A Synthesis of Decision Models for Tool Management in Automated Manufacturing

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The evidence is clear that a lack of attention to structured tool management has resulted in the poor performance of many manufacturing systems. Plant tooling systems affect product design options, machine loading, job batching, capacity scheduling, and real-time part routing decisions. With increasing automation in manufacturing systems, there is a growing need to integrate tool management more thoroughly into system design, planning and control.

This paper critically evaluates various tool management approaches, identifying the operational tradeoffs and analyzing the models developed to address management decisions involving tooling. These decisions range from selecting the optimal machining parameters and the most economic processing rate for a particular operation, to the loading of tools and jobs on machines and the determination of the optimal tool-mix inventories needed for a particular production schedule. We present an integrated conceptual framework for resource planning to examine how tool management issues, depending upon their scope, can be classified into tool-level, machine-level, and system-level concerns. This framework specifies how decisions made at one level constrain those at lower levels, and how information from lower levels feeds back to higher level decisions. The framework structures our critical evaluation of the modeling approaches found in the academic literature and points to promising directions for future research.
(*Flexible Manufacturing Systems; Production Planning; CIM; Performance Evaluation; Automated Manufacturing Systems*)

1. Introduction

There are critical tool management issues that affect the productivity of many automated and flexible manufacturing systems (FMSs). Manufacturers and machine tool suppliers recognize that a lack of attention to such tool management issues is a primary reason for the poor performance of many facilities (Kiran and Krason 1988, Rhodes 1988, Martin 1989, Gruver and Senninger 1990). Conceptually, tool management can be classified into tool-level, machine-level, and system-level issues. The "tools" we are concerned with are the cutting or shaping tools residing in an automated Computer Numerical Control (CNC) machine tool (or "machine") used to remove metal from castings.[1] A "system" is an integrated production facility with several automated machines and, perhaps, automated handling of parts and tools. The classification of tool, machine, and system-level issues allows us to portray how models of individual tools such as cutters or dies fit into machine-level models, how these machine-level models fit into system-level models, and how technological constraints directly affect key operational decisions at all levels.

To ensure the quality performance of an automated

[1] The word "tool" may be defined more broadly elsewhere to include jigs, fixtures, pallets, dies, molds, and assembly tools or grippers.

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system, a high level of integration is necessary between tooling capabilities and the other basic production functions, including process planning, scheduling, part design, and part programming. An effective, well-managed information system is necessary to collect and distribute tooling data across these functions. Tool management is broad in scope, requiring:

- a *design* strategy to coordinate tooling inventory, tool tracking, tool handling, and tool loading and unloading;
- a *planning* strategy to ensure that the appropriate tools are available when needed and are provided in the right quantities;
- a *scheduling* strategy to account for tool availability and tool changes;
- a *control* strategy to coordinate either manual or automatic tool transfers between machines and tool cribs; and
- a *tool monitoring* strategy to identify and react to unexpected tool wear and breakage.

Besides being a critical issue in factory integration, tool management has direct cost implications. Industry data suggests that tooling accounts for 25% to 30% of both the fixed costs and variable costs of production in an automated machining environment (Cumings 1986, Tomek 1986, Ayres 1988). Manufacturing management publications have recently paid considerable attention to the benefits of improving the integration of tool management within total system design, planning, scheduling and control (Gaymon 1986, Tomek 1986, Wick 1987, Ayres 1988). The benefits cited include reductions in production costs due to minimizing the number and types of required tools, increases in productivity due to reduced tools' stockouts and setup delays, improvements in part and routing flexibility, and better tracking and cost accountability of tooling. The increasing recognition of tool management as a critical component in the cost and capabilities of automated systems is also reflected in the publication in management science journals of models aimed at specific tool-related decision problems (Stecke 1983; Vinod and Sabbagh 1986; Tang and Denardo 1988a, 1988b; Schweitzer et al. 1991).[2]

Planning, scheduling, controlling, monitoring and tracking tools among various machines in a plant requires a substantial degree of sophistication. In the metal-cutting industry, as in other automated operations such as assembly and plastic molding, many different tools must be managed. Section 2 develops an Integrated Resource Planning Hierarchy designed to structure the tool management decisions at the tool, machine and system levels. This hierarchical framework, applicable to any discrete part production system, specifies how decisions made at one level constrain those at lower levels, and how information from lower levels feeds back to higher level decisions. The framework structures our critical evaluation of the modeling approaches found in the academic literature and suggests construction of future models that will better facilitate forming an integrated tool management decision support system.

Section 3 addresses *tool-specific* issues. Individual tool-level decisions include the economic determination of tool types, feedrates, and machining speed for any given part operation. Other decisions involve standardization of tool types, real-time data monitoring, and adaptive process planning. In § 3 we group the models into subsections on Tool Life, Cutting Tool Economics, Tool Standardization, and Information Requirements for Tool Planning and Monitoring.

Section 4 identifies *machine-level* issues related to tooling a single automated machine. We examine the technological capabilities of machine tools for storing tools, loading tools, and monitoring the condition of tools in operation. Typical machine-level decisions include the simultaneous sequencing of parts and tools on a specific machine, the allocation of tools to magazine slots, and tool replacement strategies. Machine-level performance measures include tool change times, machine throughput, and tool replacement or regrinding costs. We cover these topics in subsections on Equipment Selection, Tool/Part Sequencing on a Flexible Machine, Tool Placement in a Magazine, and Tool Replacement.

Section 5 reviews *system management* tooling issues. It deals with the impact of tool allocations among several machines and the interactions between machining con-

[2] A review of the 1989 ORSA/TIMS *Proceedings of the Third Annual Conference on Flexible Manufacturing Systems* reveals that 35% of the published work directly addresses decisions constrained by planning, scheduling and control of tools.

ditions and the overall system productivity. In this section we also address decision problems involving system setup, economic production rates, part routing and scheduling, tool requirements planning, tool sharing among machines, spares management, and tool inventory management. We evaluate the applicability of various methodologies to tool management and identify many open research problems. Section 5 contains subsections on Master Production Planning, Machine Sequencing and Process Monitoring, Process Planning for Economic Production Rates, Spares Management, and Tooling Inventory Management.

Section 6 summarizes our conclusions. Conceptually, analyzing tool-specific, machine-level, and system-level issues allows us to evaluate how models of individual tools fit into machine-level models, how these fit into system-level models, and how technological and performance constraints directly couple decisions at all levels.

From studying the literature, it is apparent that few models fully consider practical tooling issues. Models for equipment selection seldom consider the selection of tool types and requisite tool inventories. Most researchers have given little attention to the actual selection of tool storage, handling, loading, changing, and monitoring technologies. Planning models that include tooling constraints and the planning of tooling inventories are now being developed. In this paper we discern critical research areas including tool replacement strategies, spares management, and the integration of the various tool management decision levels.

Scheduling research sometimes considers the size of the tool magazine, and there have been some efforts to consider the number of magazine slots used by each tool. We notice that issues of tool life, loading of duplicate tools, and tool change times are often overlooked. Several studies have proposed implementing adaptive control measures to optimize the machining parameters for each tool during actual production. This work has progressed from initially optimizing tool use on a single machine to optimizing system-wide tool use.

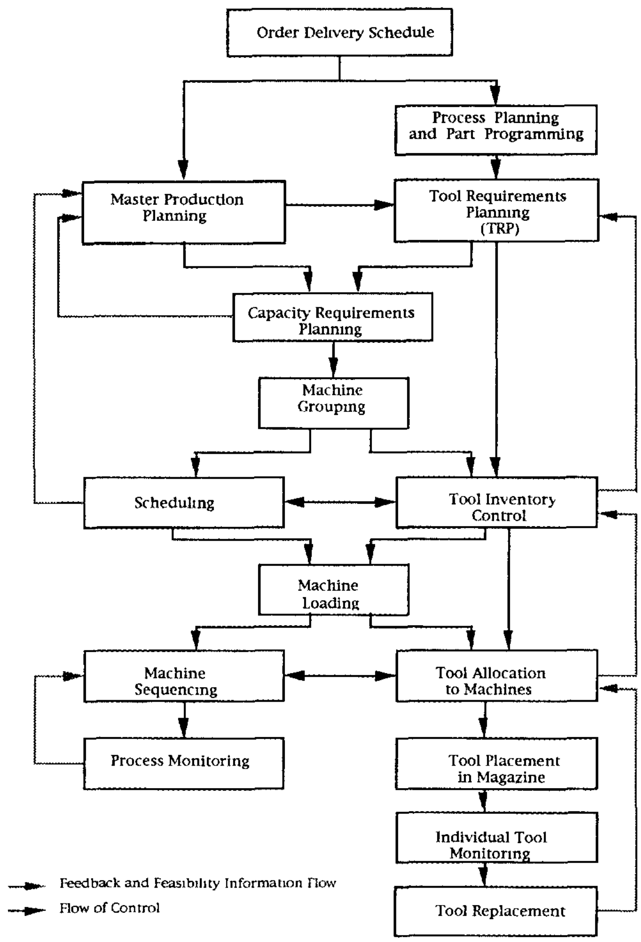
With further development, many existing design, planning and scheduling models could realistically account for tooling issues. Unfortunately, we show that the lack of appropriate attention to these issues invalidates some of the published models.

2. An Integrated Resource Planning Hierarchy

In automated manufacturing, resource planning consists of many interconnected decisions, such as facility loading, tool allocation and scheduling. The hierarchical structure of the conceptual framework proposed in Figure 1 imposes a set of interrelated resource planning and tool management decisions that guarantees the appropriate coordination of key decision factors. The framework allows for the planning, scheduling and control of tools, parts and machines.

In the resource planning framework, control flows top-down. The hierarchical structure acknowledges that the options available at a higher level of the structure (e.g., system level) are constrained by those available

Figure 1 **An Integrated Resource Planning Hierarchy**



at lower levels (e.g., machine level and tool level). The *Order Delivery Schedule* triggers *Master Production Planning* and calls up *Process Planning and Part Programming*. The use of a Master Production Plan enables the process planner to consider desired production volumes and lead times when setting up part routes and tool selections. Information from *Master Production Planning* and *Process Planning and Part Programming* feeds into the *Tooling Requirements Planning* (TRP) decision module, which generates the profile of net tool requirements over time as a function of (a) the number of each part type to be produced, (b) the machining times for each operation using each tool, (c) the tool types required, (d) the expected tool lives and (e) the probability of premature breakdowns. Several plants have already successfully set up TRP systems (Gaymon 1986).

The Master Production Plan and the Tool Requirements Plan determine the capacity requirements, and *Capacity Requirements Planning* takes place. Assigning sets of tools, jigs, pallets and fixtures to groups of machines facilitates *Machine Grouping*, which reduces part setups and may reduce the traffic of both parts and tools. *Scheduling* the groups of machines, which takes place next, can be particularly sensitive to the availability of the right type and number of tools. Certain custom-made tools require long lead times for delivery, and their availability imposes tight constraints on scheduling. Some machines can share several tools during one planning period. This allocation policy creates tool scheduling and part synchronization problems.

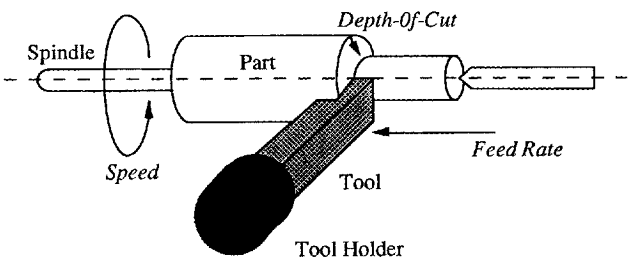
The *Tool Inventory Control* function deals with maintaining appropriate safety stocks of the various tools and mitigating the random effects of tool supply and demand. This function also includes monitoring the wear of tools, forecasting replenishment orders for worn tools, and predicting tool regrinding requirements. *Tool Allocation* decisions assign specific tools to machines, and models of *Tool Placement in Magazines* subsequently assign tools to individual slots in the tool magazine. *Tool Allocation* is tightly coupled with *Machine Sequencing*. As machines or tools break down, and as parts need reworking, as determined through *Process Monitoring* and *Individual Tool Monitoring*, there is an immediate effect on tool availability and the possibility of again performing *Machine Sequencing*. Wear rates are accounted for in real-time control through *Individual Tool Monitoring* and subsequent *Tool Replacement* decisions. The following sections discuss the impact of these decisions and the models developed to execute them. Additionally, many design issues are detailed. Since it is necessary to determine the tool handling technology and machine tool magazine capacity before actual startup, these design problems do not appear in the integrated resource planning hierarchy, but they clearly affect planning decisions. Critical process planning and tool selection decisions depend upon the key attributes of the available machines (i.e., horsepower, precision, tool shank parameters), and upon the production volume of each type of part.

3. Tool Specific Issues

Tool specific issues include the number and types of tools, tool speed rates, tool feed rates and the technology used to monitor and control machining and tooling conditions. With a given set of machine tools, these factors determine the quality of the parts produced and the effective capacity of the machines. In automated manufacturing, these are more critical choices than in manual operations because of (a) the level of integration necessary between the various production functions and (b) the greater capital and time involved in developing hardware, software and technical support for automated manufacturing.

Figure 2 illustrates a tool being used in a turning operation. In this type of operation, the part moves while the tool remains stationary. In other operations, the part may be stationary while the tool moves against it. Movement of the part (or tool) takes place through a powered spindle. The "speed," "feed rate" and "depth of cut" define how a particular cutting tool is being used, whether on a lathe, drill press, planer, shaper,

Figure 2 **Parameters of a Typical Turning Operation**



mill or saw. The "speed" of the operation refers to the rotational rate at which the tool is drawn through the workpiece. The "feed rate" is the distance that the tool proceeds into the workpiece with each rotation of the spindle. The "depth of cut" indicates how far the tool penetrates into the workpiece. Further details are provided in Salvendy (1992).

The framework described in Figure 1 shows how the data collected by *Individual Tool Monitoring* activities affects *Tool Replacement* decisions due to wear and breakage. *Individual Tool Monitoring* and *Process Monitoring* data relate machining parameters, such as the feed rate and the depth of the cut, to the rate at which tools must be replaced. This data is used to determine the desired number and type of tools to be assigned during the *Tool Allocation to Machines*.

Classic tool life and tool economics models address the effects of limited tool life, tool breakage and tool change times. Yet many of these studies appear to be unknown to many researchers in the area of manufacturing management. As a result, many published planning and scheduling models ignore the effects of these critical variables. The following subsections address four key tool-related issues that represent the major tool management concerns at the individual tool-level: (1) tool life, (2) tool economics, (3) tool standardization and (4) information requirements.

3.1. Tool Life

The cutting or shaping edges of a tool wear down with use until the tool becomes dull and no longer operates with acceptable quality. Empirical studies show that the useful life (the time during which the tool can produce its cuts within the required tolerances) of a tool depends primarily upon the machining environment, including the speed and feed rate, the material composition of the part and of the tool, and the depth of the cut. In pioneering research, Taylor (1907) developed the classic relationship between average tool life and cutting velocity through an empirical study of cutting tool wear. The Taylor tool life equation $VT^n = k$ relates cutting speed V to expected tool life T. The empirical constants n and k depend on the machining conditions and on the material composition of both the part and the tool. The constant value k is numerically equal to the cutting speed that gives a tool life of one minute. It is evident from the Taylor tool life equation that tool life decreases rapidly with an increase in machining speed. Including the feed rate and the depth of the cut provides a better empirical description of tool life. Today, many use the extended tool life equation (Cook 1973, Jain and Gupta 1987). This equation has the form $V_t = C/d^x f^y$, where V_t is the equivalent cutting speed (or the machining speed for a given tool life), d is the depth of the cut, f is the feed rate per revolution, and C, x, and y are empirical constants.

These tool life equations provide expected values based on random tool life data. Empirical curve fitting of shop floor and laboratory failure data have justified the use of the normal, log normal, Weibull, exponential and gamma distributions (as well as various combinations of them) to describe the life of a tool under various machining conditions (Wagner and Barash 1971; Ramalingam 1978; Ramalingam and Watson 1978a, 1978b; Ramalingam et al. 1978).

Making decisions on tool choice, machining conditions, capacity planning and tool replacements mandates characterizing and distinguishing the failure patterns of various tools. In general, tool life distributions depend upon the nature of the failure mechanism (Cohen and Black 1977, Batra and Barash 1972, Yaohua et al. 1987, Wayne and Buljan 1989). As an alternative to selecting a single distribution, a failure rate function may be developed from the actual tool failure data. This is most appropriate when the tool is more likely to fail due to a single injury, such as a fracture, than due to gradual wear of the tool's surface, as is common (a) during high speed cutting, (b) when using impact-sensitive tools and (c) during rough machining (Pandit 1978).

3.2. Cutting Tool Economics

Tool wear increases the probability of a tool chipping or suffering some other type of catastrophic failure that may damage the part being machined. To minimize the risk of damaging expensive parts, it is more economical to replace the tool early than to damage a part or have the machine shut down. The optimal time interval between planned tool replacements is referred to as the "economic tool life." The following tradeoff is basic to most operations: as machining speed increases, tools must be replaced more often and tooling expenses rise exponentially; on the other hand, with the increase in throughput rates a part requires less machine and labor time, providing for higher throughput rates. This basic tradeoff illustrates that machining speed should be carefully controlled when considering the economics of the facility operation.

A simple relationship between the number of times a tool is reground and the cost of each regrinding operation is given by Cook (1973). Cook uses this data to compute the "mean tool usage cost" Y as: $Y = (Y_0 + nG)/(n + 1)$, where Y_0 is the initial cost of the tool, n is the number of times that a tool is reground (sharpened), and G is the cost of a single regrinding operation. The cost of each regrind and the number of possible regrinds are inversely proportional to the relative time interval allowed between regrinds and to tool life. The economic tool life is found where the "mean tool usage cost" (also called "mean edge cost") is minimized. This problem has been extensively studied since Gilbert (1950) presented a seminal work entitled "Economics of Machining."

The interaction between machining conditions and the economic performance of a given machine is discussed by Hitomi (1971, 1976). In practice, the operation cycle time, which depends on the machining speed, feed rate and spindle revolution rate, is the decision variable used to optimize production. In different environments, this may require maximizing production rate, minimizing variable cost or maximizing profit rate. Hitomi (1989) derives the optimal machining speed for the case where tool replacement can be made within the setup time for a part.

The extended tool life equation reproduced above is commonly used within the industry to find both the most efficient feed rate and machining speed (Drozda and Wick 1983). In some cases, there is a tradeoff between making multiple passes of several shallow cuts of a workpiece or making fewer deeper cuts to obtain the same result (Lambert and Walvekar 1978). It may be worthwhile to determine the optimal sequence of machine tools to use and part surfaces to be processed to meet the dimensional constraints of a finished part with maximal accuracy, as is done by Iwata and Sugimura (1987) using a simple branch-and-bound algorithm. Parameter optimization specific to milling, drilling, reaming, turning, single-pass, two-pass or multipass operations have also been treated in the literature (McCullough 1963, Crookall and Venkataramani 1971, Chang et al. 1982, Yellowley 1983, and Hough 1986). Additionally, Trappey et al. (1987) find optimal machining conditions under a fuzzy set of constraints and Malakooti and Deviprasad (1989) specify a multiple-criteria approach aimed at simultaneously minimizing the production cost per part, the machine cycle time, and the surface roughness. Primrose and Leonard (1986) and Boucher (1987) stress the need to appropriately trade off material, labor and tool costs by omitting irrelevant overhead allocations historically included in earlier studies. All of these studies deal with manufacturing a single part at a time and assume that tool life is deterministic.

In attempts to more realistically capture tool life economics, tool life is treated as a random variable whose distribution is determined by machining conditions (Ermer 1970; Hati and Rao 1976; Levy and Rossetto 1978a, 1978b; Zompi et al. 1979; and Sheikh et al. 1980). Rossetto and Levy (1975) present a profit rate distribution function by superimposing random tool fractures on a continuous random tool wear process. Conard and McClamrock (1987) develop a stochastic control model that uses sensory feedback information to determine economic drilling conditions. One study suggests, however, that deterministic models are fairly close to their stochastic counterparts in prescribing the optimal machining parameters, explained by the convex structure of their machining cost functions (Fenton and Joseph 1979).

The widespread industrial practice of using the same tool for processing a mixture of part types minimizes the number of tool changes and the number of tools required and increases part routing flexibility. However, existing tool life models are unable to provide reliable predictions of tool life under these conditions. The single machine studies discussed here are important precursors to the system-level decision models of setting machining speed and optimizing overall system performance.

3.3. Tool Standardization

Metal-cutting facilities commonly require hundreds of tool types and maintain thousands of tools in inventory. Standardizing tools can be done either by redesigning the part or process, or simply by comparing the capabilities of similar tool types and assigning more operations to the same tool type. Standardization results in substantial savings in tool inventories and data management and may improve system reliability by reducing the need for custom tools with long lead times for delivery (Hartley 1984).

Group technology methodologies have been proposed to aid in process planning efforts (e.g., Burbidge 1975, 1990; Chang and Wysk 1985). Most of these are limited to the generation of tool commonality subsets. Daskin et al. (1990) is one of few recent studies aimed at the practical issues of tool standardization. It describes a punch-and-die facility which was converted to laser punch-press technology capable of cutting 900 round holes unique in diameter, depth-of-cut and tolerance. The study details an algorithm for selecting the smallest set of tools that can punch the holes, subject to tool magazine capacity and tool change constraints. Industrial implementation of tool standardization on a large scale, however, will only be possible once general classification, coding and pattern clustering schemes are developed for automating the standardization process.

3.4. Information Requirements for Tool Planning and Monitoring

Interactions among different levels of the integrated tool resource planning hierarchy (Figure 1) are better facilitated when using a common tool management data base. The data record for a tool type, for instance, should be linked to vendors, part types, machines, and specific operations for each part/machine combination. Each of the numerous tools in the plant must be located, tracked for use limits, checked for repairability, and followed through regrind and offset processes (Gruver and Senninger 1990).

Information requirements for both planning and monitoring tooling are extensive. Data on the behavior of tools under different machining conditions is required for tool selection, for process planning, and in coding and classifying tools for standardization. Tools must be monitored for wear to permit planning for replacement and regrinding. If wear is monitored continuously, adaptive control can be implemented to adjust machine speed and feed rates appropriately. Moreover, inspecting tool conditions off-line increases the nonproductive machine times and may result in workpiece damage when the tool fails between the scheduled inspections (Tarn and Tomizuka 1989). When tool breakage is detected the system can react by arranging for a replacement tool, terminating the processing of the part if it is already damaged, and/or possibly rerouting subsequent parts to other machines (Kendall and Bayoumi 1988).

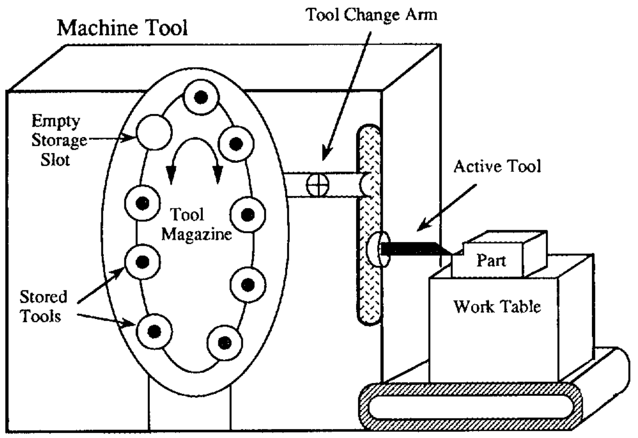
Several companies have developed sophisticated information systems to (a) coordinate delivery of the proper tools to specific machines in time, (b) provide location information, (c) correlate the number of tools needed for the quantity of parts to be produced, and (d) offer acceptable substitutes when needed (Gaymon 1986, Wick 1987). As shown in Figure 1, these tool delivery systems interface with machine loading and sequencing functions. Bar-code labeling of tools or tool cabinets or memory chips embedded in the shanks of toolholders are used to track tools and collect real-time data (Cumings 1986, Ryan 1987). In lieu of these developments, it is possible to bypass many of the static-deterministic models of tool life and move directly to adaptive control schemes, where tool performance is directly controlled during a machining operation. To do so it is necessary to understand the main issues associated with operating individual machines with multiple tool types as discussed in the next section.

4. Tool Management Issues at the Individual Machine Level

Machine-level decisions are influenced by both higher system-level decisions and the technology constraints and capabilities of the individual tools discussed in § 3. Thus, as can be interpreted from Figure 1, individual tools can be allocated to the magazines of the various machines after capacity requirements planning decisions are finalized and machine grouping is determined. There are three key tool management issues at the single machine level: (a) loading and placing a set of tools in the machine's magazine, (b) determining the part input sequences to meet certain magazine constraints, and (c) establishing tool replacement strategies. To ensure a smooth operation, rules for handling exceptions and the proper methods of continuously monitoring the system must also be determined.

A typical CNC machine tool with an automated tool magazine is depicted in Figure 3. The part in process is attached to the work table using chucks or fixtures. The

Figure 3 A Schematic of a Machine Tool with a Nine-Slot Tool Magazine



tool holder holds the tool. The tool changer exchanges tools between the tool holder and the tool magazine. The tool magazine is an online local storage device holding tools of different types and shapes, as well as spare duplicates. Tool magazines with 30 to 60 tool slots are common, and 70 to 100 tool slots are sometimes available. Some vendors offer machines equipped with several interchangeable tool magazines and others provide a carrier that shuttles the tools between the individual magazines and a centralized tool storage that can contain several hundred tools. This capability is particularly useful for lathes because of the relatively short economic tool lives of many turning tools (Salvendy 1992).

The availability of high power, high precision machines may permit both rough-cut and surface finishing operations at the same machine tool. Moreover, the availability of multiple tools of a given type, and the availability of space in the tool magazine, constrain the *Machine Sequencing* decisions. These decisions determine the allocation of part operations and tools to machines. Existing resource planning models like MRPII address the planning and control of material flows and machines (Nahmias 1989), but are incapable of dealing simultaneously with the constraints imposed by most tool requirements.

4.1. Equipment Selection

Several of the information and control features available on machine tools support tool management. These options include tool holding and changing capabilities and tool breakage and wear monitoring functions. Specifications of a tool magazine and an automatic tool changer include (a) the tool storage capacity, (b) the type of accessing system, (c) whether tool loading is manual or automatic, (d) the tool standards used, and (e) the maximum tool diameter, length and weight.

Tool magazine capacity and speed are among the most significant parameters for the determination of expected system throughput (Arbel and Seidmann 1984). Yet little work has been done to evaluate the relative cost imposed on the system by the size of the tool magazine, by interchangeable tool magazines versus changing tools at the machine, or by manual versus automated tool delivery and loading.

Most current research on equipment selection does not consider tooling costs, tool change technologies, magazine size, tool commonalities and tool lives. Alberti et al. (1989) separate tooling and fixture costs from the equipment investment decision, claiming that they do not affect system performance. Believing otherwise, Graves and Redfield (1988) consider tool costs, tool commonalities, and tool change times in equipment selection. They assume, however, that when several operations using the same tool are assigned to the same machine, only one tool is required. This accounts for tool commonalities and saves space in the tool magazine, but it may not always be appropriate for tools with short lives relative to machining time, where duplicates may be necessary, nor does it account for systems in which spare tools are used to ensure system reliability.

4.2. Tool/Part Sequencing on a Flexible Machine

The total number of tools required to process a set of parts on a flexible machine is usually larger than the available magazine storage capacity. As a result, a required tool may be absent from the magazine and a tool change must occur before that operation can begin. Tang and Denardo (1988a, 1988b) explore this issue for a single machine with a limited tool magazine, assuming that production requirements are known in advance. The decisions are: (1) how the parts should be sequenced and (2) which tools to change on the machine prior to processing each part. Their objective is to minimize the number of group tool change instances or to minimize the number of individual tools changed. The former is appropriate only when the changing time is roughly constant regardless of the number of tools changed. These studies assume that there is a deterministic change time and that all changes are due to part mix, ignoring tool changes due to wear.

Bard and Feo (1989) address the problem of minimizing the total setup, tool replacement and machining times for individual batches subject to tool magazine and metal volume removal constraints. This approach requires that all feasible tool paths be generated manually before being considered by the optimization algorithm.

Silver (1990) studies the possibility of slowing down the processing rate in order to reduce the inventory holding cost in a single machine economic lot sequencing problem. Mittal and Lewis (1989) present a mixed-integer programming (MIP) formulation to minimize the sum of the machining time, the tool change times, and the tool travel times. They use a special set of constraints to handle tool life economics and tool changes due to accumulated wear. Their model considers various tooling aspects, but it does not include the option of loading duplicate tools in the magazine.

4.3. Tool Placement in a Magazine

The selection and placement of tools in a tool magazine involve many important issues. The machining of a typical part can require a sequence of operations using many tools of various sizes. A large tool may block adjacent slots in the tool magazine, so the relative placement of individual tools may determine the effective magazine capacity. Another potential consideration is weight balancing of a tool magazine (Stecke 1983 and Rajagopalan 1986). Tool magazine weight balancing and tool overlaps of magazine slots are formulated as a mixture of integer and nonlinear capacity constraints.

Tool search time is important in some environments (Stecke 1989). This is the time required for the magazine to rotate into position for the next tool interchange. Tool search time can take eight to ten seconds; however, if aluminum parts, for example, are being cut, some tools might only be used for two or three seconds at a time. For high volume production, the resulting idle search time can be high and the correct placement of tools in the magazine can significantly reduce such idle time.

Different operations may require the same tool or several of the same tools. If these operations are assigned to the same machine, only one copy of each tool may need to be loaded, saving magazine capacity. On the other hand, multiple copies may be beneficial, or even necessary, if they are used often or have short lives. It then becomes desirable to load duplicate (sister) copies of these tools into the magazine. This can reduce the number of times that a machine is stopped to change tools, but it also reduces the effective magazine capacity and the machine flexibility. An important, unanswered research problem involves determining the optimal number of copies of each tool type to load into a magazine.

Walas and Askin (1984) address the problem of sequencing operations within part programs and assigning tools to slots for punch presses to minimize the part cycle time, including both table move times and tool change times. Their formulation is a combination of the travelling salesman problem (TSP) and the quadratic assignment problem. Comparing three part programs generated by TSP-based commercial software used by a specific company, the Walas and Askin algorithm generates cycle times 8.2% to 24.5% shorter. This study requires two conditions: (a) that it is possible to permute the sequence of operations and (b) that weight balancing of the tool magazines can be ignored.

4.4. Tool Replacement

A complete tool replacement strategy specifies a tool change schedule based upon the economic service lives of tools and a control policy regarding unscheduled tool changes following breakage. Tool replacement strategy is two-fold, consisting of, first, a decision on when to replace a particular tool due to wear or failure, and second, a decision on which additional tools to change early, given that a tool change must take place.

The most realistic replacement strategies consider the distributed nature of tool lives under actual machining parameters, as well as the option to change several tools once one fails (Bao 1980, LaCommare et al. 1983), rather than considering only expected lives and single tool replacement (McCullough 1963, Cook 1966, Armarego and Brown 1969). All of these tool replacement studies consider one machine in isolation.

If the machine does not have the potential to create a bottleneck, then a tool change may not result in lost system throughput. On a bottleneck machine, one would be more likely to change several tools when one tool fails. Sharit and Elhence (1989) go beyond the single machine model to examine tool replacement strategy at the system-level. Rather than proposing an automated, optimizing strategy, the study emphasizes the limitations of both human and computer at making the tradeoff between economic tool replacement costs and system throughput in a real-time, dynamic environment. They suggest determining an appropriate mix of human and computer input into the decision process.

Currently, many tool replacement models are deficient because they (a) ignore the relationship between the processing rates and the tool replacement policy, and (b) tend to overlook the impact of sharing tools on setup times and on resulting production lot-sizing decisions.

5. System Management Issues

At the factory management level, tooling issues arise in production planning, scheduling, spare tool management and tool inventory management. Production planning involves machine grouping and tool allocations to machines. Once production planning and scheduling is complete, facility loading takes place. This involves machine sequencing and tool placement in the magazine. The integrated resource planning hierarchy presented in Figure 1 illustrates the necessary interface between the machine-level decisions presented in the previous section and the system-level decisions discussed here.

5.1. Master Production Planning

Each time production requirements call for a system set-up change, a new system set-up problem must be resolved. The set-up problems for an automated facility are more difficult than for production lines and job shops because additional part mix and routing flexibility greatly increase the number of decision variables to be addressed simultaneously. Effective planning models must take into account tool magazine sizes, tool commonalities, tool changing times, and tool lives. Choosing to produce a set of part types with common tooling requirements simultaneously will reduce the need for tool changes when magazine sizes are active constraints. Mazzola et al. (1989) propose a Material Requirements Planning (MRP) framework for automated machining that provides for tool magazine constraints and tool commonalities. Their framework ignores tool changes due to tool wear and is generally appropriate when tool wear is not a significant cause of tool replacements.

Because the entire system set-up problem is too large to be solved directly, it is often divided into subproblems to be solved independently and iteratively. Each problem employs a surrogate objective for some criteria, i.e., maximizing expected production or minimizing part movements among machines. Stecke (1983) introduces various FMS production planning problems (including part-type selection, machine grouping, machine loading, production ratio, and resource allocation), which the FMS manager must address to set up a system before production begins.

Tool management issues are particularly visible in part-type selection, machine grouping, and loading problems. Tool/part scheduling for a particular single machine problem was discussed previously, and in §5.1.1 we discuss how tooling affects part-type selection. In §5.1.2, we discuss approaches to solving machine grouping and loading problems jointly, and various approaches to solving the loading problem independently. In §5.1.3 we focus on the choice of tool handling systems.

5.1.1. Part-Type Selection. There are two basic approaches to addressing the part-type selection problem. A batching approach partitions the part types into distinct and separate batches and batches are machined individually (Whitney and Gaul 1985, Hwang 1986, Rajagopalan 1986, Afentakis et al. 1989). When a batch is finished, all tools are taken out of the tool magazines and other tools are loaded for the next batch. A *flexible approach* selects the part types to be produced next and machines them according to ratios that balance workloads until all requirements for some part type are met. The tools for this part type can then be taken out of the tool magazines and new tools loaded for another part type, if necessary (Stecke and Kim 1989, 1991).

Although tools are changed more frequently with a flexible approach, the time to change tools is much less. The flexible approach results in a more uniform utilization of machines and set-up personnel. It leads to better system performance than batching in terms of decreased order leadtimes and increased productivity (Stecke and Kim 1988), but the flexible approach often requires more duplicate tooling and may require a more sophisticated tool transport system.

5.1.2. Machine Grouping and Loading. The machine grouping problem seeks to partition the machines into groups in such a way that each machine in a particular group is tooled to be able to perform the same set of operations. The loading problem attempts to allocate the operations and required tools of the selected part types among the machine groups subject to technological and capacity constraints. These two problems can be considered jointly or separately and iteratively.

Balancing the aggregate expected workload across machines has been suggested as a potential surrogate for maximizing expected production in a flexible machining environment. Balancing is an objective of Kusiak (1983), Stecke (1983, 1985, 1989, 1992), Ammons et al. (1985), Stecke and Morin (1985), Whitney and Gaul (1985), Berrada and Stecke (1986), and Stecke and Kim (1989). Stecke and Solberg (1981) show that the loading and control policies that may work towards maximizing production in a conventional environment may not be suitable for application in a more flexible environment because they do not take advantage of the potential system flexibility.

Stecke (1983) investigates machine grouping and loading decisions under several different loading objectives, including balancing machine processing times, maximizing the number of consecutive operations on a machine, balancing the workload per machine for a system containing groups of pooled machines of equal sizes, and unbalancing the workload per machine for a system containing groups of pooled machines of unequal sizes. The major problem constraints are tooling requirements and tool magazine capacities. The MIP formulation of the problem has commonly been solved after linearization of the nonlinear terms.

Shanker and Srinivasulu (1989) consider the loading problem for a nonstationary part mix and machine dependent processing times. They use a bicriterion objective of minimizing the workload imbalance and maximizing the throughput rate while considering critical resources such as the number of tools available and the number of magazine slots. In a related study, Tomek (1986) suggests several approaches to allocating operations and tools to machines based upon his experience in planning several Czechoslovakian FMSs. These systems have difficult tooling problems (many tools required for each part being machined), identical machines, and a tool delivery system that can deliver up to five tools at a time. The loading approaches suggested include (1) assigning part types (all operations) to specific machines subject to throughput requirements, current tool magazine content, and technological (process) constraints, (2) assigning a set of tools for a group of parts to machines considering common tooling requirements and (3) assigning tools to machines and allowing parts to travel between machines. The appropriate approach is a function of the time and complexity of changing tools and of moving parts between machines versus moving tools between machines and a tool crib or spare tool magazine.

Machine grouping and loading has also been studied for some more restrictive system configurations. Chakravarty and Shtub (1984) consider these problems for a flexible flow line, where similar part types follow the same route. Parts of different types are first grouped together by similarities among tool requirements. Na et al. (1987) present a nonlinear integer programming formulation for tool loading with workload balance constraints aimed at minimizing the amount of tool traffic among machines and between machines and a central tool crib.

The studies by Kusiak (1983), Ammons et al. (1985), and Na et al. (1987) do not consider tool commonalities. They ignore the fact that, when operations requiring the same tool type are assigned to the same machine, (a) space is saved in the tool magazine, (b) fewer tools may be needed and (c) tool changeovers may be avoided. Models that do consider tool commonalities often assume that only one tool of each type is needed to process several part types on the same machine. This may not be the case if tool lives are short relative to processing requirements.

Overall, we found a lack of consideration of tool lives and tool reliability to be a major limitation of some planning and scheduling papers in this area. Most approaches center on a single period planning horizon.

Many culminate in a solution found by partial enumeration, which limits the size of the solvable problems. Reports of their applicability to real production problems are rare.

5.1.3. Manual Versus Automatic Tool Handling and Loading. Some vendors (i.e., Cincinnati Milicron) offer automatic tool delivery and loading. Sometimes, special tools are delivered to the machine on the same pallet as the part itself. In the Mazak FMS (Florence, Kentucky), automated guided vehicles are used to transport magazines with a capacity of forty tools to the presetting rooms and back to the required machine tools. The parent company of Mazak, Yamazaki, in Nagoya, Japan, also has interchangeable tool magazines but never uses this capability. The foreman prefers to change only the few tools that are worn. Using tool transporters requires a very large additional investment in the tools, the magazines, the set-up and the delivery system. Some set-up time on the tool magazines is reduced but at the expense of requiring a parts batching approach, which can result in system idle time. Also, all tools are changed although they are worn to varying degrees. This option necessitates another level of coordination and causes additional scheduling problems. Even if automated, interchanging tools takes some time, and tools are typically changed in the magazines manually. A study of a COMAU-Torino FMS notes that the major operational problems are tooling and loading (Stecke 1989). The scheduling problems in this industrial facility turned out to be relatively easy.

We noted that currently there is no formal characterization of the operational tradeoffs between automated and manual tool handling (and loading) systems. This is one of the many open design problems in automated manufacturing.

5.2. Machine Sequencing and Process Monitoring

Scheduling and control issues arise upon completion of the *Capacity Requirements Planning* stage (Figure 1). The complexity of scheduling and control generally increases with machine, operation and routing flexibilities. Few scheduling models fully consider the implications of tooling constraints. Although they may include tool changeovers due to part variety and tool magazine constraints, they seldom include tool life and tool changeover times due to tool wear. Tools are resources that must be scheduled and controlled along with parts. When a machine breaks down, workpieces must be rescheduled and delivered along with tools to alternate machines (Carrie and Bitici 1989, Veeramani et al. 1992).

In a scheduling and control model, Chakravarty and Shtub (1986) include tool magazine capacity constraints and tool changeover times for part-mix changes and allow for periodic review of schedules to correct for problems such as bottlenecks, machine breakdowns and urgent orders. An order release policy may take into account the time necessary to interchange entire tool magazines instead of individual tools (Chakravarty and Liu 1989). The rate of tool exchange can be a basic measure of the workload of the tool management system (Rhodes 1988).

Several heuristic scheduling techniques intended to reduce the need for tool changes are presented in the literature. One strategy places parts on each machine, or on the system as a whole, in a sequence that minimizes tool changeover time between part types. In an empirical study, Carrie and Petsopoulos (1985) found that part sequence has little effect on the performance of a modeled FMS. This is because, for the particular system that they examine, the availability of fixtures largely determines when parts are input; if parts return several times to a few key machines, their progress depends on the utilization of these few machines. This concern is also shared by Shalev-Oren et al. (1985), who study the implications of fixture/pallet availability constraints and of priority scheduling on FMS performance.

Another technique places parts in sequence so as to minimize both the part variety and tool variety at any one time. Menon and O'Grady (1984) suggest sequencing parts so as to minimize a weighted sum of deviations from a desired level of six factors: machine hours, due dates, magazine capacity, the number of tools available of each type, the number of standard tools at each machine, and the number of nonstandard tools required by each part type. While this approach may be promising, it is not clear how to classify tools as standard or nonstandard, nor how to determine appropriate weights for each factor.

Carrie and Perera (1986) post-process data from simulation models of a particular FMS in Anderson-

Strathclyde, UK, to compute tooling requirements for several schedules and to evaluate these schedules based on the frequency of tool changes driven by part variety and tool wear. They find that, for this particular system, tools are changed *ten times more often due to wear than due to part mix.* This observation indicates that greater consideration should be placed on minimizing tool changes due to wear, in contrast to most recent research, which focuses on minimizing tool changes dictated by part variety.

5.3. Process Planning for Economic Production Rates

Schedules are sometimes implemented while assuming a given processing time for each operation on a part type using a particular machine tool. Once a throughput target is set, however, the processing times can be manipulated to reduce costs and increase tool lives (as well as improve surface qualities) at no expense to system throughput. This interaction between machining conditions and the overall system throughput suggests that improved scheduling performance can be based on a production rate / tool wear tradeoff.

Hitomi (1976, 1977) tackles the joint problems of determining the optimal machining speeds and optimal cycle time in a deterministic multistage flow line. Unlimited buffer space is assumed between machines. Cost savings are obtained by slowing down noncritical machines until their cycle times match that of the bottleneck machine. McCartney and Hinds (1982) introduce a procedure to review the machining rates of parts that are first scheduled using maximum production rates. Their procedure will slow some machining rates to reduce production costs (on machines off the critical path) while maintaining due-date performance. Their policy is similar to classical PERT / CPM heuristics (see, for example, Whitehouse 1973).

Koulamas et al. (1987) discuss determining buffer capacity along with optimal machining speed and tool replacement policy in a two-machine system. A penalty cost is imposed for tool failures during production. They show that the tool replacement policies determined independently for each operation do not change when these two operations are coupled, and that the buffer size is sensitive to the tool change times.

Queueing network models are now being used in industry to optimize the process rates and to determine changes in bottlenecks and queue lengths as the processing rates are altered. The optimization of processing rates in a queueing network is particularly intricate due to the phenomena of shifting bottlenecks. Schweitzer and Seidmann (1991) and Schweitzer, Seidmann and Goes (1991) present several nonlinear queueing network optimization methodologies, which determine the minimum cost processing rates given the FMS throughput target, the work-in-process level, part routes, transporter delays, and tool cost functions. Using industrial sample data, they show that a slight acceleration of the processing rates at a few economic bottleneck machines allows for significant rate reductions in others. This provides for substantial gains in tool lives as compared with the conventional one-machine process planning models. Their results also prove that it is not optimal to balance utilization of all machines, to balance waiting times at all machines, or to use the processing times to compensate for local transporter delays.

Watanabe and Fujii (1988) find that, when adaptive control systems adjust machine feedrates and machining speeds due to changes in workpiece hardness and tool dullness, predetermined schedules are often violated. They propose a heuristic control model that links the operation speed to the order tardiness. The system proposed is likely to result in major operational improvement. Given the heavy computational demands of this control scheme, however, its applicability to full-scale, real-time adaptive control is currently unclear.

5.4. Spares Management

Ensuring the availability of required tools is critical to system performance. Even if a specific tool is present at a machine tool at the start of a day, its unplanned replacement may be necessary upon detecting a problem such as breakage, wear, poor quality finish, or excessive machining temperature.

Results from studies of spares management in multiechelon inventory systems can be extended to the optimal allocation of spare tools among machines. Gross et al. (1983) were early explorers of this idea. They examine the tradeoff between spares levels and the capacities of repair facilities using a hybrid queueing network optimization model, assuming spares may be allocated among machining centers. Their work is extended by Vinod and Sabbagh (1986), who present a closed queueing network model for this allocation, capturing the availability of tools by requiring that the necessary tools be located at the machine before a part is dispatched to it. Their model minimizes the cost of spares and of repair capacity by considering failure rates for multiple tool types.

The specific storage locations of spare tools—in magazines, in racks near machines, or in remote tool cribs—may affect system performance (Kusiak 1986). Pan et al. (1986) analyze tooling reliability using models for serial systems performance. They predict the reliability of an automatic tool changing system with various carbide inserts and spares subject to Weibull failures. Their work complements many studies of multilevel spare parts allocation that have appeared in the management science literature (e.g., Bryant 1983, Baker et al. 1986, Gerchak et al. 1988). Most are aimed at generic machine component spares and may be extended to handle the particular characteristics of spare tool allocation. In designing a spare tools management policy, one needs to account for the following major system attributes:

(1) the capability of the tool handling system, required and existing,
(2) the number of machine tools that can perform the same operations,
(3) the ability to substitute non-identical tools,
(4) the need to provide alternate part routes,
(5) the number of identical tools required,
(6) the tool magazine capacities,
(7) tool life distributions, and
(8) tool costs.

5.5. Tooling Inventory Management

Operational flexibility often requires many tool types. For example, Berr and Falkenburg (1985) provide statistics indicating that in practice, for each tool type, there are at least three duplicate tools required: one in a tool magazine, one as a backup (centralized or on a relevant machine), and one in preparation (i.e., refurbishing, inspection, reconditioning, presetting, or mounting into the tool shank). Moreover, the number of tool types in storage increases over time due to such factors as new product introductions, engineering changes in existing products, and the availability of more advanced tooling materials. The appropriate number of tools to be purchased of each tool type must be determined (Graver and McGinnis 1989).

Optimal tool reorder points and safety stock levels are not addressed in the literature. Custom tools can shorten processing times, but are more expensive and require extensive purchase lead times. This tradeoff has not been studied; nor has the tradeoff between tool availability, manufacturing capacity, tool reorder points, and the overall investment in tooling stocks.

6. Summary and Conclusions

We present here an integrated conceptual framework for understanding and modeling tool management decisions in the context of resource planning in automated manufacturing. This framework identifies the major decision tradeoffs associated with tooling and specifies the critical information interfaces between the various manufacturing management tasks. It also supports our structured critique and evaluation of key research approaches to tool management problems in automated manufacturing.

Our taxonomy of the major tool-based research problems discussed here and a summary of future research directions are highlighted in Table 1. It conceptualizes the taxonomy around design, planning and control aspects at the tool, single machine and system management decision levels. Our analysis of the tool management decision issues explains why decisions made at one level constrain those at lower levels, and how information from lower-level decisions feeds back to higher-level decisions. For example, the choice of machining parameters depends upon tooling economics (a tool-level decision), which is used as information in determining the spare tool allocation (a system-level decision), but spare tools inventories influence system reliability and the potential for parallel processing of identical parts on several machines (a system-level decision). Similarly, a decision to increase the number of identical tools loaded simultaneously into the tool magazine of a single machine reduces its product scope. This limits the grouping and loading strategies (a system-level decision), reduces the number of setups needed for changing worn tools (a single machine-level decision), and allows the process designer to increase the machining speed for certain operations (a tool-level decision).

Table 1 Tool-Related Research Areas

Design	Planning	Control
	TOOL-LEVEL	
Standardization of Tool Types [10, 15. 44]	Assignment of Tool Types to Operations [9, 52]	Tool Life [10, 25, 27, 49, 53, 73, 76, 77, 78, 79, 111, 114, 118]
Tool Tracking Technology [2, 4, 39]	Economic Process Planning [13, 24, 26, 29, 27, 32, 33, 35, 39, 46, 45, 47, 50, 60, 67, 74, 82, 90, 108, 119, 120]	
Tool Information Requirements [30, 36, 43, 83, 117]		
	SINGLE MACHINE-LEVEL	
Monitoring & Control Technology [*]	Tool Replacement Strategy Due to Expected Wear [5, 8, 28, 59, 67]	Tool Replacement Strategy Due to Actual Wear [54, 89]
Tool Magazine Capacity [*]	Sequencing Parts/Scheduling Tools [69, 75, 91, 92, 95, 103, 104, 112]	Adaptive Control at One Machine [32]
Tool Changing Technology [*]	Sequencing Operations/Assigning Tools to Slots [75, 92, 95, 112]	
	SYSTEM-LEVEL	
Number and Type of Machines [*]	Production Planning [65, 92]	Adaptive Control Strategies [105, 113]
Tool Loading & Handling Technoloy [*]	Part Type Selection (Batching vs Flexible) [1, 51, 75, 96, 98, 99, 116]	
Loading of Duplicate Tools [*]	Cell Grouping & Facility Loading [3, 12, 21, 57, 71, 88, 92, 93, 94, 95, 97, 98, 99, 116]	
	Tool Change Times and Detailed Scheduling [18, 19, 20, 22, 68, 87]	
	Processing Rate Determination & Bottleneck Control [47, 48, 56, 66, 85, 86]	
	Spares Levels [*]	
	Allocation of Spares [7, 14, 37, 42, 58, 72, 110]	
	Tool Inventory Control [11, 30, 36, 40]	

[#]. Reference number corresponding to related research
[*]: Open research issue.

The increase in the number of automated facilities, and the corresponding growth in the number of scientific publications associated with modeling the impact of tool management decisions, clearly attests to intensifying concern with properly integrating tooling considerations in production management. Many of the studies discussed here prove that significant operational benefits can be realized with proper tool selection and allocation policies.

Our study points to several promising research directions in this area:

Analysis of particular decision problems. These include such research issues as tool inventory levels and the dynamic allocation of duplicate tools to machines (see Table 1). We need to study the impact of design decisions, such as tool magazine capacity, on tooling costs and the effect of the subsequent tooling constraints on system capabilities.

Integration of various tool management decision levels. To date, most research efforts in tool management focus on single-level decisions. Ignoring the impact across levels leads to suboptimal results. The current research incorporating tooling economics within production scheduling exemplifies the benefits of integrating decision levels.

Improved modeling of actual industrial practice. Certain studies still make unrealistic assumptions, for example (a) that all tools require only one magazine slot, (b) that each operation requires exactly one tool, or (c) that tool costs are independent of machining rates.

Field-driven empirical studies. There is a need for systematic evaluation of current industrial tool management policies, and of various approaches recently suggested in the academic literature. In addition, useful tool-related data is scanty, particularly when estimating the expected tool life (and costs) for tools shared by multiple part types and machines.

Strategic role of tool management in product designs. In an era when product life cycles continue to shrink, managers are searching for better means to integrate product design, testing and manufacturing functions. Incorporating appropriate selection and loading models within the tooling information systems will facilitate concurrent tool / product design efforts, reduce the time-to-market for new products, and economize on existing manufacturing resources.[3]

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