make the existing loading plan impracticable (thus requiring a revision of the plan) are hardly addressed in the literature regarding loading. It is clear, for instance, that the revised plan should take into account in some way the previous plan, but how this should be done is not clear. Some attention to this problem is required in order to make the proposed loading models applicable to real-case situations. This important area needs further exploration, and could be addressed in future research work.

A third general comment considers the characteristics of the plant where the FMS operates. As already seen, a loading module is deeply affected by these characteristics. Considerations regarding the number of shifts and their characteristics, the presence of downstream assembly operations, the flow of tools in the tool room, and the policies adopted for preventive maintenance need to be introduced if realistic plans are to be generated. It therefore seems that greater effort is required to model these aspects. In particular, the problem of unpersonned shifts seems rather urgent since the possibility of working on the third shift is frequently exploited by firms and represents one of the competitive advantages of an FMS over other production systems. Also, the problem of tool life management, especially in connection with that of unpersonned shifts, is particularly important to fully exploit the potential production capacity of the FMS. At the moment, in some FMSs the third shift cannot be completely exploited because the life of the tools cannot be explicitly considered in the production planning phase (and therefore some tools may become unavailable before the end of the shift).

Regarding the type of FMS, it seems important to stress the fact that most of the new FMSs consist of parallel machine FMSs. Therefore, research efforts in this area should be increased. Also, the problem of tool transport should be considered with greater attention. One of the factors which limits the exploitation (and therefore the diffusion) of automatic tool transport systems is the lack of appropriate algorithms to manage the flow of tools. Regarding this factor, it must be noted that loading methods based on flexible or hybrid approaches should take into consideration the limitations introduced by the control software of the FMS (see P1 and P2).

A potential area of evolution of the loading problem could be represented by the explicit management at the loading level of alternative working cycles. As pointed out by Halevi and Weill (1995), normally process plans are decided by the process planners without any knowledge of the impact a given process plan can have at the management level. This lack of integration between process planning and production planning may lead to suboptimal solutions. Since, in principle, there are many ways to machine the same part, a reasonable way to integrate process and production planning would be to generate alternative working cycles at process-planning levels and choose among them at the production planning level. For instance, an operation performed with a special tool could have as an alternative a set of operations performed with standard tools. Also, there could be alternatives in the order in which operations are performed. These additional degrees of freedom could allow a better exploitation of the resources of the system even if requiring a different formulation of the loading problem. One limitation of this approach is that the control system of the FMS could introduce constraints (see P3, P4, and P5), thus preventing full exploitation of the additional degrees of freedom.

5. Conclusions

Loading is an important level of the production-planning hierarchy. In order to be effective, a loading module must be tuned to the specific application. In particular, the characteristics of the FMS, the characteristics of the whole manufacturing plant, and the production-planning hierarchy where the loading module operates deeply affect the structure of the loading module. Also, since all the mentioned areas are in continuous evolution, it is important to quickly identify the new challenges the various changes in the different areas introduce at loading level. Research, in particular, must provide tools that are coherent with these evolving scenarios to help FMS producers and users to exploit the full potential of these manufacturing systems. Our article has delved into the characteristics of the FMS that affect the loading problem. We have focused on possible evolutions and summarized the loading module approaches already available in the literature. This exercise has provided insights into the areas not completely covered by the existing methods and has given clues for possible research directions. We have also provided a taxonomy of loading problems which should lead to the definition of standard loading problems covering the most common real situations.

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