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Tool Management in Flexible Manufacturing Systems

FMS에서의 공구관리에 관한 연구

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Abstract

Tooling is now considered as a major limiting resource for highly automated manufacturing systems to be operated unattendedly. In this paper, various issues in tooling are introduced and discussed. The importance of appropriate selection of tooling strategies is discussed and simulation experiments are performed to see how the tooling strategies affect the system performance in automated manufacturing systems. This paper also presents a tool management system developed in Korea Institute of Machinery and Materials.

1. Introduction

It is now widely recognized that manufacturing flexibility is not only dependent on the capacity and capability of machining centers, but also on well developed tool management systems. As machine tools have become versatile which are capable of processing a variety of operations, the latter has more critical impact on the system performance. It is common in current flexible manufacturing systems that some operations cannot be performed even on a very highly versatile machine because the required tools are not available on the machine. Tool management is defined as the interaction of planning, execution and control functions in the tool-related information flow. [18] Its goal is to ensure the optimal deployment of the correct tool, in the right place at the right time in the right condition at the right cost, to produce the required volume of parts with the minimum investment in resources. A recent report shows that an effectively implemented tool management can increase machine cutting time by as much as 50% and reduce tool inventories by up to 40% [7]. The tools are hard to plan and control because of a variety of types and a large amount of inventory. The number of cutting tools in a medium size manufacturing system can easily run into hundreds.

Traditionally, tooling has been treated as a secondary issue and usually considered only after the other primary problems (related to machines and materials) have been resolved. This paper is motivated by understanding that the automated manufacturing systems should take tooling problems into account from new perspectives. Some of the issues associated with the tool management in flexible manufacturing systems are reviewed and discussed which include tool allocation, tool/part flow, tool handling, tool replenishment and process planning. A tool management system developed in Korea Institute of Machinery and Materials is presented to show how the tools are managed in a real-world manufacturing system. Then, simulation experiments are performed to see how the tooling strategies affect the system performance.

2. Tooling issues in flexible manufacturing systems

2.1 Tool allocation

Tool allocation involves the concept of when and which

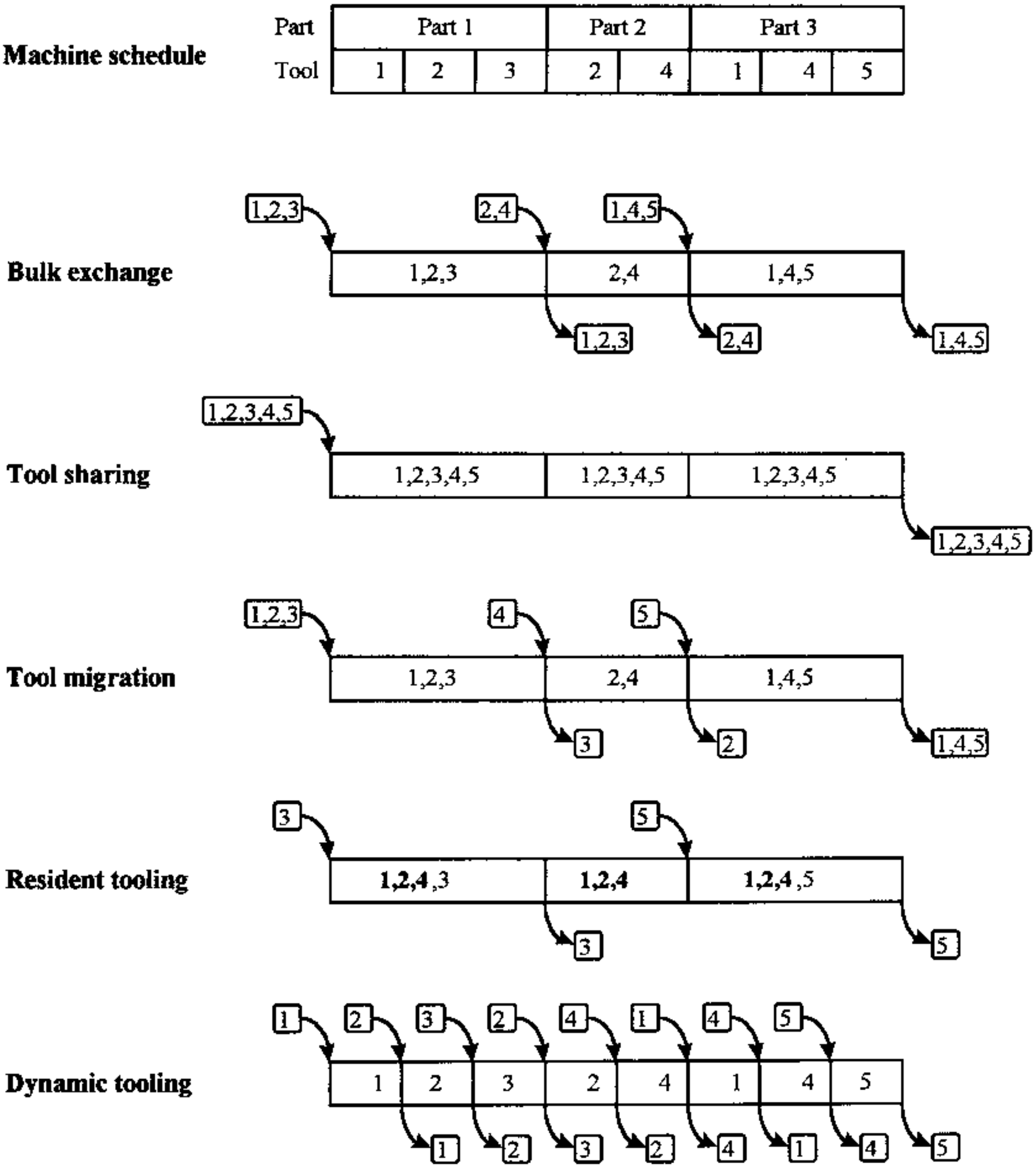


Figure 1. An example of tool flow in various tool allocation strategies

tools are to be brought to or taken from machine tool magazines. Tool allocation strategies may be divided into two categories: static and dynamic strategies. In static tool allocation strategy, tools are assigned to the machines at the beginning of a planning horizon or a production batch, and the assignment remains unchanged during the period. On the other hand, the dynamic tool allocation strategy assigns the tools to the machine over time as they are requested.

Various static tool allocation strategies are identified by Hankins and Rovito. [6] (See Figure 1 for a graphical representation of each tooling strategy.) *Bulk exchange* strategy provides a complete dedicated set of tools for each different part type. At the completion of a part run, all tools are returned to the tool room, to be replaced by a different dedicated set of tools for the next part type. With bulk exchange, easy tool control is achieved at the expense of extensive duplicate tooling. In *tool sharing* in a frozen production window, commonly used tools are shared among the various parts to be manufactured within a fixed production window. Tools are served only once at the beginning of the production window. At the end of the production window, a new set of tools for the next window is loaded. The part mix rather than the length of the production window dictates the tool matrix capacity required. The concept of *tool migration* at the completion of a part type uses more shared tools than the previous strategies. There is no complete changeover of tools. When the production run of a particular part type is completed at a machine, only those tools that are unique to the part type are removed from the tool magazine, allowing new tools for other parts to be loaded, probably during the next machining cycle. While this strategy allows a further reduction in tool inventory through sharing of common tools between part type, it requires the application of sophisticated decision logic to determine. *Resident tooling* strategy identifies the high usage tools for the entire production mix and keeps them resident on the machine tool magazine for the entire production window. The remaining slots are used for migrating tools. This strategy provides routing flexibility and therefore allows quick response to changes in the production schedule.

When the static tool allocation policy is employed, even though the system consists of versatile machines which are capable of performing a variety of operations, some of the operations may not be processed on some machines because of unavailable tools. In the *dynamic tooling* policy, no tools are assigned to the machines at the beginning, but they are delivered when they are needed. Automated (and fast) tool transporters and tool change mechanism allow the tools to be shared dynamically among the machines and interchanged (in seconds) even while the machine is in operation. With proper information flow, the machines can begin processing a job as soon as the next required tool is on the tool magazine, rather than wait for all tools for the job to be loaded beforehand. The dynamic tool assignment strategy allows the tool and part assignment decisions to be made on the fly as jobs enter the system. Changes in product-mix and demand rate can be responded quickly without critical system performance degradation. A partial system disturbance has not so critical impact on the performance in the dynamic tool assignment than in the static tool assignment policy. However, it should be noted that, in order for the dynamic tool assignment to be implemented successfully, complex computer control systems and highly automated tool handling systems responsible for managing tool flow are required.

Table 1 shows a comparison of the tool allocation strategies described above. Each policy has its own advantages and disadvantages. The appropriate tool allocation strategy depends on order handling methods, tooling requirements of the part types, batch size, tool magazine specification, the desired degree of manufacturing flexibility, tool handling systems, and the level of automation and control complexity. When the manufacturing system is stable and tool inventory is not a critical

Table 1. Comparison of tool allocation strategies

Tool allocation strategy	Manufacturing environment	Advantages	Disadvantages
Bulk exchange	Large batch size	Easy tool control	High tool inventory
Tool sharing	Low variety	Easy tool control Lowest tool transfer	Large tool magazine Low flexibility
Tool migration	Parts with similar operations	Less tool transfer Lower tool inventory	Sophisticated decision logic
Resident tooling	Unstable system	High Flexibilility	High tool inventory Sophisticated control system
Dynamic tooling	Unstable system Continuous order	High Flexibilility Lowest tool inventory	Sophisticated control system Frequent tool delivery

problem, then the static tool allocation strategies may be preferable to the dynamic tool allocation strategy because of their easy of control. However, when the tooling cost counts and the manufacturing system is unstable, the dynamic strategy may be preferable because of its flexibility and low tool requirements.

2.2 Machine loading problems

Manufacturing operation decisions are usually composed of pre-release and post-release decisions. Pre-release problems involve setup decisions made before a system begin to operate while post-release problems deal with scheduling and control decisions made when the manufacturing system is in operation. A set of pre-release decisions for FMS has been identified by Stecke [22]: part type selection, machine grouping, production mix ratio, resource allocation and machine loading problems. Among these, the machine loading decision is concerned with the allocation of operations and tools to the machines subject to the resource constraints of the system. The machine loading decision usually provides a static tool allocation where the tool assignment is fixed or static for an entire part batch or a planning horizon.

Early studies on loading problems usually deal with only operation assignment, while tooling constraints are not taken into consideration. Since operation assignment and tool assignment are reciprocal (i.e., operation assignment to a machine depends on the tools allocated to the machine, and vice versa.), they are usually performed at the same time in recent years. A few papers proposed mathematical models to allocate the tools and operations at the same time [2,25]. Later, some researches expanded the initial models by including some additional factors such as tool life [23], alternative routing [2], and material handling systems [16]. The concept of group technology is also used to address the loading problems in FMS [8].

The static machine loading decisions assumes a static manufacturing environment where the amount of the parts to be produced during a planning horizon is known with certainty and they are available at the beginning of the planning horizon. The product-mix remains unchanged throughout the planning horizon under the static environment. The focus of the machine loading decision is efficiency through stability and control. Once the tools are assigned, they are available on a limited number of machines. The parts should follow a rigid route or a route of a limited flexibility because a specific operation can be performed on a limited set of machines defined in the loading decisions. Addressing the manufacturing problems by the hierarchical approach may improve the system performance and achieve the smooth flow of resources under a static environment. However, the static decisions are often charged with problems of inflexibility to the unexpected environment changes and lack of robustness to the system disturbance.

2.3 Flow of tools and parts

Two major entities of material flow exist in automated manufacturing systems: workpieces and cutting tools. Historically, in a manufacturing system, a workpiece moves from a machine to another in search for required tools while the tools resides in machines all through the planning horizon (*part movement policy*). The part route that a part takes through the machines within a manufacturing system Is predefined because of (1) technical constraints (limited machine capability), (2) static tool allocation policy, and (3) relatively simple/easy control scheme required. Existing researches related to manufacturing flow design and control problems have therefore mainly focused on the part flow, handling and storage. For example, a vast amount of studies for solving FMS pre-release problems are mainly based on the flow of parts.

Today, manufacturing environment is moving toward mass customization which is characterized by unstable demand, proliferating variety, shorter life cycle and lead time, and time based competition. To cope with the requirement variations, it is important for the system to be flexible. A new flow concept called *tool movement policy* has been introduced. Dynamic tool assignment policy described previously allows the tools to be delivered dynamically and quickly to the machines when needed. Here, the usual flow concept is inverted: parts are kept on work centers while the tools are delivered to the machines. With the tool movement policy, when the system consists of versatile machines, all the operations of a part can be performed on a machine. This kind of system Is termed as a single-stage multimachine system [11] and provides a number of advantages as follows:

(1) Better quality and accuracy: Since a part stays on a machine all through its operations, there is less need to refixture or reposition the workpiece or re-establish tooling offset. The elimination of these processes reduces build-up of tolerance errors and hence results in higher cutting precision quality and low scrap rate.

(2) Quick response to changes: The realtime tooling reconfiguration of a machine allows the system to quickly respond to possible order changes and shop floor status changes.

(3) Reduction in work-in-process and throughput time: The simple part flow and less workpiece handling reduces the in-process inventory and throughput time.

(4) Higher machine utilization: Without additional workpiece setups, the machine utilization can be increased.

(5) Simple part scheduling: Tool movement policy can simplify the scheduling puzzle when parts no longer have to weave their way through the shop from machine to machine. (Tool flow control becomes a major decision process)

(6) Reduction of tool inventory: Tool sharing among machines leads to less tool duplication.

The tool movement policy with dynamic tool assignment is rarely implemented today in real-world manufacturing. This is because the new approach requires fully versatile machine tools, very sophisticated shop floor information systems and automated/fast tool handling systems. These prerequisites have not been available in traditional manufacturing systems. However, as modern manufacturing system is moving toward computerization/automation, the tool movement policy becomes feasible.

2.4 Tool handling

The frequency of tool change/delivery depends on tool assignment policy, configuration and capacity of tool magazine, job sequence, tool delivery unit, tool delivery system as well as part variety and tool wear/breakage. Three tool delivery methods are identified: In *tool drum change*, the tool change is done by removing a drum entirely from a machine, reconfiguring it with new tools, and replacing it in the machine. This method is usually applicable to the static tool allocation policies such as bulk tool exchange and tool sharing. In *individual tool movement*, only one tool is delivered at a time to the tool magazines with an automated tool changer. In general, high speed tool carriers with fast tool change mechanism are required for this method. This method is often applicable to the resident tooling and dynamic tooling. *Segmented tool magazine change* is a compromise between flexibility of the individual tool movement and simplicity of the tool drum change. The machine's own tool matrix is itself broken up into segments, which can be swapped in and out. Transfer cassettes (which hold a few tools) are often used as a tool transport unit.

Once a tool delivery method is decided upon, there is an issue of how to transport the tools within a manufacturing system. Various tool delivery systems have been introduced. A *gantry crane* is often used to transport tools under static tool assignment policies described in the previous section. The tools are held in a portable tool drum which is delivered between the machines and tool room. An *automated guided vehicle* is also used to transport the portable tool drums. This system is more flexible than the gantry type crane. A *rail-guided cart*, equipped with a tool transfer mechanism travels up and down the rail system to transport tools between the tool storage rack and the individual machines. An *overhead tool carrier* such as gantry robot and monorail is now widely used to transport a tool or small groups of tools. Recently a linear-induction motor has been introduced as a fast tool delivery system. [5]

The selection of an appropriate tool delivery system depends on manufacturing environment both internal and external. In mass production, the tool drum change with tool transporters of large capacity (e.g., AGV or gantry crane) may be preferred. Here, tool transporters need not be so fast or fully automated. In mass customization, since a variety of parts often need to be produced, flexibility in tooling is the most critical issue. As fast tool transporters and automated tool change mechanism are introduced, the individual tool change with overhead tool carriers is paid more attention because it provides higher flexibility and requires less tool inventory.

While extensive amount of researches have addressed the issues related to material handling systems transporting the workpieces, only a small amount of studies have been done for addressing the tool handling problems. Some simulation approaches are used to evaluate the effect of the number, speed and type of the tool carriers, tool handling system topology, and tool magazine capacity. However, design, planning and operational aspects for tool handling systems have been rarely seen in the literature. The increasing importance of tool flow in modern manufacturing systems requires more extensive works on tool handling systems. The problems associated with tool handling systems may be closely related to those for part handling systems because they both deal with 'material handling', and hence some of the solution approaches to the part handling systems may be used to solve the problems involved in the tool handling systems. However, additional attention should be taken to the tool handling systems due to their distinct characteristics which include the enormous number of tools involved, possible disturbance such as excess tool wear and tool breakage, interaction between operations and tool requirements, and so on.

2.5 Tool requirement planning

Tool requirement planning refers to how many tools of each type should be maintained in a manufacturing system. Deciding the appropriate level of tool duplication is a very fundamental and important issue since it significantly affects the tool investment cost and the operation of the systems. Poor tool requirement planning results in tool shortages, low machine utilization, poor workpiece quality, increased work in process, and excessive tool inventory. It is reported that the investment in standard tooling made necessary by the purchase of a new machine is between 20 and 30% of the total cost of the machine. [14]

As far as the tool duplication level is concerned, there are conflicting viewpoints between a shop floor manager and the company. From the view point of the shop floor manager, high tool duplication is usually preferred because it will smooth out the production processes with less production delay due to tool shortage. However, to the company, high tool inventory is unfavorable because of the high capital cost involved. Early studies for tool requirement problems were usually done within the framework of a material requirement planning system. Later, arguing that the concept of material requirement planning was not suitable in tool requirement planning, Chung [3] and Khator and Leung [9] proposed mathematical models to predict the tool requirement level for flexible manufacturing systems under static tool allocation policies. Zavanella and Bugini [27] and Wang et al. [24] used queueing models to include the stochastic characteristics in determining tool requirements. Koo et al. [13] presented a queueing network-based method to predict a tool requirement levels under a dynamic tooling policy. In their model, tool waiting time for each operation is also predicted whenever tool duplication levels are determined.

The existing researches on tool requirement planning have ignored some important factors. The followings are some of the factors which should be additionally considered in tool requirement planning: (1) The relationship between tool requirements and tool handling approaches such as tool allocation policies, tooling topology and tool delivery unit should be identified. (2) In order to maintain tools on the shop floor to a specific level, the tool procurement planning should be made in parallel for each period. (3) Tool regrinding should be considered In a replenishment planning because tool life can be extended via regrinding processes. (4) Flexible process planning which allows alternative tools for a specific operation can affect the tool requirements.

2.6 Tool life and replacement

A typical tool replacement approach is to replace the tools when the sum of the tool's usage times and upcoming processing times exceeds the tool's expected life or when the tools suddenly break. There are some problems associated with determining tool life prior to the use of the tools. Since the tool life is usually conservatively determined in advance, the tools are often replaced well before any damage to the workpiece or machine is likely to happen, which lead to the loss of tool life. In addition, a tool is often used on more than one workpiece with different work materials and other cutting conditions, thereby invalidating the previously determined tool life.

The problems involved in the fixed tool life lead to another approach to tool replacement policy, tool condition monitoring-based replacement. Kiran and Krason [10] argued that, since the individual machining centers in computerized manufacturing systems are usually unmanned, it is essential to monitor cutters for wear and breakage. One widely used method for monitoring tool conditions is by using a fixed probe permanently mounted on a machine. The tool wear/breakage may be also monitored by various sensors which measure cutting force, power input, temperature, vibrations, radioactivity, electrical resistance and acoustic frequencies. If the measured value exceeds the predetermined value, the tool is replaced. Vision systems are also used to monitor the tool condition in which any change in the tool pattern indicates tool wear or breakage. The monitoring-based tool replacement method may result in optimal tool utilization and reduction in wasted tool life. In addition, as they monitor the tools and spindle force in realtime, sensors are also used to provide feedback to the machine tool for adjusting the spindle speed and the feed rate to avoid loss in machining accuracy.

2.7 Process planning and tooling

Process planning function involves the preparation of detailed work instructions to convert a part from its initial form to a final predetermined form. In the process planning function, part route, process method and parameters, operation sequence, machine and cutting tools are determined. Traditionally, the process planning function attempts to select the most desirable processes, not considering the availability of resources at the particular time, and usually generates one fixed process plan (linear sequence of operations and resources to be used) per part type based on technological and/or economic considerations. The fixed process plan is blamed for inflexibility. The adverse effect of the fixed process plan is highlighted when the manufacturing systems are unstable and manufacturing resources are limited. In conventional manufacturing systems, the fixed process plan is an unavoidable choice because there are several constraints for the flexible process plans to be implemented. The constraints involve large amount of data for a part, very complicated decision logic, realtime information on shop floor, and technical constraints such as tool path change, interference between tool and workpiece. Since shop floor information/communication systems are at hand in most FMSs, these constraints become less critical now.

To cope with the uncertain nature of manufacturing environment, a few researches presented dynamic and alternative process planning models in which the process plans are not predefined but rather generated on a real-time basis with consideration of the current status of resources on the shop floor. Various issues in the flexible process planning have been addressed which include the effectiveness of alternative routings in an FMS [20, 26], the effect of sequence flexibility on performance of dispatching rules [19], realtime operation selection [17] and integration of process planning and production planning/scheduling [4,15].

Most existing research works overlook tooling constraints in applying flexible process planning in real time. This may make sense under conventional static tool loading policies where the tools reside on a set of machines through a planning horizon. However, it could happen that some tools are not available at some point of time when tools are shared resources or under replacement due to breakage. In this case, consideration of tooling information for selecting operations in realtime under flexible process planning environment may reduce possible machine idleness due to tool shortage.

3. Tooling information management

3.1 Tooling information system

Sound information management of tools is a key prerequisite for the effective planning and control of tools in automated manufacturing systems. The complexity of the information system required is proportional to the level of tool automation in a manufacturing system. Tooling information includes identification code, tool offset data, tool geometry (length, diameter), tool material, tool location, tool wear, tool life, cutting condition, and so on. Bar codes and memory chips are major means for tool identification. Some parts of information may be stored in a distributed fashion in devises or machine tools with various degrees of information processing capabilities while other pieces of information are stored in a centralized database. For example, such tooling information as predefined tool life, tool material, tool geometry, processing time and tool-machine compatibility, which remains unchanged over time, may be stored in databases on mainframe computers, while other tool data (changing over time) such as tool wear, tool offset, remaining tool life and tool usage status can be held directly on an electronic memory device embedded in the tool.

Tool information management is especially critical in some applications, such as in the case of tool movement-based manufacturing systems. The tool information management supports the tool management functions (such as tool loading, tool scheduling, tool inventory and replenishment, tool handling and tool crib management) described in the preceding section. It also facilitates such shop floor control functions as part dispatching, order releasing and scheduling.

The issues of tool information management have been investigated by several researchers and practitioners who regard information management as an essence of tool management. Ranky[29] proposed a structured tool description method using a RDBMS (relational database management system) as an approach to tool management. He illustrated how the FMS control system can utilize this database. Aoyama et al. [30] presented a distributed automatic tool management method where intelligent cutting tools (that are constructed using memory, sensors and a processor) are used. They classified the tooling information into four categories: (1) information for tool specification (tool name, application, and shape), (2) information for tool life (tool wear, cutting temperature, cutting time, and cutting force), (3) information for error compensation (tool wear, cutting force, and cutting speed), and (4) information for the history of cutting tools.

3.2 An example of tool management system

This section describes a tool management system (TMSID) for an FMS, developed in Korea Institute of Machinery and Materials. [31] The TMSID uses EEPROM IC (256Byte) tag to manage tooling information (cutting condition, processing time, usage frequency and tool wear status) and tool preset information (diameter, length, wear rate of the tools) automatically. The system is developed under a client/server environment for the network-based FMS. The system uses Access as a common DB for managing tooling data, Windows NT 4.0 for network OS of the server, and Visual Basic for a development tool in the client.

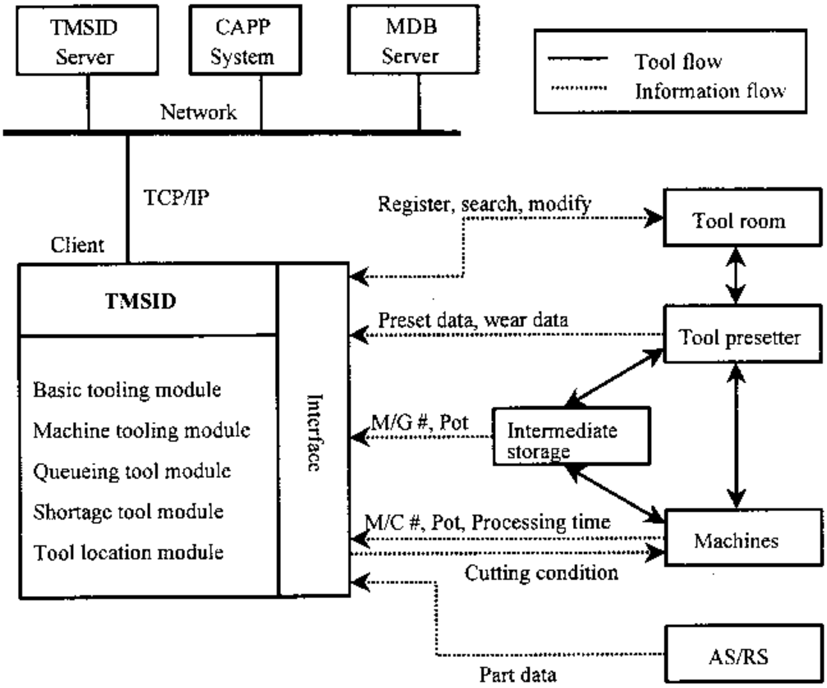


Figure 2. System configuration of TMSID

Figure 2 shows the configuration of a system with the TMSID. The TMSID selects the tools required for the parts to be processed, based on the tool sheet generated by a CAPP (Computer-Aided Process Planning) system. A list for the selected tools is then uploaded to a manufacturing database (MDB) at the higher level. In the TMSID, the local database of clients manages information intrinsic to the tools. Other information related to parts and processes are managed in MDB or CAPP system at the higher level.

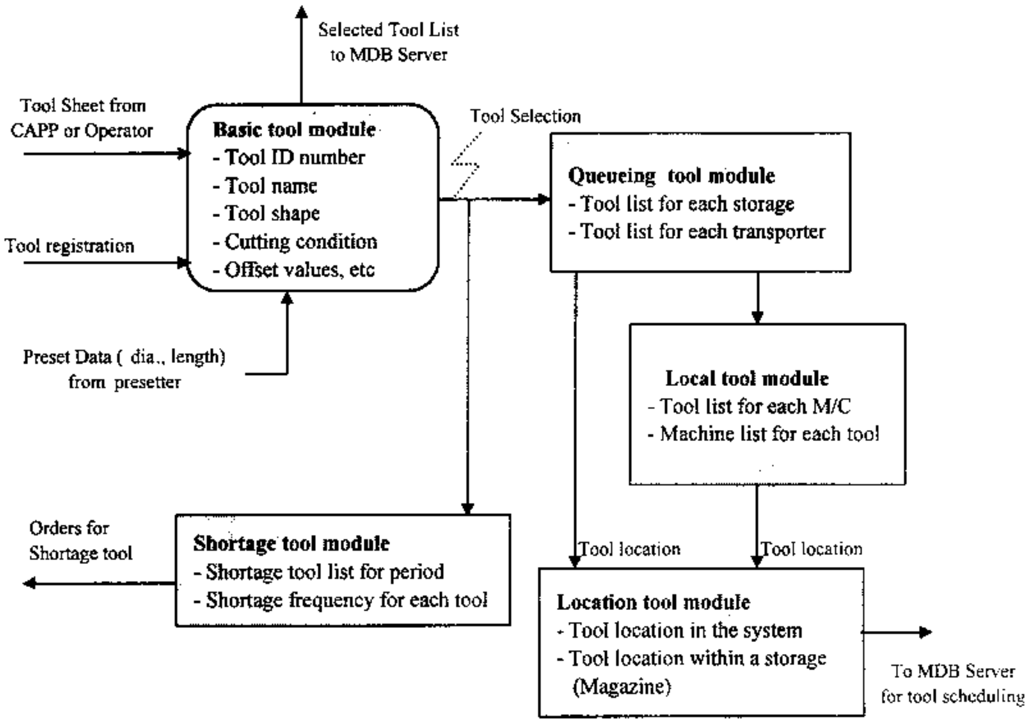


Figure 3. Relationship between the submodules of TMSID

The TMSID consists of five tool management modules: basic tool module, local tool module, queueing tool module, shortage tool module, and tool location module. Figure 3 shows input/output data for each submodule in TMSID. The basic tool module manages general information and process information for all the tools in the system. It registers the tools to be stored in the tool room and performs the functions to search for a specific tool, and modifies and deletes data related to the tools. It communicates with a tool presetter to have an access to the information on tool geometry and tool identification system. The local tool module manages the tools inserted in the tool magazine of each machine while the queueing tool module manages the tools resident on the tool transporters or intermediate storage. The tool location module provides the current location of the tools. This module interacts with the local tool module and the queueing tool module. The shortage tool module makes orders for the tools under shortage as the tools are checked periodically.

When a part is to be released to the system, the process information for the part is given to the TMSID. A set of tools required for the part are prepared in the tool room and transferred to the tool presetter where tool geometry is measured and stored on the IC tag attached to the tool. The tools are then loaded on the tool magazine to process the operations for the part. When an operation is completed, the process data for the corresponding tool is stored on the IC tag attached to the tool. The tool life and cutting condition for each tool are transferred to the machine tools through a PMC (programmable machine controller) and/or an external PLC (programmable logic controller). Figure 4 shows a configuration of the system with PMC, PLC, machine and TMSID.. The PMC is a special type of PLC located on machine tools. Its function is to control and monitor machine actuators The TMSID can read external signals such as tool offset values and time spent for processing sent from CNC machines. [32] PMC and PLC are connected through DI/DO(Digital Input/Digital Output) system which has 32 input channels and 48 output channels.

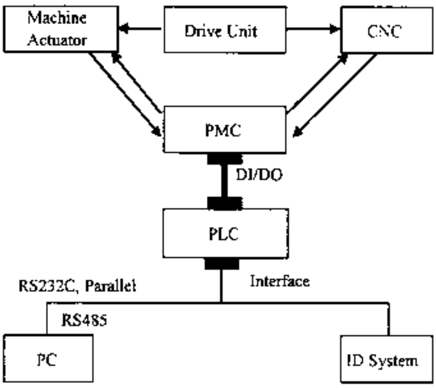
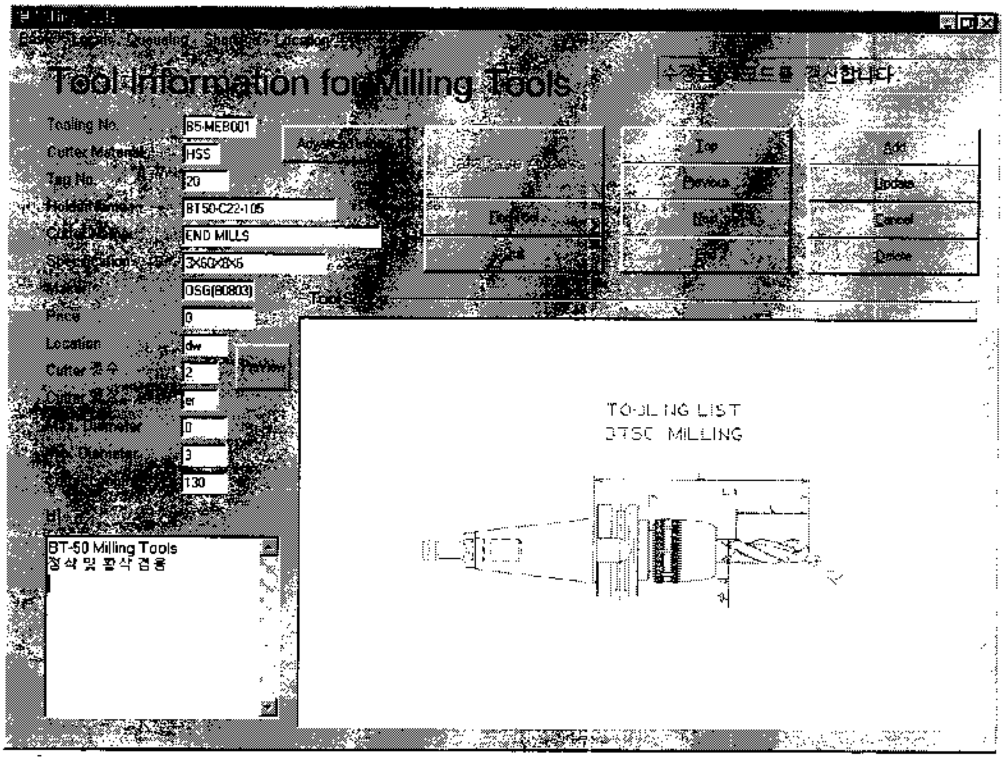


Figure 4. Connection between TMSID and machine tools through PLC and PMC

When all the operations for a part are completed, the tools are returned to the tool presetter for their tool



Tooling No. B5-MEB001

Cutter Material HSS

Tag No. 20

BT50-C22-105

END MILLS

3X60X8X6

OSG(80803)

Price 0

Location dw

Cutter 날수 2

er

0

3

130

BT-50 Milling Tools
정삭 및 황삭 겸용

Figure 5. An example screen of the TMSID

geometry to be measured. The new data are stored on the IC tag and the database of the TMSID. The tools are then returned back to the tool room. As discussed in section 2.1, this type of tool allocation method is called bulk exchange. [6] In the bulk exchange, the tools are delivered to machines when a part or a group of parts are loaded on the machines. When the other allocation methods are applied, a tool loading module may be additionally needed to the existing TMSID submodules.

The TMSID has been implemented in an FMS in a company that produces machine tools and their components. Figure 5 shows a screen of the TMSID under operation. With the tooling information, various shop floor functions can be realized including dynamic tool sharing and dynamic part scheduling in response to the tooling changes. The TMSID helps the system to realize higher machine utilization and higher product quality, and lower time loss due to tool shortage.

4. Experimental studies

This section examines the effect of tooling in flexible manufacturing systems through simulation studies. The underlying system consists of eight versatile machine tools. There are 20 part types to be machined. Each part has its own process plan in which operation sequence, operation methods, and required tool for each operation are determined. All the (different) operations of a part are performed on a machine with a single setup so that each part visits only one machine for its entire processing. Parts are produced according to customer orders (with an assumption of exponential interarrival time).

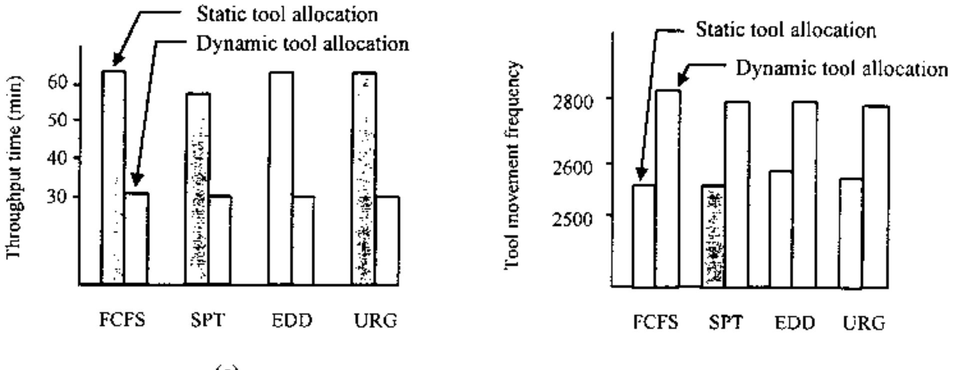
Automated guided vehicles move parts while overhead tool carriers transport tools (one at a time) among the machines or between the central tool storage and machines. When an operation is finished, an automatic tool changer with two hands takes off the tool from the spindle and sets up a new tool to that spindle from the tool magazine within an ignorable time. The tools are replaced when the sum of the tool usage time exceeds the tool's expected life or when they are subject to premature breakage. Once all its operations are performed, a part is unloaded from the machine and put in the output buffer where it waits for a vehicle to transport it to the unload station. A previously used tool is either moved to other place where it is requested or stay where it is.

The simulation experiments are performed with SLAM II and a user-written Fortran program on a Unix System. The SLAM II model is used to manage simulation time clock and define a few global variables while an actual control of manufacturing resource flow is performed by the Fortran program. An input data file that represents a manufacturing system must be prepared before a simulation run starts. Various manufacturing system settings can be simulated by modifying the input data file and/or by changing parameters of the system variables in SLAM II network code. The simulation runs were replicated at five different random seeds for each manufacturing environment to reduce the effect of randomness on the performance. The random seeds create the different part interarrival times so that each run creates a different manufacturing demand environment (while mean interarrival time remains the same). Since the manufacturing system is empty at the start of the simulation, there exists a period of transient state at the beginning of simulation. The statistics during this period are discarded.

The performance measures used for an analysis include part tardiness, part throughput time and tool waiting time. The part tardiness refers to the number of parts which do not satisfy their due dates while the part throughput time is defined as the amount of time which a part spends in the system. Tool waiting time is closely related to the part throughput time in that shorter tool waiting time usually leads to shorter throughput time.

4.1 Effect of tool allocation strategies

This section investigates the effect of tool allocation strategies on the system performance in an FMS with various part release rules. The manufacturing system is simulated under two tool allocation strategies: static and dynamic tool allocation. The static tool allocation is made according to a machine loading decision. Here, the parts can be processed only on a specific machine. In the dynamic tool allocation, tools are not assigned to the machine in advance but they are delivered to the machines when they are needed.



(a)

(b)

Figure 6. Effect of tool assignment on performance measures over different part release rules (FCFS: First come first served, SPT: Shortest processing time, EDD: Earliest due date, URG: Urgent part first)

Figure 6 shows the system performance under different tool allocation policies with a variety of part release rules. The dynamic tooling policy provides much lower throughput time than the static policy for any part release rule. The high efficiency in dynamic tooling is mainly attributed to the machine load balance realized by dynamic tool sharing. An interesting finding is that the tool movement frequency is higher in the dynamic tool allocation than in the static tool allocation. This result contradicts the common idea, 'the less tool movement (tool waiting time), the higher performance' which provides a basis when tool and part loading problems are solved with an objective of minimizing tool movement frequency. The experiments in this study show that, even with the higher tool movement frequency, the dynamic tool allocation provides better results in the major performance measures such as tardiness, lateness, and throughput. This is because the effect of the tool allocation scheme dominates that of tool movement frequency.

Although the dynamic tooling provides better performance in the manufacturing environment assumed in this experiment, this result does not mean that the dynamic tooling is always superior to the static tooling in any environment. As Koo and Tanchoco [12] argued, when part demands are known at the beginning of the planning period and the manufacturing systems are stable, the static tooling can be preferable to the dynamic tooling. This indicates that the performance of the tool allocation strategies depends on the underlying manufacturing environment.

4.2 Effect of flexible process sequencing under limited tool availability

In the underlying manufacturing system, (since they are shared among the machines) the tools may not be available on a machine while they are used on the other machines. When an operation sequence is fixed for a part and the tool for the next operation is not present on the machine on which the part is loaded, the machine remains idle until the required tool is delivered. However, if the operation can be substituted by another operation for which the required tool is available, then the operation may be continued without major disturbance.

Simulation experiments have been performed to investigate how a manufacturing is affected when the operation sequence is not fully determined at the process planning stage but opportunistically selected in real time based on the current tooling condition. Table 2 shows the effect of existence of alternative operation sequence on various performance measures. It is seen that the flexible sequence provides better performance than the fixed process plan in terms of the tardiness, throughput time and tool waiting time. The higher performance in the flexible sequence is realized because the tool requirement is taken into consideration in operation selection decision and so their usage is leveled over time. The table also shows that having flexibility in operation sequence is especially beneficial when the tool inventory is tightly controlled.

Table 2. Effect of flexible sequencing

Tool inventory	Process sequence	Number of tardy parts	Throughput time (min)	Tool waiting time (min)
Low (Tightly controlled)	Fixed Flexible	67.4 47.4	37.0 34.0	3.4 2.3
Moderate	Fixed Flexible	17.2 16.0	30.0 29.3	0.72 0.37
High (Loosely Controlled)	Fixed Flexible	13.6 13.6	29.0 28.8	0.25 0.13

It must be noted that the full benefit of flexible process sequencing can be realized when appropriate tooling decisions are made beforehand. Tool information systems and automated tool handling/delivery systems are prerequisite for the flexible process planning to be implemented.

4.3 Effect of Tool Carriers

Simulation experiments have been performed to see the effect of the number of tool carriers on system performance. Since the tools are shared among machines, the tool carriers play an important role in delivering the tools in time. Figure 7 shows the average tool waiting times (with 95 % confidence intervals) as the number of tool carriers varies.

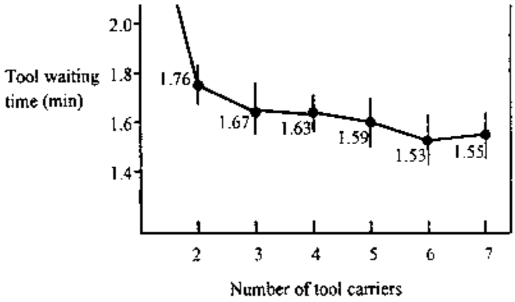


Figure 7. Tool waiting time under varying tool carrier size

The problem in terms of the tool carrier size in a system has two aspect, the operational aspect and the economical aspect. [28] It is desirable to have the smallest number of carriers in the system (from the economical point of view) but still be able to achieve the performance requirements. As shown in Figure 7, the tool waiting time decreases as the number of tool carriers increases. However, the addition of more carriers can result in increased congestion: in the simulation experiment, an additional tool carrier beyond six does not reduce the tool waiting time. Using too many carriers in the system can cause the performance to go down due to heavy traffic and blocking of the carriers, causing delays in delivering the tools. Using too few carriers can cause the machines to be idle due to tool shortage, resulting in underutilization of machining resources. A trade-off between operational aspect and economical aspect should be considered in determining the tool carrier size.

5. Conclusions

It is now believed that the largest single factor contributing to the inflexibility or disturbance in automated manufacturing systems is the difficulty of managing the tooling required to enable the production of a wide variety of parts. The tooling issues discussed in this paper is only a part of the problems which could be faced when system designers and operators work with the real manufacturing systems. The complexity and dynamic nature of tooling make the tool management more difficult. Tooling information system is a key prerequisite for the effective planning and control of tools in automated manufacturing systems. The TMSID, a tool information system developed in Korea Institute of Machinery and Materials, has been presented. It was seen through the simulation experiments that the system performance is greatly affected by the tooling strategies. The appropriate tooling strategy depends on the underlying manufacturing environment.

There are two major resource types in manufacturing systems to produce parts: machine tools and cutting tools. Traditionally, the problems related to the cutting tools have received less attention than those related to machine tools. As machine tools become more versatile and the capability of manufacturing systems is often limited by the tooling, the tooling problems should be taken more attention.

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