12-2000

The impact of tool allocation policies on selected performance measures for flexible manufacturing systems

Kevin M. Smith

To the Graduate Council:

I am submitting herewith a dissertation written by Kevin M. Smith entitled "The impact of tool allocation policies on selected performance measures for flexible manufacturing systems." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Industrial Engineering.

Ken Kirby, Major Professor

We have read this dissertation and recommend its acceptance:

Rupy Sawhney, William Hamel, Hampton Liggett

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Interim Vice Provost and
Dean of The Graduate School

THE IMPACT OF TOOL ALLOCATION POLICIES ON SELECTED PERFORMANCE MEASURES FOR FLEXIBLE MANUFACTURING SYSTEMS

A Dissertation
Presented for the Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Kevin M. Smith

December 2000

DEDICATION

I dedicate this dissertation to my mother, America B. Smith. As a mother, she has given love, wisdom, and support to me throughout my life and to the lives of her children and grandchildren. I also dedicate this dissertation to God who gave me the inspiration, perseverance, faith, courage, and hope to complete this educational goal.

ACKNOWLEDGEMENTS

First, I am grateful to Dr. Ken Kirby for his leadership, support, and guidance as the chairperson of my doctoral committee. Second, I wish to express my sincere appreciation to my doctoral committee members. They include Dr. William Hamel, Dr. Hampton Liggett, and Dr. Rupy Sawhney. I am thankful for their encouragement and advice during my career as a Ph.D. student. Third, I wish to thank Mr. Mike Newman for sharing his knowledge in the field of statistics. Also, I wish to thank Mr. Chad Toney for sharing his knowledge in the area of simulation. Finally, I am grateful to my loving wife and friend, Priscilla Smith, for her support, patience, and prayers to God as I pursued this Ph.D. degree.

ABSTRACT

The allocation of cutting tools to machines is an important concern for managers of flexible manufacturing systems. This research was conducted to study the impact of four tool allocation strategies on five performance measures, contingent upon three part-type selection rules. In addition, the average tool inventory and tool consumption rates were evaluated for each tool policy and selection rule. The four tool allocation policies consisted of the bulk exchange, tool migration, tool sharing, and resident tooling. The five performance measures consisted of the average flowtime of parts, the average machine utilization, the robot utilization, the percentage of parts late, and the mean lateness. Simulation was used to study the impact of the tooling strategies on the performance measures. Analysis of variance procedures, graphical comparison charts and Bonferroni multiple comparison tests were used to analyze the data.

The results show that clustering tools, based on group technology, is the preferred method for allocating cutting tools to machines. Tool sharing was the preferred tool allocation strategy. Also, tool allocation policies that require tool changes, after a part's machining cycle, increase part flowtimes because parts are delayed in the system due to the increase in tool changing activities. In addition, tool allocation strategies based on tool clustering methods reduced the utilization of resources. The results of this study show that bulk exchange produced lower tool consumption rates per production period during the early periods of production. During the middle and later production periods, tool sharing produced lower tool consumption rates.

This study concluded that grouping tools based on the commonality of tool usage results in a lower average inventory per production period. Furthermore, this study showed that the uneven distribution of part-types to machine, under tool clustering methods, affected the average mean lateness of part-type. Moreover, no part-type selection rule outperformed another on all performance measures. The earliest due date rule produced the lowest mean lateness values for all tool policies. Tool policies that produce low mean flowtimes may not produce low mean lateness values. Managerial implications are discussed with respect to the findings from this study. Further research is needed to evaluate flexible manufacturing systems, which include using different part-type selection rules, machine failures, and hybrids of tool allocation strategies.

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CHAPTER 1

INTRODUCTION

Cutting tools represent the interface between the workpiece and the manufacturing process. A well-developed tool management system contributes to the overall production efficiency of a flexible manufacturing system (FMS). Due to the increased use of computer-integrated manufacturing methods, work is needed in integrating tool technology concepts and tool management. Tool management provides a key source of flexibility for an FMS. The combination of proper tooling on the machining center with the product flow is a strategic feature for the manufacturing process. The objective of this research proposal is to study the impact of tool allocation policies on selected performance measures for flexible manufacturing systems.

First, Chapter 1 introduces the research topic, the need for the study, the theoretical framework for the proposed study, the statement of the problem, limitations of the study, and the contributions of the study. Second, Chapter 2 introduces the literature review on the selected research topic. The literature review provides information on tool management decisions, tool allocation strategies, and tool allocation models. Chapter 3 introduces the research methodology for the proposed study. The methodology includes the research design, the simulation model, data collection, data analysis, and pilot study. Chapter 4 provides the data results, analyses, comparison, and discussion. Finally, Chapter 5 presents the main conclusions, implications, other limitations of this study, and recommendations for further research.

1.1 DEFINITION OF A FLEXIBLE MANUFACTURING SYSTEM

Kashyap and Khator [38] have defined an FMS as a group of machine tools. Each machine is capable of performing more than one operation on a workpiece without the workpiece being removed from the machine. Stecke [34] defines a FMS to consist of NC machines that are used to perform operations needed to manufacture part-types. The machines are linked by automated material handling equipment. Each operation may require more than one cutting tool. The tools are stored in the machine's tool magazine chamber. The tool magazine is limited to the number of available tool slots. An automatic tool changing system is located on each machine tool. This allows rapid tool changing capabilities with no tool set-up time between operations. Therefore, tool requirements must be planned prior to production.

Hankins and Rovito [24] define an FMS as an automated batch manufacturing system comprised of CNC machine tools with an automatic tool handling system. The required cutting tools are stored in the machine tool's magazine. These tools are used for all operations. However, the tool's magazine capacity is limited. Automatic tool changing provides capability and flexibility for the FMS. For this research, the FMS consists of a manufacturing cell with five CNC machines, which utilize a material handling and tool loading robot.

1.2 FMS PRODUCTION PLANNING

Flexible manufacturing systems are being implemented to adapt to market demands and to improve product quality and productivity. The efficiency of an FMS mandates the allocation of machines with limited production and magazine capacity.

These machines fabricate part-types with known cutting tool requirements and part processing times [59]. Advanced technologies are being incorporated into the FMS. The technologies include manufacturing cells with precision machine centers, transportation systems with load and unload mechanisms, and advanced tool exchange technology [52]. An FMS is used to produce consistently high quality and cost effective products with short lead-times [33]. This is necessary to compete in the global market.

However, an FMS is more difficult to manage than production lines and job shops for several reasons [34]. The machine tools are versatile, and they can perform many different operations. Also, different part-types can be machined simultaneously. In addition, part routing is flexible. As a result of the above reasons, the number of decision variables and constraints are increased for an FMS.

The manufacturing objectives for planning a new flexible manufacturing system include the following [1]:

- to reduce the throughput time for parts,
- to decrease inventory,
- to reduce production cost,
- to maintain and improve quality,
- to handle different part-type batches,
- to accept design alterations and new product design with minimum tooling,
- to automate handling and eliminate manual operations.

An FMS is identified by the following characteristics [29]:

- workstations that are capable of performing different operations if the proper tooling, fixtures, and materials are available,
- workstations with minimum set-up times between operations,
- a flexible material handling system that can execute any part routing.

1.3 DEFINITION OF TOOL MANAGEMENT

Tool management has various meanings. Veeramani et al. [54] state that tool management requires a planning strategy, a control strategy, and a monitoring strategy. The planning strategy ensures that the right tools are available in the right quantities. The control strategy coordinates tool transfers between machines and the tool crib. The monitoring strategy identifies and reacts to tool conditions with respect to tool wear, tool breakage, and tool life. Gray, Seidmann, and Stecke [10] include design and scheduling strategies into tool management. The design strategy coordinates tooling inventory tracking, handling, loading, and unloading. The scheduling strategy accounts for tool availability and tool changes.

Hankins and Rovito [43] state that "tool management is the capability of having the correct tool on the appropriate machines at the right time so that the desired quantities of workpieces are manufactured while maintaining acceptable utilization of assets." Also, tool management has been described as having the correct tools on the appropriate machines at the right time for part processing [20]. One objective of tool management is to deploy the correct tools to the right place at the right time in order to reduce cost due to the variety and volume of cutting tools in the manufacturing system [21]. The key decision in loading the FMS is the assignment of parts to machines along with their tooling requirement [24]. Thus, tool management decisions are necessary for planning tool allocation strategies.

1.4 NEED FOR THE STUDY: TOOL MANAGEMENT IMPACT ON FMS

Tool management is a support system that affects a manufacturing process. Tool management is interrelated with production planning and machine grouping [10]. Tooling can affect the attainment of manufacturing objectives [1]. Also, the variety of parts, operation times, the number of operations, the number of workstations, and tool life are parameters that influence tool management for an FMS [38].

Metal cutting companies have introduced capacity requirements planning and material requirements planning to address resources such as machining capacity, materials, and worker allocations. However, the tooling resource has been ignored [53]. Companies are not achieving their objectives because of an inadequate infrastructure that does not support tool management. As a result, the companies are experiencing sub-optimal use of the implemented technology. Thus, for many companies, tooling has become an expense instead of an asset or a planned activity.

In surveys conducted by Mason [37] and Boyle [55], the authors found the following observations:

- 30-60% of tool inventory is on the shop floor instead of in a storage area.
- 16% of scheduled production is not achieved because of unavailable tools.
- 40-60% of a foreman's time is spent expediting material and tools.
- An operator may spend one-half hour per shift searching for cutting tools.
- 30% of tooling inventories consist of tooling that is not accounted for.
- 45% to 55% of the average tooling inventory contains obsolete tooling.
- The annual budget for tooling, fixtures, and related supplies may be 7-12 times higher than the capital equipment budget.

Melnyk [53] states that poor tool management increases production cost. Tools that are poorly maintained reduce overall production quality; these types of tools contribute to scraped and reworked products or parts. Also, a lack of tool control results in (1) poor management of obsolete tooling, (2) excessive overtime in tooling stockrooms or tool cribs, (3) excessive investment in tooling, and (4) inaccurate tool purchasing. Inadequate control of the tooling resource may result in unsuccessfully implementing new manufacturing systems. Cummings [11] noted that tooling accounts for 25% to 30% of fixed and variable cost of production in an automated manufacturing system. Macchiaroli and Riemma [60] state that tooling is a major constraint for a computerized FMS. The tooling constraint could prevent an FMS from achieving its full flexibility.

The performance and cost effectiveness of a flexible manufacturing cell depends on organization and preparation of the tooling required to process work [18,10]. Planning and control of tool flow should be considered concurrently with work flow [18]. In many manufacturing systems, the interaction between work and tool flow is dominated by the work schedule. This work and tool interaction is constrained by a production schedule that is dictated by due dates and work order priority [18].

Flexibility is required in a metal cutting manufacturing system, especially when diverse products, high quality, and short lead times characterize the market environment. Automation and manufacturing technologies have created sophisticated machine tools that can process multiple operations. These machine tools are constrained by the availability of tools. The machine's tool magazine may not have the capacity to fit all required tools. If the magazine's capacity is increased, then this requires an increase in tool inventory as well as tool cost. [26]

Poor tool management decisions affect the FMS. Mohamed and Bernardo [31] state that productivity and competitiveness of an FMS have not been fully realized because of poor tool management decisions. Kusiak [30] states that tool management decisions have not been properly developed or incorporated into the FMS. Boyle discovered that 16% of production time is lost due to the unavailability of cutting tools. Veeramani et al. [35] state that the full flexibility of a flexible manufacturing system is not realized because of tooling constraints. Khator and Leung [22] state that as much as 25% of the total production cost is attributed to tooling batch operations. Thus, a reduction in total production cost can be realized by implementing appropriate tool allocation procedures [10] [60].

Veeramani et al. [35] have identified constraints that have affected the FMS. The constraints were acquired from model formulations that addressed the tool allocation requirements problem. The constraints include cutting operation assignments, tool magazine capacity, tool assignment, production capacity, due dates, and additional resource constraints.

Stecke [35] has identified five FMS production planning problems. Stecke states that the problems may be solved sequentially. The problems are identified as follows:

(1). <u>The part-type selection problem</u>:

From a set of parts with specific order sizes, select a subset of part-types for immediate and simultaneous production. Each unique part is considered a part-type. A set may contain several different part-types.

(2). <u>The machine grouping problem</u>:

Partitioning machines into groups. Each is capable of performing the same set of operations.

(3). <u>The production ratio problem</u>:

Determine the relative ratios of part-types to be processed.

(4). <u>Resource allocation problem</u>:

From the selected part-types, determine the allocation of the limited pallets and fixtures of each fixture type.

(5). <u>The tool loading problem</u>:

For the selected part-types among the machine groups, determine the allocations of operations and tooling requirements subject to FMS constraints.

Because of tool magazine capacity constraints, the part-type selection problem and the tool allocation problem must be solved simultaneously due to the following reasons [3, 4, 9, 35, 59]:

- The part-type selection problem is considered a batching problem that contains identifiable constraints such as tool magazine capacity.

- The machine's tool magazine capacity constrains FMS flexibility by limiting the number of tools that can be mounted in the tool magazine.

- The machine's tool magazine may not have the capacity to fit all required tools for processing of all part-types.

- Tool magazines must be reconfigured after a part-type has been processed because of the tool slot limitations.

- Tool magazine weight restrictions.

- Production plan must divide part-types into batches because of tool capacity constraints for each machine.

- A machine may not be able to process all required operations.

The above literature shows that there is a need to study tool management for an FMS. The next section introduces hierarchical frameworks that include tool management decisions in production planning.

1.5 HIERARCHICAL FRAMEWORK FOR TOOL MANAGEMENT

The tooling resource must be planned and managed to achieve the benefits of advanced manufacturing technologies [28]. In the literature, tool management has been included in resource planning hierarchical models. Gray at el. [10] presented an integrated resource planning hierarchical framework that is designed to structure tool management decisions at the systems level, tool level, and machine level. The integrated resource planning hierarchy is illustrated in Figure 1.1. The framework recognizes the interrelationship between resource planning and tool management decisions. The framework facilitates planning, scheduling and control of tools as well as parts and machines. The framework shows that decisions made at the upper level constrain decisions at the lower level. Also, information from the lower level feeds back to higher levels. For example, decisions that are made at the systems level are constrained by machine tool capacity and cutting-tool availability, which are lower level management decisions. Thus, Figure 1.1 shows that tool planning affects production planning decisions.

Coleman et al. [18] proposed a tool management system hierarchy that contains both systems and machine levels. The schematic hierarchy is located in Figure 1.2. The systems level concerns the transfer of required tools from the supplier to the machining cells. This includes tool procurement, tool storage, tool refurbishing, inventory control, and tool tracking information systems. The machine level concerns tool allocation strategies to individual machines.

Khator and Leung suggest [36] that tool planning and tool control are the two basic categories of the tool management problem. The planning problems consist of the design of tool related facilities, tool requirements planning, and tool allocation and replacement. The control problems consist of tool routing strategies, database support, and real time tool monitoring. These areas and their subtopics are depicted in Figure 1.3.

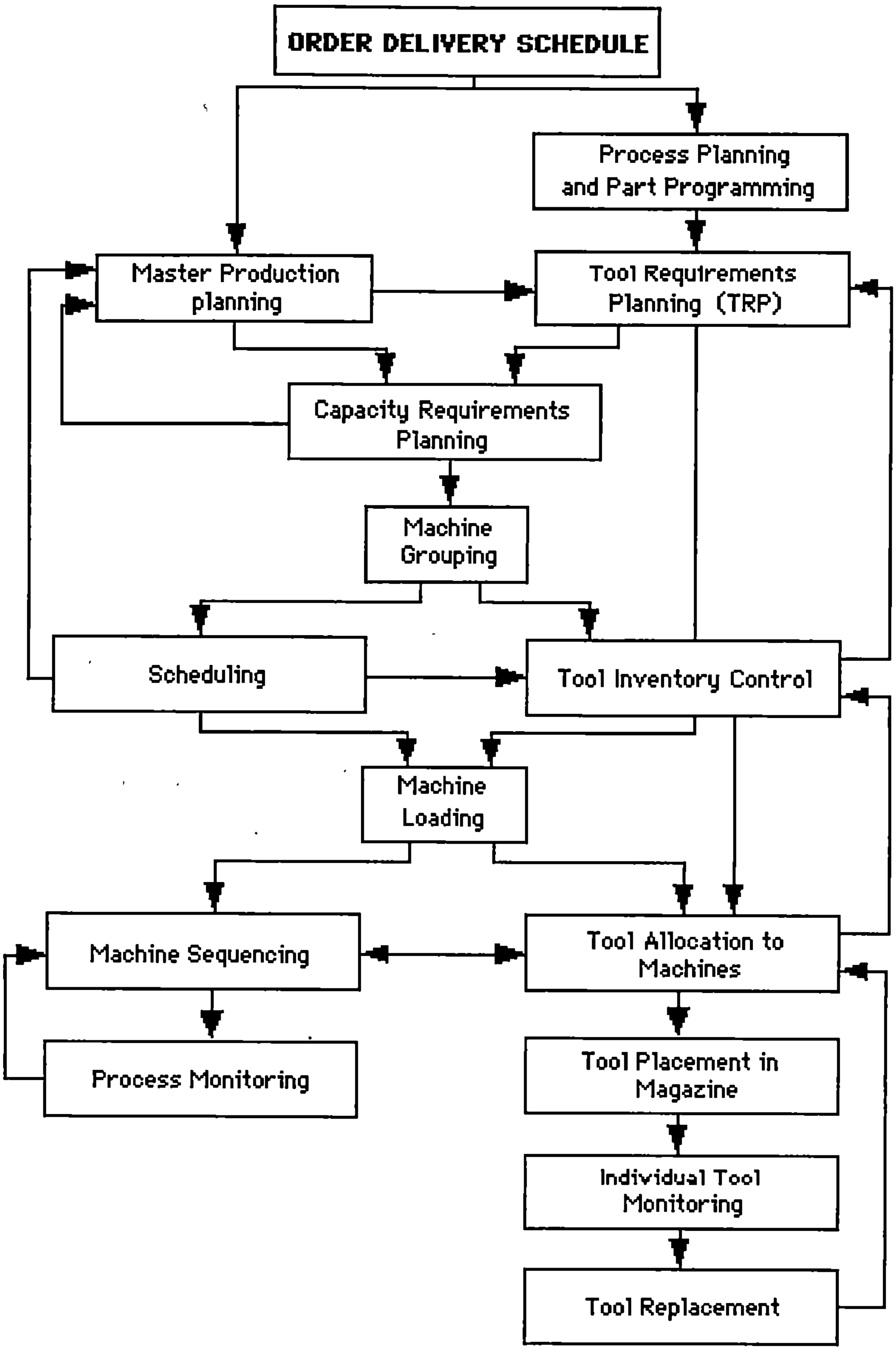

Figure 1.1. An Integrated Resource Planning Hierarchy

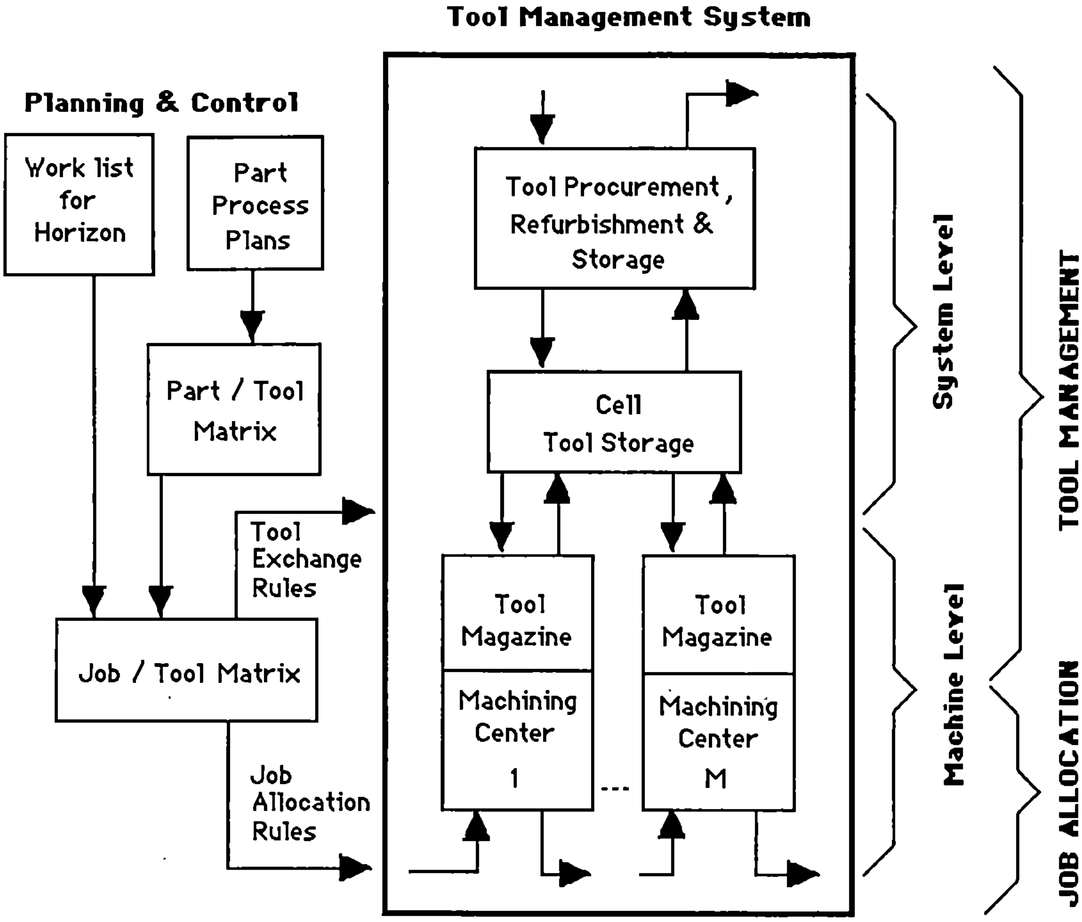

Figure 1.2. Overview of tool management and job allocations

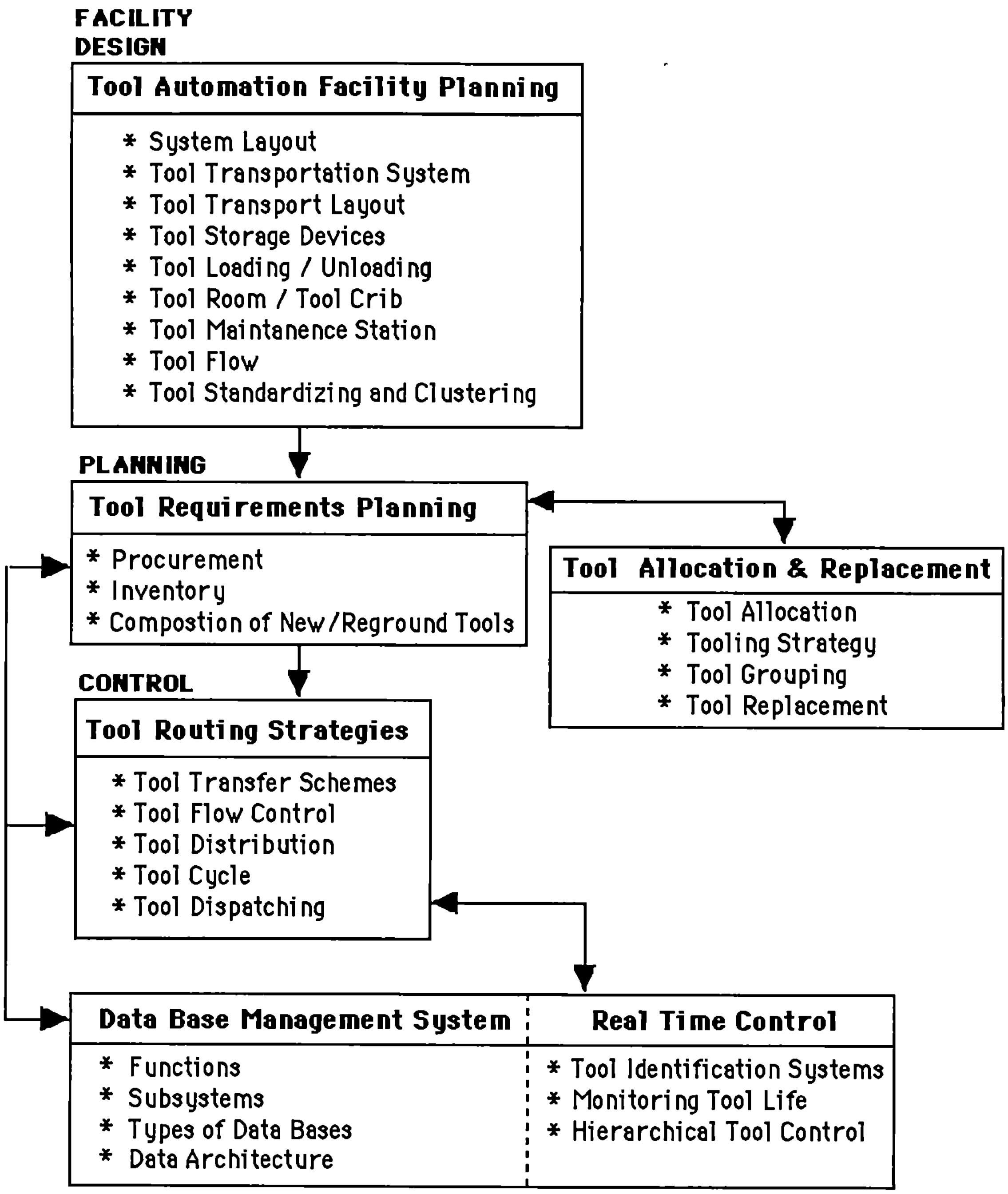

Figure 1.3. Design, Planning, and Control Issues in Tool Automation

1.6 STATEMENT OF THE PROBLEM

This section identifies the reason for the proposed study. In the literature, an excessive level of tooling has been an issue within manufacturing environments. To achieve tooling availability, managers are purchasing excessive tools to eliminate the probability of tool shortages. As a result, excessive tooling has contributed to tool inventory and production cost.

In addition, due to tool magazine constraints, the allocation of cutting tools is a problem for the FMS. Because of limited magazine capacity, all parts cannot be processed during a planning period. Production planning must divide part-types into batches because part mix tooling requirements exceed tool magazine capacity. A machine may have a tool magazine that accommodates either 12, 30, 60, 80 or 120 cutting tools. Therefore, cutting tool allocation and part-type selection must be solved simultaneously by assigning the required cutting tools to machines for a given family of parts. The affective assignment of parts and their required tooling to machines may eliminate many tool management problems. [3, 4, 5, 9, 12, 35, 59]

This research will be conducted to study the impact of four tool allocation policies on five production measures within an FMS manufacturing environment, contingent on three part-type selection rules. The tool allocation policies consist of the bulk exchange, tool migration, tool sharing, and resident tooling [20, 24]. The production measures include the mean flow time of parts, machine utilization, robot utilization, average part tardiness, and the percent of parts tardy. The mean flow time will depend on part release rate, processing time and movement. Mean flow time, and machine and robot utilization relate to production cost. Average part tardiness and percent of parts tardy relate to customer service.

The study will be evaluated under three part-type selection rules. Part-type selection involves selecting a subset of parts to be machined simultaneously [35]. Previous researchers have formulated heuristic procedures to address the part-type selection problem for the FMS [5, 6, 7]. The three part-type selection rules are defined in the Literature Review under the Section entitled "Batching for the FMS."

The four tool allocation policies, five performance measures and the three part-type selection rules were selected from previous researchers in the area of tool allocation research [3].

1.7 RESEARCH QUESTION AND OBJECTIVES

The research question is as follows: What are the impacts of different tool allocation policies on production measures that affect production cost and customer service while using part-type selection rules in an FMS environment?

The objectives of this research are as follows:

- To use simulation to study the impact of tool allocation policies on part flowtime, machine utilization, robot utilization, lateness of parts, and the percent of parts late, contingent on part-type selection rules.

- To use simulation to study the average cutting tool inventory and tool consumption rates per production period for each tool allocation policy and part-type section rule.

1.8 LIMITATIONS OF THE STUDY

This research objective involves consumable cutting tools. Consumable tools consist of production tooling such as drill bits, end mills, inserts, and other cutting tools. Consumable cutting tools are discarded or refurbished after usage.

This research does not address the following tooling concerns:

- tool breakage due to incorrect selection of cutting tool parameters,
- explaining the underlying physics of tool wear and tool failure,
- the affects of tool allocation policies on the quality of parts,
- random machine failure and machine downtime,
- tool tracking from tool room to machine and from machine to tool room.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This literature review provides an overview of tool management areas, a discussion of tool allocation policies, and a review of tool allocation models with respect to a flexible manufacturing system (FMS). Section 2.2 defines a cutting tool. Section 2.3 reviews tooling provisions. Section 2.4 reviews tool requirements planning. Sections 2.5 through 2.9 review the literature on tooling information, tool monitoring, batching for the FMS, tool allocation and scheduling problem, and tool allocation strategies, respectively. Section 2.10 reviews the literature on tool allocation models. Finally, Section 2.11 discusses the contributions this study will make to the literature.

2.2 DEFINITION OF A CUTTING TOOL

The definition of tooling is very broad. Tooling is classified as jigs, fixtures, drills, reamers, pallets, chucks, collets, inserts, shanks, tool holders, templates, angle blocks, and other items that may involve transportation tooling, set-up tooling, and production tooling [53]. The taxonomy of tooling is classified into two categories: durables and consumables. Table 2.1 illustrates these two categories of tooling [41]. Durable tools consist of transportation and set-up tooling such as of fixtures, pallets,

Table 2.1. Taxonomy of Tooling

CATEGORY	TOOLING ITEM CLASSIFICATION: Durable	TOOLING ITEM CLASSIFICATION: Consumables: Perishable and Renewable
Equipment	Fixtures, pallets, gages, gigs	Cutting tools, inserts, end mils, drill bits
Lead Time	Long lead times	Short lead times
Cost	Very expensive	Moderate to less expensive
Monitor and Control Capabilities	Easy to monitor and control	Difficult to monitor and control

jigs, and gages. These tooling items are usually expensive. Consumable tools consist of production tooling such as drill bits, end mills, and inserts.

Consumable tooling can be subdivided into perishable and renewable [53]. Perishable tooling has a finite tool life. When the tool's cutting life is reached, the tool is disposed of or discarded. Whereas, renewable tools are used during a production cycle. After the production cycle is complete, the tools are withdrawn and refurbished. For this research objective, consumable tools will be the primary focus, specifically cutting tools.

In a flexible manufacturing system, a cutting tool is considered a tool assembly [33]. This is illustrated in Figure 2.1. The tool assembly allows a variety of cutters to interface to the machine tool. A cutting tool is composed of a tool holder and tool insert. The insert is inserted into the holder. The holder is mounted in the tool magazine. The cutting tool has a cutting edge. The edge is either brazed to the tip of the cutting tool or the edge may be an indexable insert. Cutting tools become dull after usage. As a result, the worn tools need refurbishing. The tools can be replaced, reground, or indexed. Oftentimes, cutting tools are duplicated. Duplicated tools or copies of tools can be loaded in tool magazines. However, the tool's magazine capacity must be considered.

In addition, Figure 2.1 shows how the cutting tool would be characterized in tool requirements planning and a tool information system. The characteristics of a cutting tool include the geometrical data, physical data, and tool holder requirements [15].

2.3 TOOL PROVISIONS

When designing the flexible manufacturing system, a company must determine the number and type of each tool that must be purchased. This is known as the tool

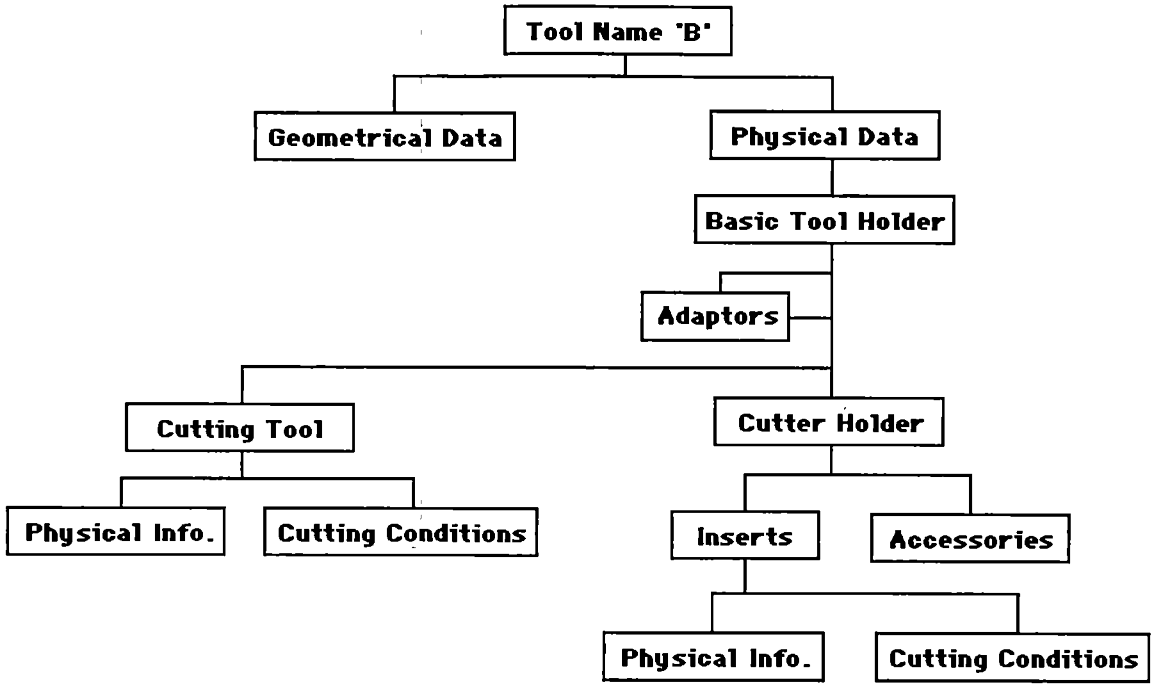

Figure 2.1. Definition of a Machining Tool

provisioning problem. The tool provisioning problem is important because tools contribute to the overall production cost. In addition, tool provisioning has a large impact on space allocation. Thus, an improper tool provisioning solution can reduce the efficiency and capacity of a manufacturing facility. [14,16]

The objective of tool provisioning plans is to guarantee that there is a sufficient quantity of tools to prevent limiting production. Thus, to facilitate the tool management system, the design phase of the production system must determine an accurate number of required cutting tools. If the tool-provisioning plan is inadequate, this may cause delays in the introduction of parts and product delivery dates. Several measures of a tool provisioning strategy include maximizing production output and minimizing the number of captive tools, tool holding cost, and the rate of tool exchange. [14, 16]

A tool flow systematic diagram is depicted in Figure 2.2. Normally, tools arrive to the facility as components. The tool room is where the tool cycle begins. The components are assembled and preset. The assembled tools are grouped together to form sets of tools. This is referred to as tool kitting. A set of assembled tools is sent to a machine for placement into the machine's tool magazine slots. The tools are required for the machining operations. After an operation is completed, a tool remains in the magazine or the tool may be transported to another machine, depending on the tool allocation strategy. Once the entire batch of part-types is completed, the tools are returned to tool maintenance for inspection, regrinding, refurbishing or replacement. [36]

2.3.1 FACTORS IN STRATEGIC TOOL PROVISIONING

Managers of flexible manufacturing systems need a strategic plan for tooling provisioning solutions. As the variety of parts increase, the number of tools

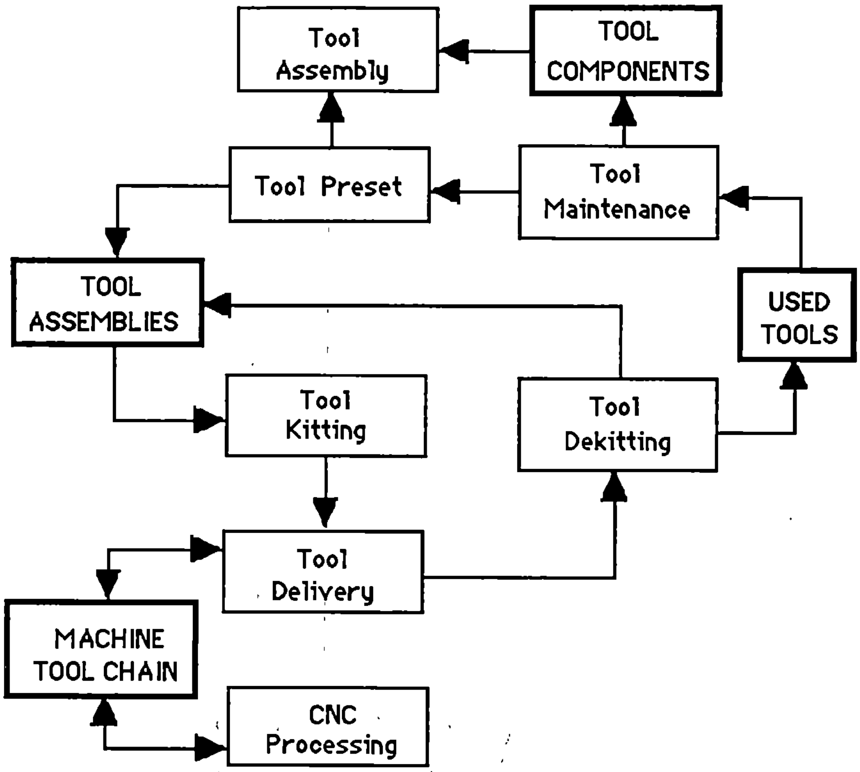

Figure 2.2. Tool Flow in a CMS

increase. As a result, a company's current tool provisioning strategy will have to be modified or permanently changed to suit production needs.

The factors that determine the choice of a tool provisioning strategy include machine specification, tool transfer automation, part mix, machining complexity, reliability of tool information, and cost [14, 16]. The first factor, machine specifications, concerns tool magazine characteristics. The characteristics include magazine capacity, permanent or changeable magazines, magazines with variable tool storage location, and the cost of retrofitting a magazine. The second factor concerns tool transfer automation. If the tool transfer is not automatic than a dynamic strategy is not feasible. Other considerations include the speed, capability, and reliability of the automated tool transfer system.

The third factor, part mix, concerns the variety of parts that are manufactured. A larger variety of parts will require an increase in tool handling. In addition, magazine capacity concerns will arise if the part mix varies over time. The fourth factor, machining complexity, concerns the operation time for each batch, the tool requirements for each batch, and tooling inventory. This factor compares operation times with tooling transfer and exchange activities. A dynamic strategy would be infeasible if operation times are less than tool transfer and exchange times on the machine.

The fifth factor, reliability of tool information, is used on the machine as well as in the production area. On-machine information includes tool breakage and wear detection. Tool tracking and identification are performed in the production area. Finally, tooling cost of a tool provisioning strategy is an important factor. The total number of tools in the system has an impact on the tooling cost. This contributes to the overall production cost.

2.4 TOOL REQUIREMENTS PLANNING

Material requirements planning (MRP) models address the planning and control of material flows. However, MRP models do not simultaneously address material flows with constraints imposed by cutting tool requirements [10, 36]. In the literature, planning requirements of tools have been treated as secondary when compared to materials and capacity planning [24]. A lack of tool availability constrains production flow, resulting in an increase in WIP inventory and sporadic tool changes [32]. The number and type of tool affects the production process. The lack of duplicate copies produces long production lead times and reduced route flexibility. On the other hand, too many tool copies increase tooling cost and increase inventory. In addition, decreased FMS productivity is realized with poor tool planning. Poor tool requirements planning may result in low machine utilization, unacceptable tool levels, and machine downtime. Thus, in an FMS, the proper quantity of each tool type must be determined before tools are allocated to machines. [31]

Tool requirements planning (TRP) determines the total number of tools and each tool type needed in the system so that the workload can be completed in the shortest period of time [30]. Tool requirements planning is often dictated by the tooling strategies or policies [22, 23, 24]. Tooling requirements significantly affect tooling cost and performance [26]. Proper tool requirements planning is important because tools incur costs for carrying, purchasing, inspection, regrinding, quality, and other related costs [22].

TRP is as important as material and capacity planning. TRP and tool management activities must be coordinated to achieve the effectiveness and the efficiency of the overall hierarchical planning process of the production system [23]. Maropoulos [57] states that linking tool management to scheduling and production control will improve the supply of tools.

Chung [23] has proposed a Manufacturing Planning and Control (MPC) hierarchy structure that includes the FMS with respect to tooling requirements planning, tool routing, loading, part family grouping, and rough-cut tool planning. The hierarchy is depicted in Figure 2.3 where the right side consists of the tradition MPC system. The left side illustrates the FMS tool related issues. The Rough-Cut Tool Planning (RTP) estimates the required tools implied by the Master Production Schedule (MPS). The RTP and the Rough Capacity Planning (RCP) are equivalent. The RCP checks capacity availability with respect to machine and worker allocation. RTP checks tooling availability, and RTP provides early planning for tool requirements suggested by the Master Production Schedule. The capacity is relatively fixed in RCP. However, in RTP tools can be purchased or re-tooled in a relatively short period of time [22]. Likewise, TRP and Capacity Requirements Planning (CRP) are counterparts in the hierarchy structure. CRP ensures that sufficient capacity is available to accomplish the planned production [25].

Khator and Leung [22] stated that tool requirements are affected by tooling strategies such as the bulk exchange, tool sharing, migration of tools, and resident tooling. These tool allocation strategies have their own tooling requirements. Their readiness depends on the degree of tool automation, tool room support, tool transport devices, tool monitoring systems, spare tools, new tools, and reground tools.

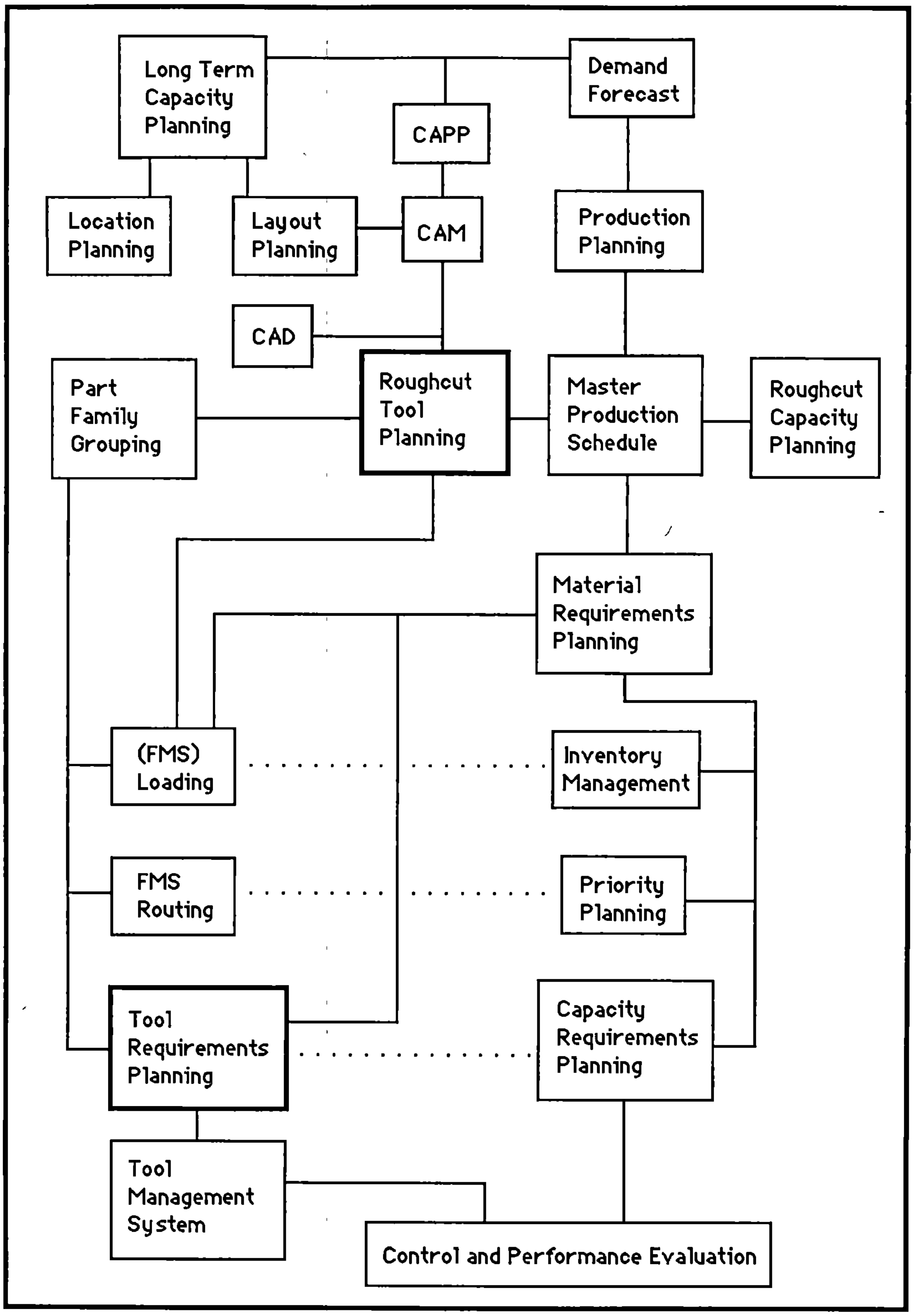

Figure 2.3. Planning and Control for Computer-Integrated Manufacturing

Mohamed and Bernardo [31] developed an Aggregate Tool Planning (ATP) model. The ATP model determines the number of duplicated tools for each tool type to satisfy the FMS workload. The flow of tool information is depicted in Figure 2.4.

The aggregate production plan determines both the Master Production Schedule (MPS) and ATP. The MPS determines the part-type demand requirements. The processing charts calculate the processing rates of each required operation by tool type and machine. Once the part type demand, tool requirements, and processing rate are known, the tool loading and part routes are assigned. Finally, operational performance measures are calculated to determine the efficiency and effectiveness of the system. The operational performance measures include part throughput time, route flexibility, and tool cutting edge productivity.

2.5 TOOL CONDITION MONITORING

Tool condition monitoring is important in tool management decisions [44]. Monitoring a tool's condition for breakage and wear results in optimal tool utilization [36]. When tool breakage occurs or when tool life expires, a tool replacement is needed [43, 42]. Tool life depends on several factors such as tool material, work material, spindle speed, feed rate, and depth of cut [36]. Tool life does not influence a production schedule. However, to economize work set-ups, tool life must be considered especially for large quantities of work [44].

Leung and Khator [36] discuss several types of tool monitoring systems. The monitoring systems include probes, sensors, and adaptive control. Probes are mounted on machine tools. A probe comes in contact with the cutting tool. The probe verifies the

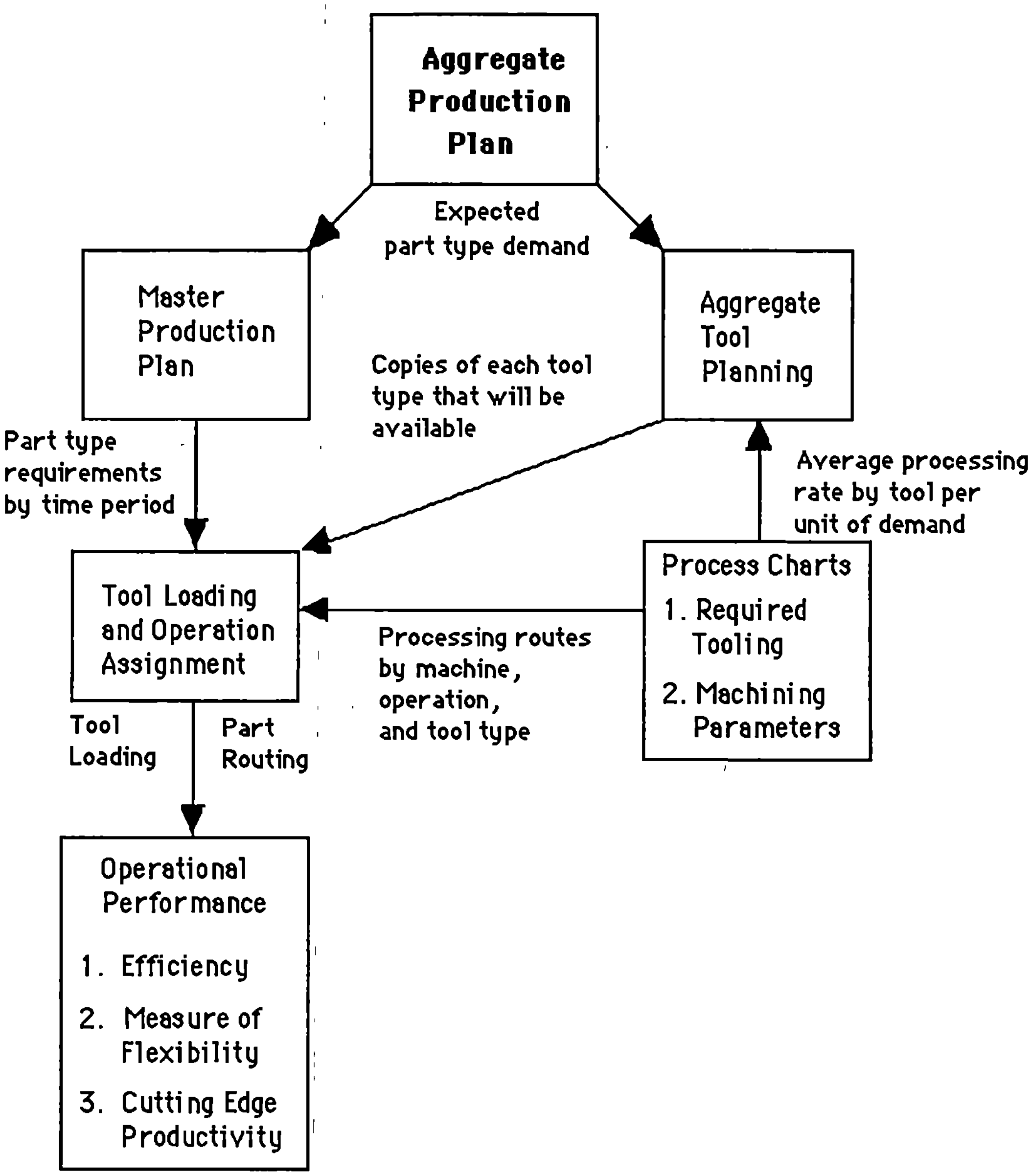

Figure 2.4. Tool Planning Information Flow

tool's length. This tool length is compared with the tool's pre-recorded length. A change in the tool's length indicates a worn or broken tool.

The most commonly used sensors are the force and power sensors. Sensors have been developed to measure various parameters that include the following [36]:

- the cutting force,
- spindle force and spindle horsepower,
- the temperatures at the cutting edge,
- vibration frequency,
- electrical resistance,
- sound frequencies.

Adaptive control systems adjust spindle speeds and feed rates to avoid tool breakage and machining accuracy reduction. During a machining operation, the sensors measure the spindle force or the spindle horsepower. The value is compared with the predetermined value for these parameters. Also, an adaptive control system uses controllers to monitor the machine tool's cutting power. Each cutting tool has a predetermined maximum load. When the tool's maximum load is exceeded, the feed rate is reduced until the load is decreased to the preset value. [36]

Maropoulos [57] recognizes that tool wear prediction and control can be employed off-line or on-line. Off-line or predictive approach refers to non-sensorial predictions and monitoring. Tool feedback information is accomplished using a computer-based modeling tool. The feedback information is collected by an operation. The objective is to determine the best cutting conditions and machining efficiency for a machine tool. Maropoulos notes that off-line monitoring results are influenced by human compliance. Off-line monitoring is applicable for non-fully automatic systems that employ multi-skilled operators.

On-line or real-time tool monitoring improves responsiveness and allows unattended processing by utilizing multiple sensors that measure cutting forces, spindle current, and vibration and acoustic emission. However, the author notes four problems of using several sensors:

(1). noise in data,

(2). sensitivity to cutting conditions,

(3). increased capital cost,

(4). varying reliability.

Maropoulos states that using a hybrid system, which consists of both predictive and sensorial approaches, may be employed to solve the above problems. For example, sensors would collect data and interpret this data to assist the predictive system's manual feedback. Improvements in the predictive system would allow a reduction in the number of sensors. As a result, a more simplified and reliable data processing system could be realized. Moreover, the author lists several organizations and universities that are doing research in the area of real-time tool condition monitoring.

In a study conducted by Martin [56], a company integrated a tool monitoring system within a manufacturing cell. The system monitors the horsepower and tool cutting time for each tool. Each tool's horsepower limit is programmed into a programming macro. A tool may reach a maximum horsepower limit due to tool wear, tool dullness, and hard spots in part materials. Also, each tool's lifetime is entered and stored in a computer. Once a tool's lifetime has expired, the tool is ready for replacement. Once the replacement is complete, the monitor tracks the lifetime of the replacement.

2.6 TOOL INFORMATION HANDLING

Khator and Leung [36] discuss the importance of tool management database systems for tool information handling. Tool database systems can provide information to management with respect to tool purchasing, tool inventory control, utilization of tools, tool requirements, and tool cost control. Static and real-time (on-line) databases are used. Static databases require data to be updated after the end of the production period. Whereas, real-time databases require data to be updated while machines are in operation. With respect to tooling, static databases include files that contain information such as tool code number, tool type, tool manufacturer, tool geometry, and tool type holder, processing times, and part operations by tool types. Real-time databases contain information such as useful tool life, regrinding history, tool location, tool breakage, idle status, in use status, and tool magazine information.

Tool identification is needed on a real-time basis for various reasons [36, 42, 53]. Tool identification is needed because of the large number of tools in integrated manufacturing systems. Each type of tool that is loaded in the magazine must be identified. Tool information handling involves the identification and coding of each tool. For each tool, information may be passed and stored between the toolroom, machine tool, and the host computer. Computer hardware and software are used to input and store tool data. Once the tool's information is properly stored, a link is established between the tool and the manufacturing planning system. The data for each tool consists of the following [36, 42, 53, 54]:

- name and number of the tool,
- length and diameter of the tool,
- tool offsets,
- tool supplier codes,
- tool life, accumulated usage time, and remaining life,
- cutting parameters,
- tool crib location,
- price,
- current state of assembly,
- vendor information,
- insert description.

Two common methods of tool identification include bar coding and memory chips [36]. Bar coding is commonly utilized. Tool information may be stored in the bar code by an attendant or a presetting machine. The label is attached to the tool holder. A tool's status and information are transferred to the host computer. A laser reader that is mounted on the tool magazine provides the transfer. A memory chip may be inserted into the tool holder. The chip stores all the tool's information. The tool is placed in a presetting machine. Tool measurements are performed and stored in the chip. A chip reader is located at the machine tool. Information on each tool may be updated after inspection.

The benefits associated with tool information handling include reduced tool proliferation, reduced quality problems, proper tracking and location of tools, and minimization of the time spent searching for tools. Tool information management supports tool scheduling, tool handling, and tool crib management. Also, tool information handling facilitates machine loading, materials handling, inventory control on the systems level, and cutting tool purchase orders. In addition, tool information handling affects process planning and design. Furthermore, tool information handling becomes necessary in manufacturing systems that share tools among machines. [42, 53, 54]

In the literature, authors are addressing the need for a complete tool information system from the design phase to replacement. Boyle [55] proposes a detailed computerized tool tracking and inventory control system. The system features include tool on-line check-in and check-out, tool location, tool reordering, tool usage, tool coding, tool standardization, and process planning. The benefits of this system include reductions in tool overstocking, tool stockouts, tool inventories, and excess tooling purchases. Also, a benefit includes the identification of obsolete tools. Likewise, Berr and Falkenburg [29] propose a database management system that tracks cutting tools from the design phase, to process planning, to scheduling, to reordering, to inspection, to stocking, to utilization, and to reconditioning. Moreover, Veeramani et al. [54] provide a comprehensive list of vendors who have software packages that facilitate tool tracking, purchasing, tool retrieval, tool dispensing, tool crib operations, process planning, inventory control, design, and production planning.

Martin [56] identifies a company that utilizes a cell controller that supports tooling information. Tool data is input into the controller, and the controller is used to determine tooling requirements and tool routing. The controller generates a list of tools that are needed and creates tooling files that are interfaced with various scheduling and routing software routines. The company's objective is to combine tool management with automatic cell control for unattended operations.

The software allows the user to determine tooling requirements based on previously stored part cutting requirements. Tools can be matched with tooling inventory. The required tooling data may be output to the tool crib and pre-setter station. Then, the tools are transported to the machine tool. Figure 2.5 illustrates how tool information management supports cellular manufacturing for unattended operations, where the physical tool movement may be either manual or automatic [56].

2.7 BATCHING FOR THE FMS

The five production planning problems for a flexible manufacturing system are identified as follows [4]:

(1). The part-type selection problem;

(2). The partitioning of machines of each type into the machine groups;

(3). The determination of part mix variability;

(4). The allocation of pallets and fixtures

(5). The allocation of operations and required tooling for the selected parts among machine groups.

This section is primarily concerned with the relationship between the part-type selection problem. The part-type selection problem involves the determination of a subset of parts out of a larger set to machine simultaneously over a given time horizon [4]. The part-type selection problem is considered a batching problem that contains identifiable constraints such as magazine capacity, meeting due dates, and work-in-

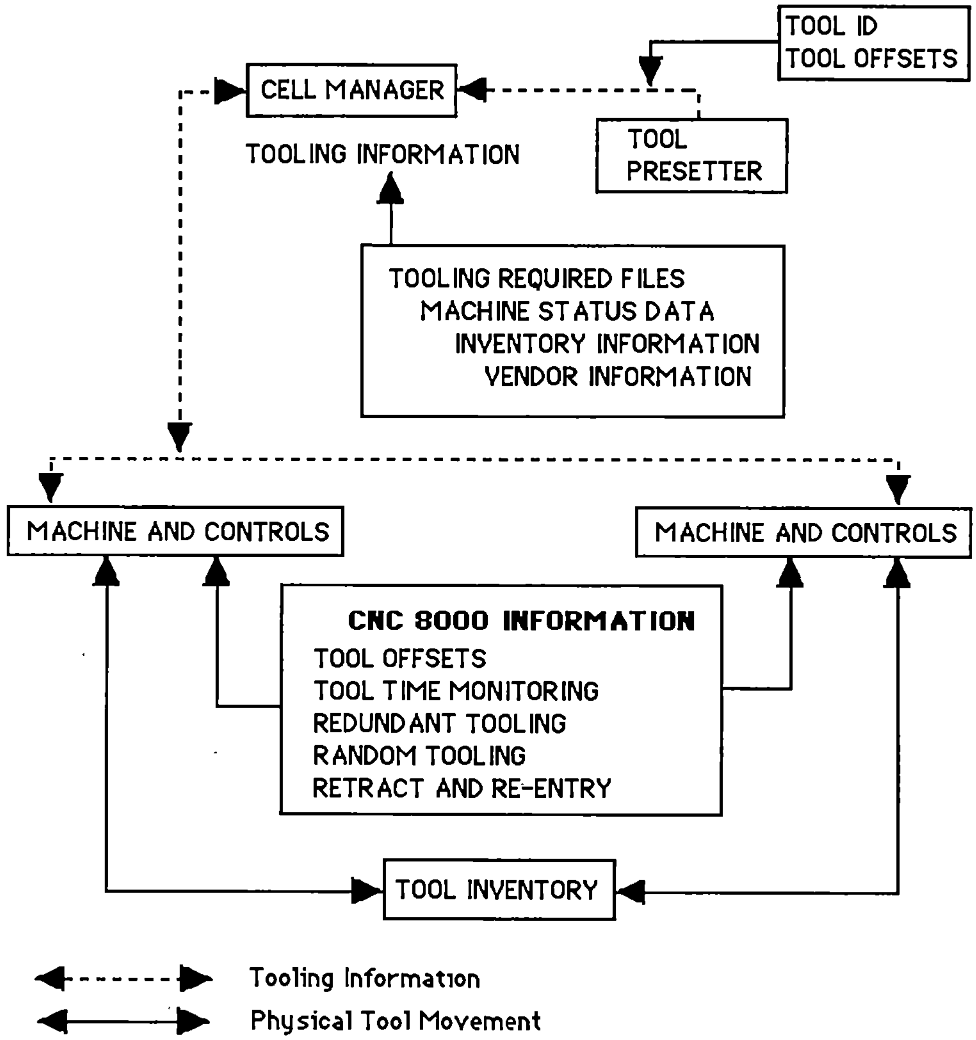

Figure 2.5. Tool Management Supports Cellular Manufacturing

process inventory [8, 3]. The number of tools required to fabricate a batch of parts is often larger then the tool magazine's capacity [10].

Co et al. [59] state that jobs, in an FMS, should be partitioned into batches to maintain proper shop floor control. As a result, a smaller variety of jobs may be loaded concurrently on the manufacturing floor. Also, batching is necessary because the FMS has limited resources. For example, a machine tool may not be able to process all required operations. Fixtures may need to be changed or reassigned. In addition, tool magazines must be reconfigured after a part-type has been processed because of tool constraints.

The authors noted the benefits of batching. These benefits include identical tooling, commonality in tooling among machines, pooling of machines, production enhancement, less variety of jobs, and reduced batch routing and scheduling conflicts. However, the batching procedure may result in increased tool inventory due to tool commonality among machines. Nevertheless, the part-type proportions and their batch assignments must be determined.

Likewise, Suri and Whitney [9] state that the FMS production plan must divide part-types into batches because of tool capacity constraints for each machine. This is necessary because if part mix tooling requirements exceed the machine's magazine capacity, then the part mix must be divided into batches. Tool changes must occur between batches. The batching procedure ensures that part-type batches are processed on schedule with the objective of minimizing work-in-process inventory. In addition, the batching procedure for parts should satisfy the following objectives:

(1). minimization of the total throughput time of parts.

(2). minimization of the number of batches required to process all parts, (3). maximization of the average machine utilization over all batches.

Rajagopalan [5] states that the part-type selection problem is considered a combinational problem. The part-type section problem, part mix variability, process operations, and required tooling are linked. Therefore, they must be solved simultaneously. However, Tomek [13] discussed several systems that had difficulty allocating operations and tools to machines with regard to part-types. The systems had difficult tooling problems. Each part that was being machined required many tools. The study suggested the following: (1) assign part-types to machines subject to throughput requirements, magazine capacity, and process constraints, (2) assign a set of tools for a group of parts to machines, and (3) assign tools to machines and allow parts to travel between machines.

2.7.1 PART-TYPE SELECTION RULES

Various researchers in the literature have proposed heuristic procedures that address several part-type section rules [5, 6, 7]. The part-type selection problem involves selecting a subset of parts from a larger set to be machined over a production period [3, 5, 6, 7]. These part-type selection rules include the largest number of tool requirements (LNT), the smallest number of tool requirements (SNT), and the earliest due date (EDD). These part-type section rules are defined in the following sub-sections.

LARGEST NUMBER OF TOOL REQUIREMENTS (LNT)

In the LNT procedure, high priority is assigned to part types that require the largest number of tool slots. Rajagopalan [5] has proposed heuristic procedures for this part-type selection problem. Rajagopalan's LNT part-type selection procedure states that "if the number of tool slots required by part $i = T_i$ and for part j is T_j, and if $T_j <= T_i$, then selecting part i first will ensure that the number of tool changes on the machine will be minimized." [5] Rajagopalan's heuristic assumes that improvements in machine utilization will be achieved by minimizing the number of tool changes. This would be applicable for a process that requires frequent tool changes.

THE SMALLEST NUMBER OF TOOLS (SNT)

The SNT rule assigns higher priority to parts that require the smallest number of tool slots. If the parts are selected with minimum tooling requirements, then this creates the selection of a large number of different parts, which forms one batch. Thus, the total number of batches is minimized. Also, the idle time between batches is reduced, and higher machine utilization is achieved. [6]

EARLIEST DUE DATE REQUIREMENT (EDD)

The EDD rule is important with respect to the part-type selection problem because the rule assigns higher priority to parts with the earliest due date [3]. Ramesh, Smith, Dudek, and Blair [7] conducted a survey of 22 FMS users. The results of the survey concluded that meeting due dates was the most important scheduling criteria.

2.7.1 PART-TYPE VARIABILITY

Flexible manufacturing systems contain machine tools that fabricate different part-types [29, 34, 59]. The different part-type can be machined simultaneously [34]. However, there is a limited number of part-types that can be processed within an FMS. Jaikumar [63] conducted a survey of 35 FMS companies in the United States. In that study, the average number of part-types manufactured in a system was 10 part-types. In a related study, Jaikumar [62] conducted a survey of 28 FMS users; the survey reviled that 25 of the 28 systems manufactured between 4 and 22 part-types.

However, in a survey conducted by Molt [64], most FMS manufactured between 15 and 30 part-types. This information will be helpful in determining the different levels of part-types introduced in an FMS.

2.8 TOOL ALLOCATION AND SCHEDULING PROBLEM

Tool allocation is a machine loading problem and is the most challenging problem in tool management [20]. A set of cutting tools is allocated to each machine tool. The best allocation utilizes the machine capabilities. Tool allocation involves a decision for every part-type operation and the required tooling. The tool sets remain with their assigned machines for the duration of the planning period. [46]

Tool allocation and scheduling is a critical consideration in the overall tool planning strategy [28]. Tool allocation and scheduling for an FMS involves the grouping and movement of tools so that the right tools are at the right machining centers at the needed times for the processing of scheduled parts and products [3]. Berr and Falkenburg's [29] research concluded that each tool must have at least three copies: one in the tool magazine, one as a backup, and one being reconditioned or refurbished. Tool allocation involves when and which tools are brought to the machining station as well as how the tools are stored or removed from the tool magazine [42]. Khator and Leung [36] state that tool allocation concerns tool life availability in the machine tool's magazine. This involves the type of tools and the tool duplications that are loaded on a machine during a given production cycle. Also, the tool allocation must consider the process plan, part type mix, magazine constraints, and tooling inventory.

2.9 TOOL ALLOCATION STRATEGIES

The four tool allocation strategies that are important in this study are presented in this section. The tool allocation policies include the bulk exchange, tool sharing, tool migration, and resident tooling [20, 35, 42].

2.9.1 THE BULK EXCHANGE

The bulk exchange strategy allocates a copy of each tool for each job assigned to the machining center. At the beginning of a planning period, cutting tools for each job are allocated to the machine for a given production window [3, 42]. After the production period, the cutting tools are removed from the machine and sent to the tool room. A new set of cutting tools replaces the prior set for the next batch of parts [12]. The new tools must meet the tooling requirements for each new part-type during the subsequent production period.

The bulk exchange policy assumes that each tool has sufficient tool life to complete the fabrication process. A part may visit a machine if and only if all the required cutting tools can be placed in the tool magazine. Furthermore, this tool policy is easy to control because tools are not shared, and tools do not migrate to other machining centers. With regard to cellular manufacturing, each work cell must have all the required cutting tools for each part-type in the cell. [3, 16, 17, 40, 58]

The bulk exchange has limitations. The bulk tool exchange is recommended for production areas with high-volume and lower-variety part mix on machines that contain large tool magazines. A static magazine may be retrofitted to the machine to increase magazine capacity to accommodate the bulk exchange policy. The bulk exchange policy allows tool duplication. However, tool duplication increases tooling cost, tooling inventory, and tool handling. Also, tool sharing is not allowed during a production period. [3, 16, 17, 40, 58]

2.9.2 TOOL MIGRATION

Under the tool migration policy, tools do not remain in the magazine during the whole production period. After a part is processed and completed on the machine, the tools are removed from the magazine. This increases magazine capacity and permits the processing of new parts. Like the bulk exchange, the assignment of parts to a machine is done randomly. This strategy fosters tool inventory reduction because common tools may be shared between production periods as well as within a production period [54]. With regard to cell manufacturing, tools may be moved from cell to cell during the same production cycle. A tool that is not being used may be transported to another cell if needed. [3, 40, 42]

Tool migration requires information concerning which tools are to be transferred to different cells as well as different machines. Also, information is needed concerning when the transfer is to take place. Therefore, a decision support mechanism is necessary to determine the tools that need to be transferred or replaced. [3, 40, 42, 58]

2.9.3 RESIDENT TOOLING

Tools that are frequently utilized are made resident to the machine for the entire production period [42]. The remaining tool slots may be used for tools that migrate. This allows for unexpected part production or changes in production scheduling. Therefore, resident tooling allows greater flexibility with respect to uncertainty of part-types and machine breakdowns [14]. When the useful life of a tool has been reached, the tool is replaced. [3, 42]

There are advantages and disadvantages to the resident tooling. An advantage is the policy is easy to implement. Because tools are made resident to the machine, tool monitoring and tracking is reduced. Also, parts are assigned to machines on a non-random basis. In addition, the tool transportation and handling system is required only when tools need to be replaced due to tool wear or breakage. Furthermore, parts may be assigned to a machine that already contains the required tooling. A disadvantage to resident tooling is increased tool inventory. Also, resident tools cannot be shared among machines. In addition, the tool magazine must contain the capacity to accommodate resident tools. [17, 42]

The gross resident tooling policy requires all tooling for all parts to be resident at the machine. This allows flexibility in scheduling jobs. However, this tooling policy requires high levels of tooling inventory, tool duplication, and additional floor space. As a result, tool inspection becomes difficult. Tools are replaced only when they become dull. [20, 35, 42]

2.9.4 TOOL SHARING

A limitation of tool allocation is its failure to recognize that parts may have common tool requirements. Consequently, unnecessary tool duplication and under-utilization of magazine capacity result from not recognizing tool commonality [41]. This limitation may be addressed with tool sharing. Tool sharing is a hybrid between the bulk exchange and resident tooling policy [3]. When a part is introduced into the manufacturing system, the part is assigned to a family of parts that are scheduled for a machine. The tooling requirements are adjusted for the new part. Tool changing is permitted only at the end of the production period. The assignment of a part to a machine is done non-randomly. Like resident tooling, parts may be assigned to the machine that contains proper tooling. Tool sharing is an effective method to reduce tool inventory and tool inventory cost [38]. However, tool sharing is harder to implement because information is needed concerning the locations of tools and the allocation of tools during the next production period. [40, 42]

2.10 TOOL ALLOCATION STUDIES IN THE LITERATURE

One of the five production problems for an FMS is the tool allocation problem or tool loading problem [34]. This section of the literature review introduces research on tool allocation models and methodologies that address the tool allocation problem.

Kashyap and Khator [38] performed a simulation experiment to study both request selection rules and tool selection rules in a shared tool environment. A design of experiment was used to analyze the simulation outputs. The factors included the two selection rules, tool duplication, and product mix. Five FMS machines, and ten tools were used. The objective of the study was to determine the effects of the selection rules on part throughput time and transporter utilization.

For the request selection rules, the machines issue a request for tools. A machine may have tool priority over another machine based on the following rules:

- in the order of arrival on first come first serve basis,
- the machine with the least number of remaining operations,
- the machine having a part with the shortest processing time.

For the tool selection rules, tools may be assigned to machines based on the following two rules:

- shortest distance traveled by the transporter to get and deliver a tool,

- the machine with a requested tool that has the largest value of tool life.

The result of the study shows that tool duplication affects part throughput times and tool transporter utilization. With tool duplication, a 22.7 percent reduction in part throughput times was experienced. As the number of tool copies increased, the utilization of the tool transporter increased.

The tool requests are satisfied with additional tool copies. The request selection rules did not significantly affect the utilization of the tool transporter or part throughput while using duplicated tools. The product mix affected part throughput times and tool transporter utilization because part-types have variations in operation sequence and processing times. The tool selection rules had no significant effect on part throughput times. However, there was a significant affect on tool transporter utilization because tools must travel between machine stations. The shortest distance rule performed best among the tool selection rules. The tool selection rules were affected by the changes in product mix. The simulation model did not contain reliable industrial data. The processing times, the operation sequences, and the number of operations followed a uniform distribution.

Gaalman and Nawijn [39] developed a heuristic tool selection procedure to analyze three tool transportation policies in a tool sharing environment. The objective of the study was to measure transport times and transport frequencies with respect to the policies. Tsukada et al. [40] conducted a simulation study in a tool sharing environment which included artificial intelligence. The objective is to analyze the communication between modules (peer negotiation and polite rescheduling) within a manufacturing cell with regard to unexpected tooling requirements due to schedule modifications. Polite rescheduling refers to rescheduling tools by peers in communication with each other on the machine level. This allows tooling requirement decisions to be made on the machine level instead of the system level. The study shows that polite rescheduling performs well with respect to unexpected tool requirements for new tasks. Also, the method realized smaller costs with respect to rescheduling tasks. In addition, the study showed that peer communication handled scheduling disruptions locally by re-doing tool allocation requirements.

Hankins and Rovito [43] conducted a study that established the relationship between four tooling strategies (bulk exchange, tool sharing, tool migration, and resident tooling) and tooling inventory levels and levels of control. In that study, the bulk exchange policy requires a higher level of tooling inventory because of the number of duplicated tools. Figure 2.6 shows the relations between the tooling strategies and inventory levels. The migration policy requires less inventory control, due to the sharing of tools between machines and across production periods. Figure 2.7 shows that migration policy requires a higher level of control when compared to the other strategies. The control level refers to scheduling and software control. Sectors are used to illustrate the manufacturing environment, which includes the number of machines used.

In a related study, Amoako, Meredith, and Raturi [3] conducted a simulation study involving four tool allocation strategies: bulk exchange, tool migration, tool sharing, and resident tooling. The study compared the tool allocation strategies in the presence of three part selection rules.

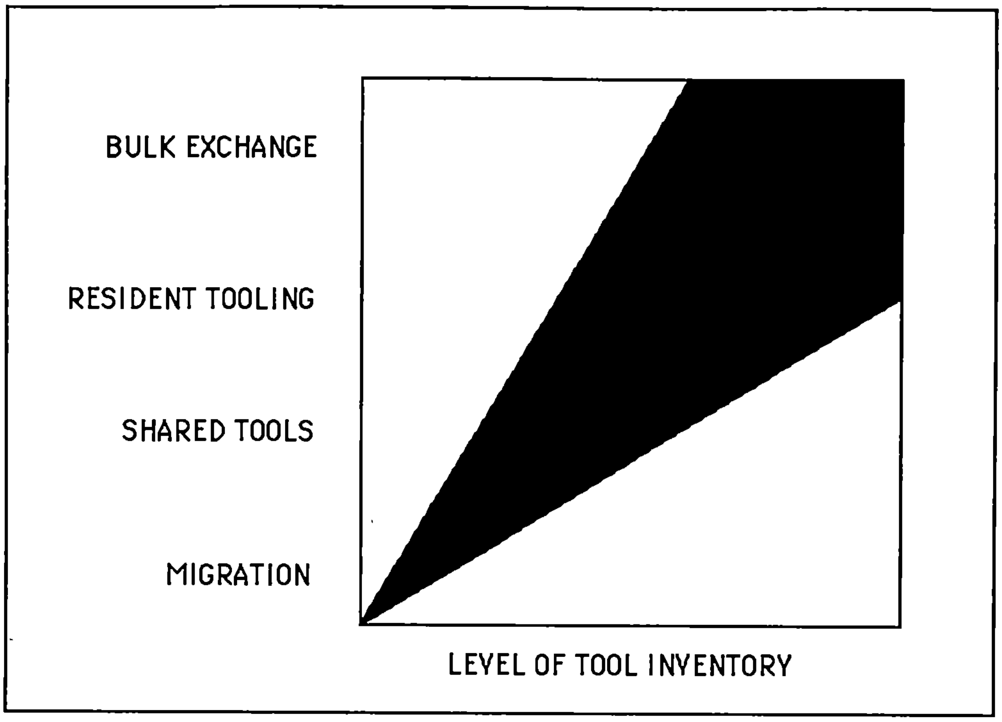

Figure 2.6. Tooling Strategies and the Level of Tooling Inventory

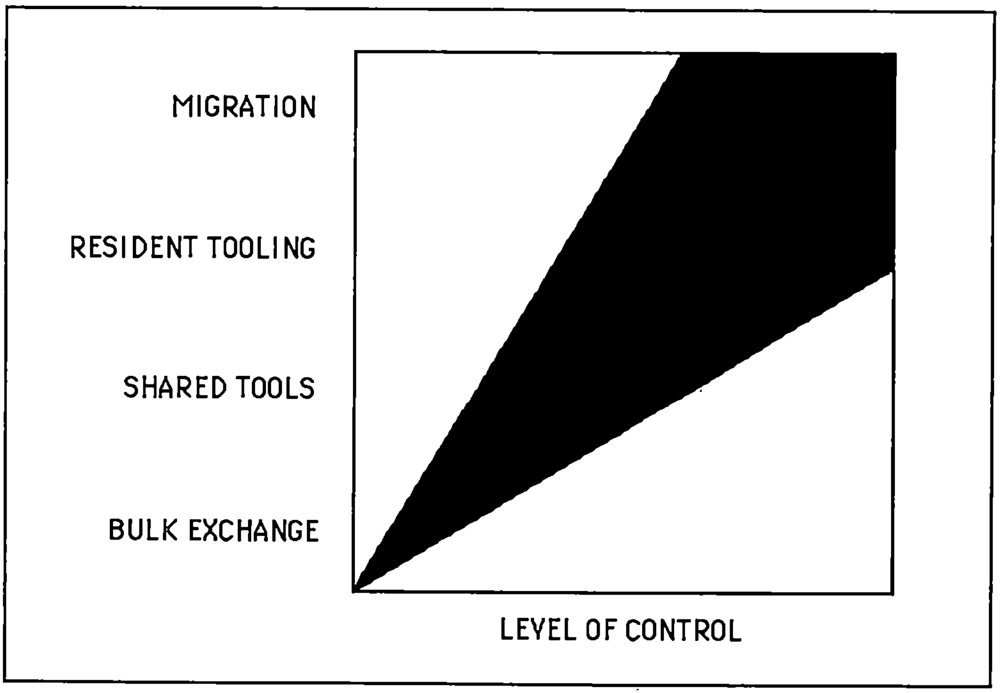

Figure 2.7. Tooling Strategies and the Level of Control

The study concluded that the bulk exchange strategy outperformed the tool migration, resident sharing, and tool sharing strategies. The bulk exchange experienced the lowest mean flow time for each part selection rule. Also, for all part selection rules, the bulk exchange resulted in the lowest mean part tardiness. In addition, the bulk exchange gave the lowest percentage of parts tardy. However, tool migration experienced the highest machine utilization; the other three policies experienced approximately the same average machine utilization. Bulk exchange and tool sharing experienced the lowest robot utilization. [3]

The success of the bulk exchange strategy was primarily due to the long cycle times of parts. The study did not include parts with short cycle times. The results may have been different if shorter cycle times were used. Also, the study concluded that there was no significant difference between the three part scheduling rules with respect to the four tool allocation strategies. [3]

Co, Biermann, and Chen [59] propose a mixed-integer programming problem to simultaneously solve the batch loading and tool configuration problems. The model incorporates a four pass heuristic approach. In this approach, tool magazine configurations are determined during the first three approaches for each machine. This determines the set of operations that can be processed at each machine. The first approach partitions the jobs into batches. The objective function seeks to maximize the number of jobs in each batch. By increasing the batches, the second approach assigns part types to more than one batch. By increasing the tool magazine size, the third approach maximized machine pooling. By reconfiguring the tool magazines for each batch, the flexibility is maximized for each machine. The objective function assigns operations to multiple machines. Finally, the fourth approach determines the proportion of each part type in each batch. Once the batches are determined, they are routed to machines based on tool configurations and operational requirements.

There are limitations to the heuristic approaches. The model does not address tool life, tool set-up considerations, or the introduction of new part types into the system.

Kusiak [30] offers four tooling policies that determine both the tools required for each machine and tool duplication levels. These policies are as follows:

(1). A unique set of tools is located at each machine. Tool duplication is not allowed.

(2). A unique set of tools is located at each machine and each tool requires one copy or duplicate tool.

(3). A unique set of tools is located at each machine. Tool duplication is allowed such that more than two duplicates are required to facilitate part routing.

(4). Each machine has the same set of tools.

Unfortunately, the above policies fail to relate tooling policies to production demand requirements for a flexible manufacturing system. Also, they do not provide an efficient and effective tool assignment of tools to machines. As a result, excess tool inventory, tool shortages, and inefficient machine utilization may result. The policies do not take into consideration machine capacity or tooling availability.

However, Mohamed and Bernardo [31] develop an aggregated tool planning (ATP) model that was compared to Kusiak's four tooling policies. Mohamed and Bernardo's model was developed to determine the number of required tools for each tool type to satisfy the expected demand within the shortest time period. Once the tool requirements were determined, a tool loading and routing model was used to determine tool usage, tool assignments to machines, and part routing. The objective is to determine tool levels that yield operational performance. The performance measures included part throughput times, tool cutting edge productivity, and part routing (actual routing flexibility and potential routing flexibility). Tool cutting edge productivity is the number of products produced per refurbishing of a cutting edge. Actual routing flexibility measures the capability of sending parts to alternative routes due to machine failures and tool failures. Potential routing flexibility measures the capability to produce new routes as well as alternative routes.

In this study, paired differences were shown between the ATP model and Kusiak's four tooling policies. The study showed that the ATP assignment resulted in an 11.9% increase in actual routing flexibility. There was no significant increase in actual routing flexibility among the other policies. The potential routing flexibility favored the ATP model. This also showed that when tool magazine slots are available, the number of potential routes increase. With respect to part throughput times, there was a statistical decrease for the ATP model. There was no significant decrease in the total production time with respect to the other policies. While maintaining route flexibility, the ATP policy did not statistically affect tool cutting edge productivity. In addition, the ATP model yields information that would help to plan tool inventory.

Stecke [34] states that production management is more difficult for an FMS than for job shops because (1) the machines are versatile and capable of performing multiple operations, (2) several part types can be machined simultaneously, and (3) the system has alternative and flexible routes for each part type. Stecke states that new loading and control strategies must be developed to take advantage of machine capabilities. Stecke identified six loading objectives, which are listed in Table 2.2.

Stecke conducted a study to mathematically define and solve the grouping and loading problems by developing nonlinear mixed integer models. The nonlinear mathematical models were linearized by various methods and applied to an FMS company. The study concluded that the linear models could be used to solve common problems. However, the models have limitations. The models may not be used for larger flexible manufacturing systems. Also, the models ignore tool availability, and tool life constraints. Nevertheless, Stecke incorporates a tool magazine capacity constraint that considers the number of tool slots required and tool magazine weight balancing.

Amoako-Gyampah and Meredith [41] state that a limited magazine capacity constrains the number of tools that can be mounted on the machine due to tool slots. Also, a limited magazine capacity constrains the number of different types of tools because of the magazine's weight restrictions. In addition, frequent tool changes are required for tool magazines with limited capacity.

The authors performed a simulation study [41] to solve the part-type selection and tool allocation problem. The objective was to compare three tool allocation procedures with emphasis on reducing the frequency of tool changes and better utilization of magazine capacity within an FMS environment. Heuristic approaches were developed for the tool allocation policies. Then, the heuristics were evaluated through simulation experiments.

The three heuristic approaches were tool and part batching, tool sharing, and flexible tooling. For the tool and part batching approach, part types are partitioned into separate batches that are machined individually during a planning period. The

Table 2.2. Loading Objectives

	Loading Objectives
1	Balance the assigned machine processing times.
2	Minimize the number of movements from each machine, or equivalently, maximize the number of consecutive operations on each machine.
3	Balance the workload per machine for a system of pooled machines of equal size.
4	Unbalance the workload per machine for a system of machines of unequal sizes.
5	Fill the tool magazine as densely as possible.
6	Maximize the sum of operation priorities.

objective is to decrease the number of batches, which lessens the time between batch changeovers. The tool sharing approach recognizes tool commonality, which leads to underutilized tool duplication and magazine capacity. Tool sharing allows tools to be shared between machines during a production period [39, 40]. The objective of the flexible tooling approach is to minimize the bottenecks associated with tool magazine capacity. When a part process is complete the tools are removed from the tool magazine to allow new tools for new part type processing. Also, the finished tools may be needed on other machines. This permits the selection of a new part type with allocation of the required tools. Table 2.3 shows a qualitative comparison of the three allocation procedures [41].

Results of the study show that for a low and high part mix the flexible tooling heuristic procedure outperformed the tool batching and tool sharing procedures with respect to performance measures. This is because tool slots are made available once a part is completed. The part's tools are unloaded and new tools are loaded for new part processing. Therefore, a part does not have to wait on its cutting tool requirements. The tool sharing approach did better than the tool batching on all performance measures. Scheduling part orders, with common tooling requirements, improves the FMS production system. This also permits more parts to be scheduled on the same machine during a production window. Tool changes occurred more frequently with flexible tooling. Flexible tooling had the lowest machine utilization for each part type level. The utilization depended on processing times, loading and unloading delays, and tool changing times.

There are limitations to this study. The study does not address all performance measures for an FMS such as tooling inventory levels. Also, the study does not address different FMS scenarios. Some examples may include part types that require more tooling, machines that are not identical, and a dynamic demand schedule as opposed to

Table 2.3. Qualitative Summary Comparison of Allocation Procedures

	Tool-Part Batching	Tool Sharing	Flexible Tooling
Description	Provide each tool for each part type every day and replace all when production is complete.	Takes into account the commonality of tools required by part type.	Completely flexible with removal /addition on completion of the required part type.
Anticipated tool changeovers per production period	One	Some	Many
Timing of tool changes and time required	Tool exchange only at end of production window. However, large amount of time spent for tool exchange.	Tool exchange only at end of production window. However, large amount of time spent for tool exchange.	Small amount of time spent for each tool exchanges. However, many exchanges within production window
Anticipated tool provisional requirements	Large	Moderate	Low
Tool inventory reduction potential	Small	High	Moderate
Ease of tool Monitoring	High	Medium	Low
Potential to handle tool failures	Low	Medium	High
Tool scheduling flexibility limited mostly by	Tool magazine capacity	Degree of tool commonality	Mechanism of tool exchange
Most appropriate implementation environment	Part types with long cycle times: low-medium volume FMS	Part types with average cycle times less than average tool life	Part types with short cycle times: high-volume FMS

static demand where production is fixed during a production period. Also, different parametric settings could be used with longer processing times, different tool life, and tool changing times. In addition, other tool allocation policies could be tested and compared.

Bell and DeSouza [44] used a Rank Order Clustering algorithm to form tool clusters and part grouping with similar tooling requirements. The algorithm was developed by King [45]. However, for this study, a duplicate-tool specification algorithm was also included in the Rank Order Clustering model to determine duplicate tooling requirements. The objective was to compare the tool clustering strategy and the bulk tool allocation with regard to magazine capacity and set-up requirements

This study consisted of a cell that contained three machining centers. Each machining station had a 120-slot tool magazine capacity, and a rail guided pallet transporter serviced each workstation. The cell produced 8 part types. The number of operations per part averaged 25.

The study concluded that the cluster tooling strategy performed better than a static bulk tooling configuration. The total gross requirements for cluster tooling were 138 whereas the bulk tooling grossed 145 tools. Also, the clustering strategy was more flexible with respect to scheduling production periods, tooling requirements planning, and work and tool allocation. In addition, fewer tool set-ups were realized with the cluster tool strategy.

However, the algorithm has limitations. The study only compared two allocation strategies. Other allocation strategies need to be investigated and compared with tool clustering to determine their effect on set-up requirements, gross tool requirements and schedule parameters. Also, the model did not address issues of re-clustering, nor did the study show how new schedules could be applied.

Macchiaroli and Riemma [46] proposed a dynamic clustering procedure (DCP) for part-type planning and scheduling based on clustering techniques. The model was designed to maximize workload balancing and to minimize common tools. The model recognizes fixed sets of tools for each part-type. The tools may be partially or totally shared among different part-types. When part-types are shared on the same machine, a reduction in tool exchanges is realized. As a result, the following may be achieved:

- reduced utilization of tool handling,
- increased availability of the tool handling system,
- reduced conflicts on tool usage.

The facility consisted of two machines that were equipped with unlimited magazine capacity. The machines are linked to an automatic material handling system for moving pallets. Tools are delivered to the magazines by a tool handling system. The machining center is a low-volume, high variety facility where orders are delivered weekly and consist of batches. The objectives of the model were met with respect to product lead-time minimization, shared tools and workload balancing among machines, and the reduction of tool exchanges between machines.

Kusiak's [30] discusses tool storage such that one tool of each type is kept in the system. One tool of each type is stored at one machine. Thus, parts requiring a specific tool must be processed where that tool is located. Duplication of tools is not allowed. Likewise, Sarin and Chen [48] proposed an integer programming formulation that addresses tool loading. The model determines an assignment of every tool operation of parts and the required tooling. During a production period, tools must stay with assigned machines. Parts are routed based on machine loading. Berrada and Stecke [49] address the loading problem with a nonlinear programming formulation that considers system and magazine capacity constraints. In this model, tool switching is not allowed.

In the above approaches, tool allocation to machines is determined prior to job routing. Then, job routing conforms to machine capability. These approaches may limit the machine's flexibility because of tool unavailability. Also, overall tool utilization is reduced because of unnecessary tool duplication.

Atan and Pandit [47] propose an integer linear program that addresses the above problems with respect to tool loading. They suggest an approach that first determines a job routing and then finds the allocation of tools for each machine. Thus, the minimization of tooling is realized. The objective is to minimize the overall tooling cost and maximize tool utilization by reducing tool duplication and maximizing system flexibility.

The model addresses issues with respect to single and multiple types of tools. For single type tools, the model contains an objective function that (1) minimizes the total number of tools in the system, (2) determines the total number of tools for a given machine, and (3) determines total number of tool types in the system. Also, branch and bound rules are provided. These rules check the feasibility of selected tools. In addition, heuristics are provided that assigns tools to machines. To solve the multiple type tool problem, a branch and bound solution procedure is provided.

The results of the study showed a high utilization of tools, and unnecessary duplication was minimized. However, for a single tool type, the number of tool copies increased with the number of machines. For multiple tool type problems, the study showed that small storage capacity was infeasible. Therefore, additional storage space would be needed. This space could be provided at the machine or a central storage area.

2.11 CONTRIBUTIONS OF DISSERTATION

This research contributes to the limited research on flexible manufacturing systems with respect to the impact of tool allocation policies on selected manufacturing performance measures. The research contributes to tool management both managerially and academically. Managerially, this research study assists FMS managers with a basic understanding of tool management. Also, this study provides further insight into hierarchical frameworks that incorporate tool management decisions. In addition, this study provides information to assist managers in making decisions with respect to employing the appropriate tooling policy to help reduce production cost and meet customer demand requirements.

Academically, this research contributes to the limited research on the impact of tool allocation policies on performance measures in an FMS environment, contingent upon part-type selection rules. Limited research has been conducted that evaluates the impact of tool allocation policies on performance measures in an FMS environment contingent upon part-type selection rules. Previous research has not fully considered the impact of simultaneous resource requirements such as flexible machines, tool magazine capacity, and automatic part and tool loading units. In addition, limited research had been conducted which analyzes, simultaneously, the impact of tooling policies on manufacturing performance measures, cutting tool inventory, and tool consumption rates.

This research extends the work of Amoako et al. Amoako et al. [3] compared four tooling polices and three part-type selection rules and their impact on five performance measures within an FMS environment. The researchers concluded that the bulk exchange policy outperformed tool migration, resident tooling, and tool sharing. A strategy that groups tools into a batch and then periodically assigns the batches to machines performs best. The success of the bulk exchange policy was primarily due to the long processing time of parts. The average processing time was 8 hours per part. The researchers state that a shorter processing time and different input parameters may produce different results. Also, because of the long processing time, no single selection rule outperformed another with regard to the selected performance measures.

Specifically, this research evaluates the impact of the tool allocation policies on performance measures by (1) increasing the tool requirements per part, (2) increasing the number of operations per part, and (3) decreasing the processing time per part. This study determines whether batching tools and then assigning them to machines is best with different input parameters. Also, this study provides information to determine whether one part-type selection rule outperforms another. In addition, this study evaluates the average cutting tool inventory and tool consumption rates per production period.

The reason for the changes in part-type attribute values is based on results obtained from a pilot study. The pilot study consisted of on-site interviews with CNC programmers, tool managers, operations managers, and manufacturing engineers at companies that utilize flexible manufacturing systems. Information was collected with regard to tool management and cutting tool parameter values. When compared with the study conducted by Amoako et al [3], the results of the pilot study showed an increase in tooling requirements per part, operations per part, and a decrease in the average processing time per part. This may be due to the advances in cutting tool technology, machine tool design, and the integration of computer aided manufacturing software. The three part-type attributes and their values are located in Table 2.4 [3, 65]. The "Tool Management and Production Operations Study" form is located in Appendix A. The pilot study results are located in Appendix B.

Table 2.4. Changes in Attribute Values Per Part

Attribute	This Study	Amoako et al.	Distribution
Tools Required	9 to 11	2 to 4	Uniform
# Operations	7 to 11	2 to 6	Uniform
Processing Time	2 hours/part	8 hours/part	Erlang

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter will introduce the research design, aspects of the simulation model, and data collection and data treatment procedures. Finally, model verification and validation will be discussed.

3.2 RESEARCH DESIGN

A flexible manufacturing system will be the system evaluated in this study. The research methodology that will be employed in this study will be simulation. The factors and their levels consist of four tooling policies and three part-type selection rules. The factors will be evaluated within an FMS environment, contingent on the three part-type section rules. The research design is a two-factor full factorial design, which will consist of all possible combinations of factors and levels. The four tool allocation policies, five performance measures, and the three part-type selection rules were selected from the study conducted by Amoaka et al. [3]. The impact of the tool allocation policies on the five manufacturing performance measures will be analyzed through the analysis of variance technique and graphical comparison charts.

3.2.1 EXPERIMENTAL FACTORS

This section introduces the experimental factors. The first experimental factor will be the tooling allocation policies. The tool allocation policies consist of the bulk exchange, tool sharing, tool migration, and resident tooling. These tooling policies were discussed in the Literature Review, under the Section entitled "Tool Allocation Strategies."

The second factor consists of the part-type selection rules. The part-type selection rules include the largest number of tool requirements (LNT), the smallest number of tool requirements (SNT), and the earliest due date (EDD). For this study, the EDD for a part-type is equal to the part's arrival time into the system plus a random number that is generated using a uniform distribution from 120 minutes to 480 minutes: EDD = TNOW + UNIF(120, 480). The first value in the distribution refers to the average processing time of parts: 120 minutes or 2 hours. The second value refers to the 8-hour production period. Various researchers have proposed the use of the above part-type selection rules [5, 6, 7, 20, 24, 41, 65].

3.2.2 PERFORMANCE MEASURES

This study will evaluate the tool allocation impact on five performance measures. The performance measures relate to production cost and customer service. For this study, the performance measures will be dependant variables.

The measures that relate to production cost consist of flowtime, average machine utilization, and average robot utilization. For this study, the flowtime is the total time that a part has spent is in the system. The flowtime depends on the part's release rate, processing time, and moving time. [3]

The measures that relate to customer service consist of the mean lateness of parts and the percent of parts that are late. The "mean lateness" is the average late time for all parts completed only after their due dates. The "percent of parts late" relates to the percent of parts completed only after their due dates. These measures determine the level of customer satisfaction because they capture due date performance. Table 3.1 contains a list of the experimental factors and performance measures. The performance measures are defined in Table 3.2 [41]. [3, 65]

3.3 SIMULATION MODEL

This section introduces the aspects of the simulation model. This will include the model's environment, parameters, assumptions, flow of logic, and tool allocation policies. A total of 12 models will be developed. Each of the 12 simulation models represents a tooling policy and part-type selection rule. The model's simulation environment, model assumptions, and cutting tool parameters and statistical distributions were selected from the work performed by Amoako et al. [3, 65]. However, the processing time per part, the number of tools per part, and the number of operations per part will be selected from a pilot study. The pilot study was conducted to ascertain the validity and reliability of the cutting tool parameter values. The results of the pilot study are located in Appendix B.

3.3.1 THE SIMULATED ENVIRONMENT

The simulated model will consist of an FMS that contains 5 CNC machines and a material and tool handling robot. The machines are all identical, and they are capable of machining any part that comes into the FMS. The robot loads and unloads parts from each machine. Also, the robot loads and unloads cutting tools from the tool magazine chambers for each machine. [3]

Table 3.1. Experimental Factors and Performance Measures

EXPERIMENTAL FACTORS	
TOOLING ALLOCATION POLICIES	
1	Bulk Exchange
2	Sharing
3	Migration
4	Resident Tooling
PART SELECTION RULES	
1	Largest number of tools (LNT)
2	Smallest number of tools (SNT)
3	Earliest due date (EDD)
PERFORMANCE MEASURES	
1	Mean flowtime
2	Machine utilization
3	Robot utilization
4	Mean lateness of parts
5	Percent of parts late

Table 3.2. Performance Measures

EQUATIONS FOR PERFORMANCE MEASURES

Mean Lateness:

$$\sum_{i=1}^{N} Max(0,L_i)/N$$

Percentage of Parts Late:

$$PT/N$$

Mean Flowtime:

$$\sum_{i=1}^{N}(C_i-t_i)/N$$

Machine Utilization:
(Average fraction of time machine are in use during simulation)

$$\sum_{k=1}^{M}\sum_{j=1}^{Q}U_{jk}/MQ$$

Robot Utilization:
(Average fraction of time robot is in use during simulation)

$$\sum_{i=1}^{Q}R_i/Q$$

Notation:

$C_i = completion\ time\ of\ job\ order\ (i)$

$D_i = due\ date\ of\ job\ order\ (i)$

$L_i = C_i - D_i$

$N = number\ of\ orders\ for\ which\ statistics\ are\ collected$

$PT = number\ of\ orders\ completed\ after\ their\ due\ date$

$j = period\ of\ data\ collection$

$Q = number\ of\ periods\ for\ which\ statistics\ are\ collected$

$t_i = time\ of\ arrival\ of\ job\ order\ (i)$

$M = number\ of\ machines$

$$R_j = \begin{cases} 0 & if\ robot\ is\ idle\ in\ period\ (j) \\ 1 & if\ robot\ is\ busy\ in\ period\ (j) \end{cases}$$

$$U_{jk} = \begin{cases} 0 & if\ machine(k)\ is\ idle\ in\ period\ (j) \\ 1 & if\ machine(k)\ is\ busy\ in\ period\ (j) \end{cases}$$

Also, the simulated environment will manufacture a specific number of parts per production period. The FMS processes 25 different part-types. Only 14 parts have production requirements per period. Therefore, for each production period, the model will randomly select 14 parts from 25 different part-types. Parts will have an average processing time of 2 hours per part based on an Erlang distribution. The Erlang distribution is generally used to represent the time to complete a task, such as the processing times of parts [66]. Each CNC machine will have a tool magazine with a capacity of 50 tool slots. The tool and part change time is 1 minute. The simulation model will run for 150 production periods. Each production period is equal to 8 hours. A total of 2100 parts will enter and exit the system. [3]

3.3.2 MODEL PARAMETERS

The number of operations per part will be uniformly distributed between 7 and 11 operations per part. Also, the number of tools per part will follow a uniform distribution between 9 and 11 cutting tools. The uniform distribution is generally recommended "when all values are considered to be equally likely." [66] This distribution is also used when information concerning a quantity is insufficient [66]. Furthermore, a total of 30 unique cutting tools will be introduced into the system. The tool life will be 30 minutes per tool. Table 3.3 shows information with respect to the model's simulated environment parameters [3]. Table 3.4 shows the processing times and operations for each part-type.

3.3.3 OTHER MODEL ASSUMPTIONS

All cutting operations for any one part will be performed on the same machine. This facilitates single setup operations. Also, the attributes for each part-type will be known prior to entering the system. These attributes include (1) tool requirements,

Table 3.3. Simulation Environment and Model Parameters

SIMULATION MODEL ENVIRONMENT

5 identical machine tools.
1 material and tool handling robot.
8 hour production period.
All operations are performed at one station or machine.
50 tool magazine chamber.

MODEL PARAMETERS

	Activity	Item #	Mean Time	Distribution
1	Number of unique tools in system	30	n/a	n/a
2	Operations per part	7 to 11	n/a	Uniform
3	Processing time	n/a	2 hrs. / part	Erlang
4	Tool Life	n/a	30 min. / tool	n/a
5	Number of unique tools per part	9 to 11	n/a	Uniform
6	Parts introduced in the system	14	8 hrs.	n/a
7	Earliest Due Date	n/a	2 to 8 hrs.	Uniform

Table 3.4. Operation and Processing Times for Part-Types

Part	Operations	Process Times for Each Operation Per Part-type												
		1	2	3	4	5	6	7	8	9	10	11	Min.	Hours
1	9	7.29	19.02	16.7	15.14	6.44	6.86	4.68	8.06	16.41			100.6	1.68
2	11	7.22	16.65	8.9	12.08	11.37	4.95	13.35	7.55	16.14	22.3	9.27	129.78	2.16
3	7	9.86	11.1	14.67	27.5	10.35	15.24	8.63					97.35	1.62
4	8	17.75	13.24	20.03	7.57	26.89	19.85	39.21	15.13				159.67	2.66
5	10	10.5	11.88	13.29	9.27	14.2	8.39	11.22	8.49	22.23	13.5		122.98	2.05
6	7	23.26	17.72	9.13	10.76	36.51	8.99	16.1					122.47	2.04
7	8	9.87	9.8	15.06	30.13	19.72	11.8	15.37	10.07				121.82	2.03
8	7	10.44	34.96	11.55	15.73	18.69	5.43	4.57					101.37	1.69
9	11	17.24	13.3	4.29	15.61	17.8	19.96	15.1	17.39	9.46	13.4	11.53	155.09	2.58
10	10	9.28	11.06	17.73	14.09	9.77	11.42	10.52	12.53	11.68	8.61		116.69	1.94
11	7	12.61	17.8	25.7	26.92	14.83	13.82	20.65					132.33	2.21
12	8	6.37	29.13	24.03	7.77	18.16	9.17	9.2	9.96				113.79	1.9
13	11	9.91	15.34	8.16	17.16	8.01	8.91	11.51	9.14	6.53	9.64	19.98	124.29	2.07
14	9	20.92	15.94	8.41	20.56	7.88	14.27	5.87	22.31	25.57			141.73	2.36
15	10	15.43	10.93	7.49	14.66	7.74	13.74	10.93	21.45	10.71	8.15		121.23	2.02
16	9	15.72	14.52	20.67	7.51	11.58	22.82	8.06	9.36	12.41			122.65	2.04
17	10	14.3	9.6	5.74	5.21	11.65	7.69	8.27	9.18	5.71	11.7		89.09	1.48
18	7	0.62	9.46	18.69	24.2	17.38	12.35	51.36					134.06	2.23
19	11	7.05	8.49	11.98	10.51	12.28	5.47	11.56	9.36	3	9.5	4.75	93.95	1.57
20	8	7.06	11.89	5.56	12.35	20.63	16.77	13.34	9.76				97.36	1.62
21	8	17.55	10.4	11.33	25.82	15.52	7.33	11.92	20.4				120.27	2.00
22	9	13.57	22.41	9.23	8.07	4.27	10.74	16.49	18.7	12.54			116.02	1.93
23	9	13.35	17.55	15.91	6.78	14.62	22.39	15.71	8.32	14.43			129.06	2.15
24	10	8.43	9.57	7.46	27.76	14.31	18.6	13.24	7.49	13.56	19.3		139.67	2.33
25	11	9.89	14	2.52	7.77	9.91	9.36	12.83	10.65	13.84	15.6	6.82	113.15	1.89
												Avg. =	121.13	2.02

(2) processing time, and (3) earliest due date. The 25 different part-types and their varied attribute values suggest a lot of variability in the flexible manufacturing system. [3]

3.3.4 MODEL LOGIC

This subsection describes the model's logic. This section also describes the model's logic for each tool allocation strategy. The simulation model has a run time of approximately 4200 hours. The tooling policy and part-type level is selected. Parts are introduced into the system at the beginning of the production period. The attributes for each part-type are known upon arrival into the system. Once in the system, the parts are placed in a queue and ranked according to the part-type selection rule. Then, the parts are routed to machines based on the selected tool allocation strategy. Only one part may visit a machine. When the part has finished machining, the robot unloads the part. Cutting tools are unloaded from the tool magazine. However, this depends on the tool allocation policy being used. Statistics are collected on the part. Finally, the part exits the system. Figure 3.1 illustrates the general flow of logic for the simulation model. [3]

MODELING LOGIC FOR THE BULK EXCHANGE TOOL POLICY

In the bulk exchange model, a part is introduced into the system with respect to the production environment. The attributes of each part-type are known upon arrival into the system. The average processing time and the average number of tools that are required for each part will be determined. Once in the system, a part is placed in a queue. The parts are ranked in the queue according to the part-type selection rule. A selected part is randomly routed to one of the 5 CNC machines. The part's toolkit is

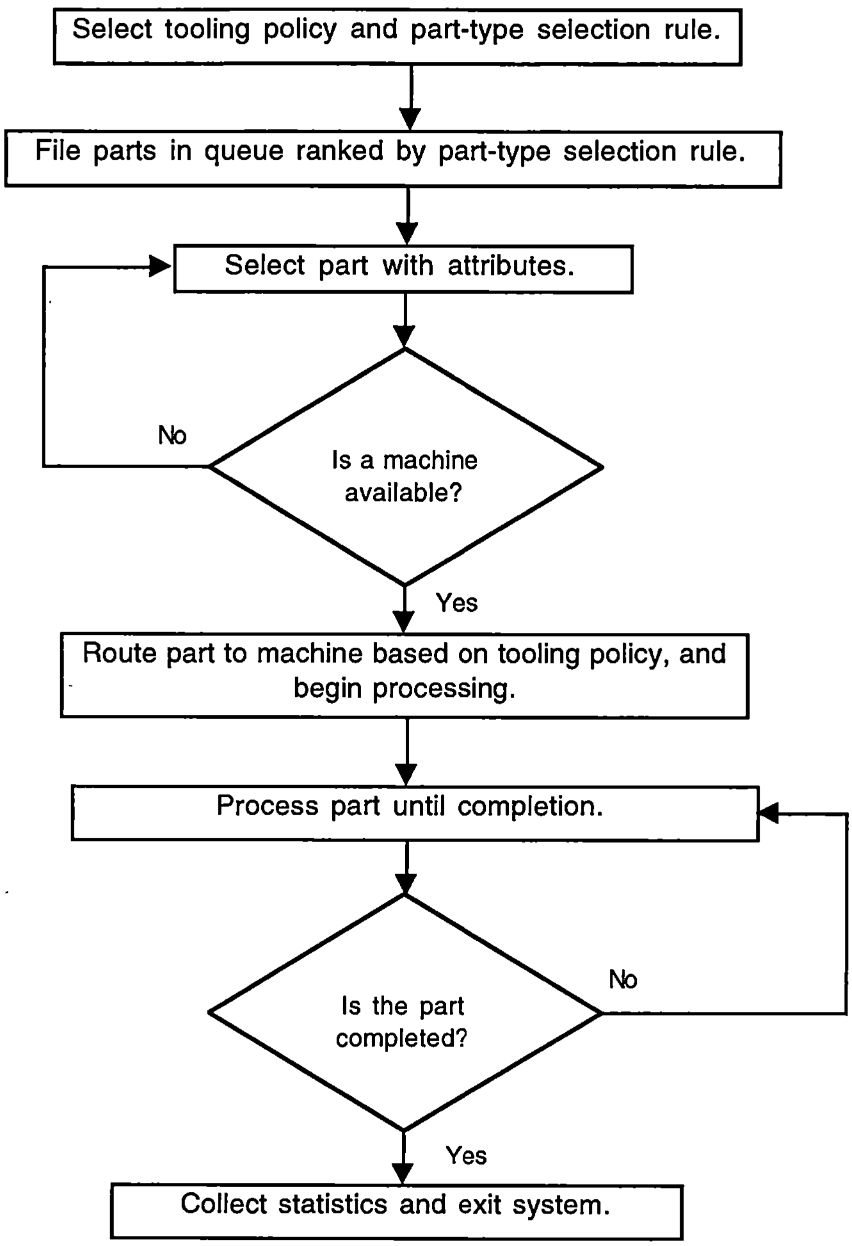

Figure 3.1. Flow of Logic for Simulation Model

sent to the machine. After the part is completed, the part's cutting tools remain in the tool magazine chamber until the end of the production period. After the production period, the tools are returned to the tool crib and examined for further usage. The toolkits are shared between production periods with the same part-type. There is no sharing of tools between different part-types. The above process is repeated for the next production period. [3, 24, 27, 42, 58, 65]

MODELING LOGIC FOR THE TOOL MIGRATION TOOL

In this policy, part routing in similar to the bulk exchange policy. However, after the part is completed, the part's cutting tools are removed from the tool chamber to permit space for additional tools. This allows for the introduction and processing of a new part-type. Tools are returned to the tool crib and examined for further usage. Tools are shared between production periods with other part-types. [3, 24, 27, 42, 58, 65]

MODELING LOGIC FOR RESIDENT TOOLING

This policy identifies high usage tools. These specific tools are used at the machines during the entire production run. The tools are changed only when their useful life has been reached. Tool migration is used with the remaining tool slots. The resident tools are grouped at machines based on the commonality of parts that they process. Parts are routed to the five machines based on their commonality of resident tool usage. A randomized parts-tools matrix was developed using SAS software. From the parts-tools matrix, five clusters of tools were formed using SPSS (Jaccard clustering technique) for the five machines. A part family, consisting of five parts, was identified for each tool cluster. The parts-tools matrix and clustering results are shown in Table 3.5.

Table 3.5. Part-Tool Component Matrix

Tool	Part-Type 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	1			1			1						1		1		1		1				1		
2	1		1				1	1					1					1		1		1	1	1	
3	1			1										1	1	1				1				1	1
4		1	1								1	1							1					1	1
5	1			1				1			1									1					1
6					1	1		1		1		1				1	1			1		1			
7	1				1		1					1				1	1		1						
8	1			1	1			1		1	1				1	1			1	1	1		1		
9		1		1		1			1		1		1						1		1	1		1	
10						1					1	1			1							1	1		1
11		1		1	1					1			1					1			1				
12		1	1	1			1		1	1				1		1	1	1		1					1
13		1											1		1		1		1		1	1			
14					1				1	1		1		1					1	1			1		1
15			1						1			1		1	1	1	1							1	
16	1	1				1	1		1				1	1			1		1			1		1	1
17				1					1				1		1	1				1				1	
18		1	1		1	1			1					1			1				1			1	
19		1						1		1		1				1									
20		1			1	1				1			1		1						1		1	1	
21					1				1	1				1				1				1	1		
22			1		1	1					1		1				1		1		1		1	1	
23	1	1				1	1			1				1				1				1			1
24	1				1			1		1						1	1	1					1		
25	1		1		1		1					1	1						1			1		1	1
26		1						1		1	1			1	1			1		1	1				
27											1	1	1				1				1	1			
28							1	1	1		1				1	1			1						1
29			1			1	1	1	1									1							1
30			1	1			1		1			1		1				1					1		

Table 3.6 shows the part and resident tool assignments to each machine based on the Jaccard clustering technique. Some tool duplication was needed at several machines to allow an even assignment of part-types to each machine. In this model, parts arrive in the system; their tool requirements are determined, and then parts are routed to machines based on their commonality of resident tool usage. Partial toolkits that are routed with part-types are unloaded at the end of the part's machining cycle. These tools are shared between production periods with other part-types. Also, these tools are monitored and examined for further usage. [3, 24, 27, 42, 58, 65]

MODELING LOGIC FOR TOOL SHARING

In this policy, tool commonality is recognized between parts within the production period. Different parts may require the same tool or tools for machining operations. Groups of parts are identified that use the same tools. The Jaccard clustering technique was used to identify five families of parts for each machine. Common tooling requirements were identified for each of the five part families. Each machine will be assigned a cluster of tools for one family of parts. The tool sharing clusters are illustrated in Table 3.7. Parts share common tools to avoid tool duplication. A part arrives in the system and is routed to the machine that contains the tool cluster for that part. Expired tools are changed at the end of the production period. [3, 24, 27, 42, 58, 65]

Table 3.6. Jaccard Clustering Results for Resident Tooling

Machine	Part-Type	Resident Tools			
Machine 1	1	21	14	30	12
	7	23	16	25	2
	22	7	1		
	14				
	18				
Machine 2	24	6	8	12	3
	4	9	15	17	
	15				
	16				
	20				
Machine 3	13	27	13	22	20
	23	18	9	10	4
	6				
	17				
	12				
Machine 4	19	29	28	5	25
	11	22	4	16	
	9				
	25				
	3				
Machine 5	8	26	11	24	8
	10	19	6		
	21				
	2				
	5				

Table 3.7. Tool and Part Allocation for Tool Sharing

Machine 1			**Shared Tools**		
Part Numbers:	1	7	12	18	25
1	2	8	13	20	26
7	9	14	3	21	27
14	5	10	15	23	28
18	6	11	16	24	29
22					30
Machine 2			**Shared Tools**		
Part Numbers:	1	6	11	17	24
24	2	7	12	18	25
4	11	12	13	14	15
15	8	3	14	19	26
16	4	9	15	20	28
20	5	10	16	22	30
					13
Machine 3			**Shared Tools**		
Part Numbers:	1	7	14	19	24
13	2	15	8	20	25
23	3	9	21	27	16
6	17	4	10	22	29
17	6	11	23	18	30
12				12	13
Machine 4			**Shared Tools**		
Part Numbers:	1	8	14	22	27
6	4	10	16	23	29
13	2	9	15	21	28
14	5	12	17	25	30
17	7	13	18	26	3
22					
Machine 5			**Shared Tools**		
Part Numbers:	8	2	14	21	25
10	4	9	16	22	27
18	5	11	18	23	28
20	6	12	19	29	24
21	7	13	20	26	
23					

3.4 DATA COLLECTION AND THE TREATMENT OF DATA

The factors and their levels include 4 tooling policies and 3 production-scheduling rules. The impact of the 4 tooling policies on manufacturing performance measures will be evaluated. These performance measures include the mean flow time, machine utilization, robot utilization, mean lateness, and the percent of parts late. Also, the average tool inventory and tool consumption rates for each production period will be collected on each tooling policy and selection rule.

A total of 12 simulation models will be developed. A simulation model will be developed for each tool allocation policy and part-type selection rule. The 12 models represent 12 treatment combinations: 4 levels of tool policy and 3 levels of part-type selection rule. *Arena* is the simulation software that will be used in this study.

A total of 10 replications will be preformed on each combination of tool policy and part-type selection rule. The results will yield 120 observations; each of the 12 combinations will have 10 replications. An average value from the 10 observations will be calculated. Confidence intervals on the mean values will also be generated.

After the data is collected, the data will be analyzed using the analysis of variance (ANOVA) procedures, multiple comparison tests, and graphical comparison charts. The ANOVA procedures will test for equal treatment means and the impact of the independent factors and their interaction on the 5 dependant performance measures. The Bonferroni multiple comparison method will be used to determine which specific tooling policies differ for each performance measure. Graphical comparison charts will be used to compare the four tooling policies for each part-type selection rule. The results will determine which tooling policy performs best in the FMS under study.

3.5 MODEL VALIDATION AND VERIFICATION

Validation establishes the reliability of the model's design and integrity of development. Validation establishes an acceptable level of confidence that the conclusions drawn from the simulation results will give an understanding of the true operating characteristics of the system being modeled. For this research, the model was based on model development data from previous research [3]. The model was developed from an actual operating system [3]. To increase the validity of the model and to provide preliminary model assessment, a pilot study was conducted. The information collected consisted of general tool management decisions, cutting tool parameter data, and machining process requirements. The data and information were used to assist in simulation modeling and parameter inputs. The study included 9 companies that utilize flexible manufacturing systems or CNC machines in their production operations. The method of information and data collection was on-site interviews with tool managers, manufacturing engineers, operations managers, and CNC programmers. In addition, the information provided a perspective from the respondents with regard to tool management problems and suggestions. The "Tool Management and Production Operations Study" form and pilot study results are located in Appendix A and Appendix B, respectively. The validation process began during the initial stages of simulation modeling and continued until completion. [69, 70]

With regard to verification, model verification is the process of ensuring that the simulation model functions in the way that it is intended to according to the modeling logic [66]. The *Arena* trace methods and animation were used to follow entities through the system to determine their location and to ensure the correctness of model logic and data summary results. In addition, hand calculations were used to validate the results of the summary statistics. [69, 70]

For each treatment combination of tool policy and part-selection rule, 10 replications were performed for each performance measure. The system and the statistics were reinitialized after each replication. The 10 random outputs exhibited variability between simulation runs. Each replication produced different results because of the different random number streams provided for by *Arena*. This was also necessary to calculate means, standard deviations, and confidence intervals for each treatment combination.

3.6 SUMMARY

Chapter 3 has presented a methodology to assist in the research study. This study will evaluate the impact of tool allocation policies on selected performance measures in an FMS environment, contingent on part-type selection rules. The tool allocation policies, part-type selection rules, performance measures, and the simulation model environment have been presented. In addition, the model's parameters, data collection, statistical method of analysis, and model validation and verification were discussed.

CHAPTER 4

RESULTS AND ANALYSES

4.1 STUDY PLAN AND PROCEDURES

This chapter will present the results and analyses of the data that were generated from the simulation models. The objective of this research is to study the impact of tool allocation policies on selected performance measures, contingent upon part-type selection rules. For each performance measure, confidence intervals will be calculated on the means for the treatment combinations, a null hypothesis will be stated, analysis of variance (ANOVA) procedures will be performed on the data, and multiple comparison tests and graphic charts will be used to compare tooling polices.

The confidence interval procedure forms end-points that will contain the parameter under study with a high probability [67]. For this study, a 98% confidence interval on the mean for each treatment combination will be calculated with respect to each performance measure.

With respect to hypothesis testing, the level of significance of the test was set at α equal to 0.05. This level was chosen before the data were collected. The level determines the acceptance or rejection of the null hypothesis. For hypothesis testing, α is the probability of committing a type 1 error. The 0.05 level implies that we run a small risk in rejecting the null hypothesis, when in fact the null hypothesis is true [67]. For the model, the rejection of a null hypothesis will imply that the means for the different treatment combinations of tooling policy and part-type selection rule may be significantly different with respect to the performance measure under study. This suggests that some treatment combinations may be preferred to others when meeting the performance objectives for the flexible manufacturing system [65].

The null hypothesis for each performance measure is stated as follows:

H_o1 : There is no difference in the mean flowtime performance measure between the various treatment combinations of tooling policy and part-type selection rule.

H_o2 : There is no difference in the average machine utilization measure between the various treatment combinations of tooling policy and part-type selection rule.

H_o3 : There is no difference in the average robot utilization measure between the various treatment combinations of tooling policy and part-type selection rule.

H_o4 : There is no difference in the percent of parts late measure between the various treatment combinations of tooling policy and part-type selection rule.

H_o5 : There is no difference in the mean tardiness measure between the various treatment combinations of tooling policy and part-type selection rule.

The Analysis of Variance (ANOVA) procedures will be used to test the null hypotheses for equal treatment means and the effects of the main factors and their interaction for each performance measure. The *F* ratio test statistic is used in the analysis of the data. The following assumptions are made with respect to the ANOVA procedure [67]:

1. Each observation represents an independent sample.
2. Each population is normally distributed.
3. The populations have equal variances.

For each performance measure, the Bonferroni *t* Tests and graphical comparison charts will be used to identify and compare the four tooling policies for all three levels of part-type selection rule. When comparing more than two means, the ANOVA *F* test determines whether the means are significantly different. However, the test does not tell you which means differ from other means. The Bonferroni *t* Test is a multiple comparison method that is used to compare three or more means while controlling the probability of making at least one type 1 error. The Bonferroni multiple comparison method will be used to identify the statistical differences between the tooling policy means at specific levels of part-type selection rule. For this study, there are 4(4-1)/2 = 6 comparisons, where 4 is equal to the number of "group means" that are being compared. Each "group means" represents a tooling policy. [71, 72, 73]

The level of significance for the Bonferroni *t* Test is equal to 5%. This level of significance is called the experimentwise error rate, which is the probability that at least one of the comparisons will include a type 1 error: a false rejection of the null hypothesis. As the number of mean comparisons increases, the chance of making at least one type 1 error increases. Various authors [71, 72, 73] recommend using multiple comparisons, with a 5% experimentwise error rate, when the number of comparisons is small in order to control the likelihood of a type 1 error. For multiple comparisons testing, the *t* statistic is used in the evaluation of every pair of means. [71, 72, 73]

The following sections will discuss the results of the study with respect to the mean flow time, average machine utilization, average robot utilization, percentage of parts late, and the mean lateness. The final sections will discuss the average tool inventory and the tool consumption rate for each tool policy.

4.2 MEAN FLOWTIME

The flowtime is a measure of the time that a part has spent in the system. The mean flow time is the overall average flowtime for all completed parts.

The null hypothesis for the flowtime performance measure is stated as follows:

$H_0 1$: There is no difference in the mean flowtime performance measure between the various treatment combinations of tooling policy and part-type selection rule.

Table 4.1 shows the treatment combinations with their mean flowtime estimators and 98% confidence intervals. The confidence interval suggests that we can be 98% confident that the mean flowtimes for the treatment combinations will be within their respective limits.

Table 4.2 shows the ANOVA procedures for the model treatment combinations, the main factor effects, and the factor interaction. The *p* value for the ANOVA test on the treatment combinations is 0.0001, which is significant at the 0.05 level. As a result, the null hypotheses must be rejected. There is statistical evidence to prove that the various treatment combinations differ in their mean flowtimes. Therefore, the different combinations of tooling policy and part-type selection rule affect the flowtime of

Table 4.1. Mean Flowtimes and 98% Confidence Intervals

Tooling Policy	Selection Rule	Mean (Hrs.)	Lower 98% C.I.	Upper 98% C.I.
Bulk Exchange	LNT	4.75	4.7416	4.7584
Bulk Exchange	SNT	4.73	4.7152	4.7515
Bulk Exchange	EDD	4.75	4.7369	4.7631
Tool Migration	LNT	5.45	5.4290	5.4710
Tool Migration	SNT	5.42	5.3981	5.4419
Tool Migration	EDD	5.44	5.4213	5.4587
Tool Sharing	LNT	4.76	4.6900	4.8300
Tool Sharing	SNT	4.77	4.7266	4.8134
Tool Sharing	EDD	4.78	4.7373	4.8227
Resident Tooling	LNT	5.87	5.8310	5.9090
Resident Tooling	SNT	5.80	5.7370	5.8630
Resident Tooling	EDD	5.83	5.7776	5.8824

Table 4.2. **Analysis of Variance Procedures for the Mean Flowtime**

DEPENDENT VARIABLE: Flowtime

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	25.35822667	2.30529333	1163.64	<.0001
Error	108	0.21396000	0.00198111		
Corrected Total	119	25.57218667			

R-Square	Coeff Var	Root MSE	Flow Time Mean
0.991633	0.856559	0.044510	5.196333

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Tooling Policy	3	25.32576667	8.44192222	4261.21	<.0001
Selection Rule	2	0.01326167	0.00663083	3.35	0.0389
Policy * Rule	6	0.01919833	0.00319972	1.62	0.1498

part-types processed in the FMS.

Because the treatment combinations differ in their mean values, the next evaluation pertains to the main effects and their interaction. First, the test for interaction is performed. If there is no evidence of interaction, then the test for main effects is conducted [67]. As shown in Table 4.2, the p value for the two-way interaction between the tooling policy and the part selection rule is 0.1498. This value is not significant at the 0.05 level. Therefore, we do not have statistical evidence of interaction between the main factors. This suggests that the relative performance of tool policy does not differ between levels of part-type selection rule. With respect to the main factors, Table 4.2 shows that the p value for tool policy is 0.0001, and the p value for selection rule is 0.0389. Their p values are significant at the 0.05 level, implying that both factors affect the mean flowtime of part-types through the system.

Table 4.3 shows the Bonferroni t Tests. The tests show the mean comparisons of tooling policies for each part-type selection rule with respect to flowtime. The ANOVA procedure shows that there is a difference between means. The Bonferroni t Tests show which specific tool policy means differ across each part-type selection rule. For this test, means with the same "Bon Grouping" letter are not significantly different. The table shows that the same three groups emerge from the four tooling policies for all part-type selection rules. Resident tooling forms group (A), tool migration forms group (B), and tool sharing and bulk exchange form group (C). Since resident tooling and tool migration do not share the same letter group, they are statistically different. Tool sharing and bulk exchange are represented by the same group letter. Therefore, they are not statistically different. Tool migration and resident tooling are statistically different than tool sharing and bulk exchange because they do not share the same letter group. In addition, tool sharing and bulk exchange outperform both resident tooling and tool migration because they have the lowest mean flowtimes.

Table: 4.3. Multiple Comparisons Test for Mean Flowtime

DEPENDANT VARIABLE: Flowtime

Scheduling Rule: Largest Number of Tools

Bonferroni (Dunn) *t* Tests for Flowtime

Bon Grouping	Mean	N	Tool Policy
A	5.87100	10	Resident
B	5.44500	10	Migration
C	4.76000	10	Sharing
C	4.75400	10	Bulk Exchange

Scheduling Rule: Smallest Number of Tools

Bonferroni (Dunn) *t* Tests for Flowtime

Bon Grouping	Mean	N	Tool Policy
A	5.80000	10	Resident
B	5.42100	10	Migration
C	4.77100	10	Sharing
C	4.73700	10	Bulk Exchange

Scheduling Rule: Earliest Due Date

Bonferroni (Dunn) *t* Tests for Flowtime

Bon Grouping	Mean	N	Tool Policy
A	5.82600	10	Resident
B	5.43900	10	Migration
C	4.77700	10	Sharing
C	4.75500	10	Bulk Exchange

In Figure 4.1, the comparison graph shows that tool sharing and bulk exchange result in lower mean flowtime values when compared to resident tooling and tool migration for all levels of part-type selection rules. Resident tooling has the highest mean flowtimes for all part selection rules, followed by tool migration. In Figure 4.1, the lines for tool sharing and bulk exchange almost join. This suggests that their mean flowtimes are not significantly different. Also, when priority is assigned to the smallest number of tools (SNT), bulk exchange, tool migration and resident tooling policies have slightly lower flowtimes when comparing part selection rules.

The difference in the mean flowtimes between the tooling policies may be attributed to tool and part loading activities and the scheduling of parts to machines. A part's flowtime depends on its processing time, release rate, and load time as well as any tool changing activity. Tools are changed more frequently with tool migration and resident tooling. Both strategies require tools that migrate; these tools are changed after part processing. For tool migration, each part's tools are changed immediately after part completion. For resident tooling, each part's loaded tools are changed, as well as any expired resident tools, after part completion. However, parts must contend for the material-handling robot with tool changing activities. Consequently, parts must wait for loading or unloading, causing part delays. Therefore, part flowtimes through the FMS are increased because of the additional tool changing needs for tools that migrate.

With regard to bulk exchange, tools are loaded during the production period. However, tools are unloaded at the end of the production period. Therefore, parts do not contend with tool unloading activities for the robot. With regard to tool sharing, tool changing activities are minimized because of tool clustering methods. Tool clusters remain resident at their respective machines. Parts are routed to specific machines to exploit the commonality in tool usage. Tools are changed only when they have expired. Expired tools are changed only at the end of the production period. For tool sharing and

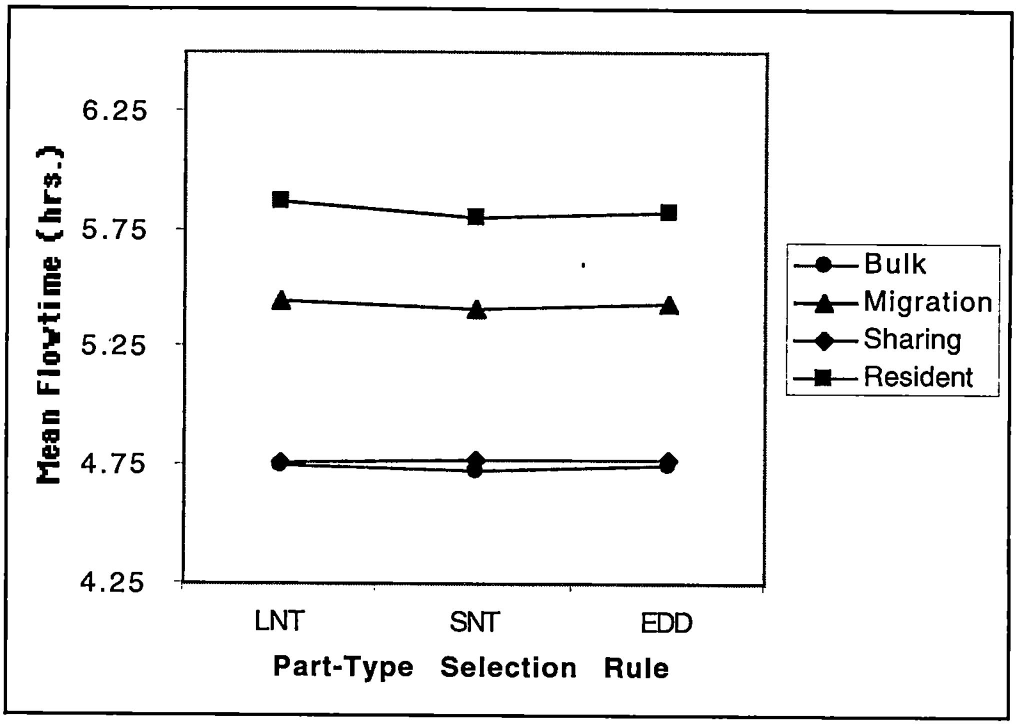

Figure 4.1. Graphical Comparison on the Mean Flowtime.

bulk exchange, tools do not migrate. Thus, the frequency of tool changing activities is reduced. As a result, part flowtimes through the FMS are significantly reduced.

4.3 MACHINE UTILIZATION

Machine utilization is a dependant variable, which is a measure of the average machine utilization. Five identical CNC machines were used in this study.

The null hypothesis for the average machine utilization is stated as follows:

$H_0 2$: There is no difference in the average machine utilization measure between the various treatment combinations of tooling policy and part-type selection rule.

The confidence intervals on the average machine utilization for the twelve treatment combinations are shown in Table 4.4. Table 4.5 shows the ANOVA procedures for the treatment combinations, the main factor effects, and the factor interaction. The *p* value for the treatment combinations is 0.0001, which is significant at the 0.05 level. Therefore, we must reject the null hypothesis. There is statistical evidence to prove that different factor combinations, of tooling policy and part-type selection rule, differ in their average machine utilization. Table 4.5 shows that the *p* value for the interaction between tool policies and selection rules is 0.0620, which is not significant at the 0.05 level. Therefore, the performance of one factor does not depend on the chosen level of the other factor with respect to machine utilization. When evaluating the main effect for tool policy, the *p* value is significant at the 0.05 level. This implies that the

Table 4.4. Average Machine Utilization and 98% Confidence Intervals

Tooling Policy	Selection Rule	Mean (%)	Lower 98% C.I.	Upper 98% C.I.
Bulk Exchange	LNT	0.5620	0.5612	0.5628
Bulk Exchange	SNT	0.5610	0.5594	0.5626
Bulk Exchange	EDD	0.5630	0.5617	0.5643
Tool Migration	LNT	0.6210	0.6183	0.6237
Tool Migration	SNT	0.6230	0.6217	0.6243
Tool Migration	EDD	0.6230	0.6209	0.6251
Tool Sharing	LNT	0.5030	0.4926	0.5134
Tool Sharing	SNT	0.4990	0.4946	0.5034
Tool Sharing	EDD	0.5000	0.4938	0.5062
Resident Tooling	LNT	0.4650	0.4591	0.4709
Resident Tooling	SNT	0.4730	0.4649	0.4811
Resident Tooling	EDD	0.4670	0.4619	0.4721

Table 4.5. Analysis of Variance Procedures for Machine Utilization

DEPENDENT VARIABLE: Machine Utilization

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.41639629	0.03785421	1144.05	<.0001
Error	108	0.00357350	0.00003309		
Corrected Total	119	0.41996979			

R-Square	Coeff Var	Root MSE	Machine Mean
0.991491	1.068771	0.005752	0.538208

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Tool Policy	3	0.41594129	0.13864710	4190.26	<.0001
Selection Rule	2	0.00004312	0.00002156	0.65	0.5233
Policy*Rule	6	0.00041188	0.00006865	2.07	0.0620

tool policies have different impacts on the average machine utilization. However, table 4.5 shows that the p value for the selection rule is 0.5233, which is not significant at the 0.05 level. Therefore, the selection rule has no effect on machine utilization.

Table 4.6 portrays the multiple comparison results, which show the letter group for each tool policy for the levels of part-type selection rule. Tool migration is represented by group (A); bulk exchange is represented by group (B); groups (C) and (D) represent tool sharing and resident tooling, respectively. These results are consistent for each part-type selection rule. Thus, no two policies share the same letter group. This implies that the means for all tool policies are statistically different at the 0.05 level of significance. Figure 4.2 shows the graphical comparisons between the tooling policies. The graph shows that tool migration has the highest average machine utilization, followed by bulk exchange, tool sharing, and resident tooling, respectively, for all levels of part selection rule.

Part processing times and part loading and unloading affect machine utilization. The machine utilization for bulk exchange and tool migration is high. Their utilization of machines is almost even because of the random assignments of parts to machines. Their machine utilization values are high primarily because of part processing times and part delays at machines due to the unavailability of the material-handling unit. The robot is busy changing tools or parts at other locations in the system. This has the potential of delaying completed parts at machines, which affects the utilization of those machines. Tool sharing and resident tooling result in lower machine utilization than tool migration and bulk exchange. These policies are used to exploit the commonality in tool usage. The low machine utilization is caused by the need to exploit tool commonality. Some machines are utilized more than others because their total part processing times are higher. This creates an imbalance in the utilization among machines because of the uneven distribution of processing times at machines during production periods. [3, 65]

Table: 4.6. Multiple Comparisons Test for Machine Utilization

DEPENDANT VARIABLE: Machine Utilization

Scheduling Rule: Largest Number of Tools

Bonferroni (Dunn) *t* Tests for Machine

Bon Grouping	Mean	N	Tool Policy
A	0.620700	10	Migration
B	0.561700	10	Bulk Exchange
C	0.502700	10	Sharing
D	0.465100	10	Resident

Scheduling Rule: Smallest Number of Tools

Bonferroni (Dunn) *t* Tests for Machine

Bon Grouping	Mean	N	Tool Policy
A	0.622600	10	Migration
B	0.561400	10	Bulk Exchange
C	0.498900	10	Sharing
D	0.473100	10	Resident

Scheduling Rule: Earliest Due Date

Bonferroni (Dunn) *t* Tests for Machine

Bon Grouping	Mean	N	Tool Policy
A	0.622600	10	Migration
B	0.562600	10	Bulk Exchange
C	0.500000	10	Sharing
D	0.467100	10	Resident

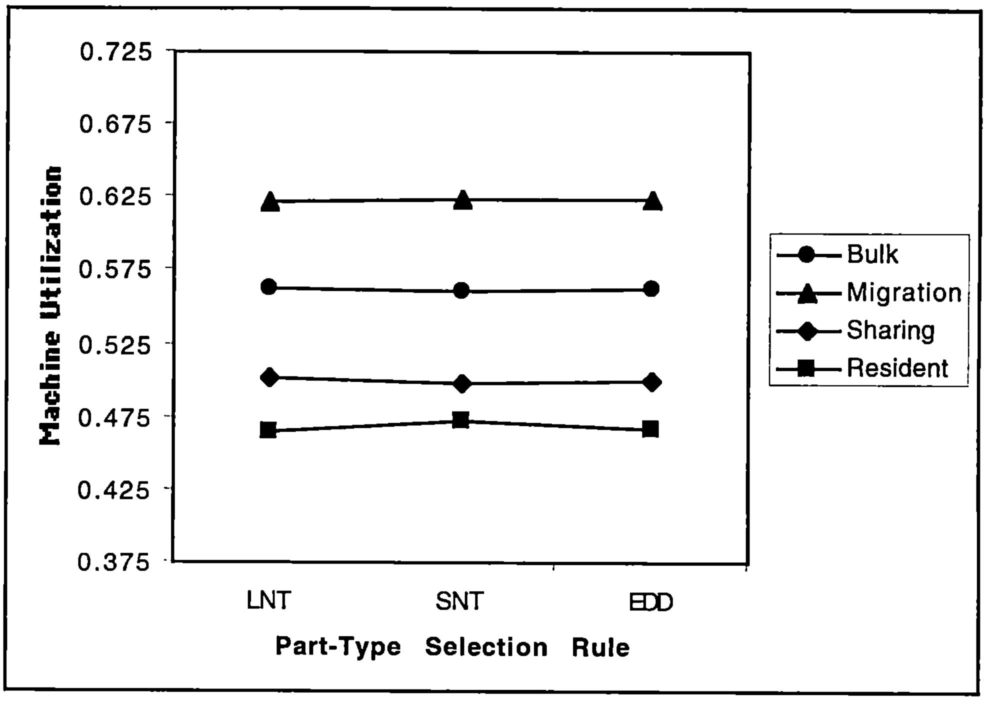

Figure 4.2. Graphical Comparison on Machine Utilization.

4.4 ROBOT UTILIZATION

Robot utilization is a dependant variable, which measures the utilization of the materials handling unit. This materials handling unit is affected by tool changing activities as well as parts loading and unloading. The null hypothesis for the robot utilization is stated as follows:

H_o3: There is no difference in the robot utilization measure between the various treatment combinations of tooling policy and part-type selection rule.

The null hypothesis is rejected if the *p* value is less than the significance level of 0.05 for this study. The confidence intervals for the twelve treatment combinations are illustrated in Table 4.7. Table 4.8 shows the ANOVA procedures for the treatment combinations, the main factor effects, and the factor interaction. The table shows that the model treatment combinations are significant at the 0.05 level of significance. This indicates that there is a difference in the robot utilization between the various treatment combinations. Therefore, the null hypothesis must be rejected. Also, Table 4.8 shows that the *p* value for the interaction between the main factors is 0.2060, which is not significant at α equal to 0.050. Thus, the relative performance of the tool policy factor does not depend on the chosen level of the part selection rule factor. In addition, the table shows that both factor main effects are significant. Therefore, the materials handling unit is affected by tooling policies and part-type selection rules, independently.

Table 4.9 shows the multiple comparisons for the tooling polices at each level of part-type selection rule. Tool migration is represented by group (A); bulk exchange is represented by group (B); resident tooling and tool sharing are represented by groups

Table 4.7. Robot Utilization and 98% Confidence Intervals

Tooling Policy	Selection Rule	Mean (%)	Lower 98% C.I.	Upper 98% C.I.
Bulk Exchange	LNT	0.5220	0.5212	0.5228
Bulk Exchange	SNT	0.5230	0.5214	0.5246
Bulk Exchange	EDD	0.5230	0.5214	0.5246
Tool Migration	LNT	0.5810	0.5783	0.5837
Tool Migration	SNT	0.5830	0.5814	0.5846
Tool Migration	EDD	0.5820	0.5795	0.5845
Tool Sharing	LNT	0.1510	0.1475	0.1545
Tool Sharing	SNT	0.1530	0.1511	0.1549
Tool Sharing	EDD	0.1520	0.1500	0.1540
Resident Tooling	LNT	0.3271	0.3233	0.3310
Resident Tooling	SNT	0.3370	0.3303	0.3437
Resident Tooling	EDD	0.3320	0.3280	0.3360

Table 4.8. Analysis of Variance Procedures for Robot Utilization

DEPENDENT VARIABLE: Robot Utilization

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	3.42200007	0.31109092	24935.3	<.0001
Error	108	0.00134740	0.00001248		
Corrected Total	119	3.42334747			

R-Square	Coeff Var	Root MSE	Robot Mean
0.999606	0.889107	0.003532	0.397267

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Tool Policy	3	3.42175620	1.14058540	91422.9	<.0001
Selection Rule	2	0.00013607	0.00006803	5.45	0.0055
Policy*Rule	6	0.00010780	0.00001797	1.44	0.2060

Table: 4.9. Multiple Comparisons Test for Robot Utilization

DEPENDANT VARIABLE: Robot Utilization

Bonferroni (Dunn) *t* Tests for Robot

Scheduling Rule: Largest Number Tools

Bon Grouping	Mean	N	Tool Policy
A	0.580600	10	Migration
B	0.522100	10	Bulk Exchange
C	0.330700	10	Resident
D	0.151200	10	Sharing

Scheduling Rule: Smallest Number of Tools

Bonferroni (Dunn) *t* Tests for Robot Utilization

Bon Grouping	Mean	N	Tool Policy
A	0.582800	10	Migration
B	0.522700	10	Bulk Exchange
C	0.336700	10	Resident
D	0.152600	10	Sharing

Bonferroni (Dunn) *t* Tests for Robot

Scheduling Rule: Earliest Due Date

Bon Grouping	Mean	N	Tool Policy
A	0.581600	10	Migration
B	0.522800	10	Bulk Exchange
C	0.331700	10	Resident
D	0.151700	10	Sharing

(C) and (D), respectively. These results are consistent for each part-type selection rule. Thus, no two policies share the same "Bon Grouping." This implies that the tooling policies are statistically different from each other for each part-type selection rule. Figure 4.3 shows graphical comparisons of the tooling policies. For each part-type selection rule, the figure shows that tool migration has the highest robot utilization, followed by bulk exchange, resident tooling, and tool sharing, respectively. The part selection rules for the bulk exchange, tool migration and tool sharing do not appear to influence robot utilization. For these policies, the robot utilization remains relatively even for each part-type selection rule. However, for resident tooling, the SNT rule produces a slightly higher robot utilization.

Because robot utilization is dependent upon tool changing activities, tool migration and bulk exchange have higher robot utilization because of the frequency of tool changing. With tool migration, a part's toolkit is changed after its machining cycle, regardless of tool life. With bulk exchange, all tools are changed at the end of the production period, regardless of tool life. Resident tooling has a lower robot utilization when compared to bulk exchange and tool migration. When comparing tool migration and resident tooling, fewer tools are sent with each part-type for resident tooling, and tools that are resident are changed only when they have reached their useful life. Tool sharing has the lowest robot utilization because only expired tools are changed at the end of each production period.

The frequency of tool changing is less for tool sharing and resident tooling than for bulk and migration tool policies. This is apparent because tool sharing and resident tooling exploit tool commonality, which decreases tool duplication by eliminating redundant tooling and assigning specific tools to machines prior to the production period. As a result, the frequency of tool changing is lower; this is a benefit for utilizing group

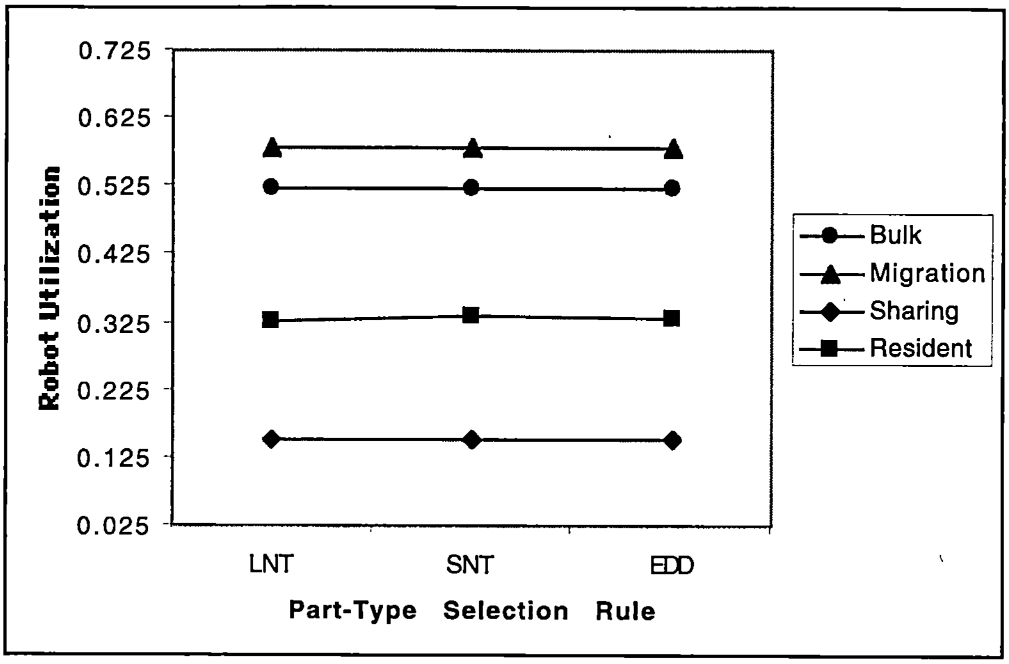

Figure 4.3. Graphical Comparison on Robot Utilization.

technology to identify common tool usage among part-types. Therefore, the selection of a tool policy influences the robot's utilization.

4.5 PERCENT OF PARTS LATE

The "percent of parts late" is a measure of the percentage of parts completed after their earliest due date (EDD) requirements. The null hypothesis for this performance measure is stated as follows:

H_o4 : There is no difference in the percent of parts late measure between the various treatment combinations of tooling policy and part-type selection rule.

The confidence intervals are presented in Table 4.10. The analysis of variance procedures for the treatment combinations, the main factor effects, and factor interactions are presented in Table 4.11. The table shows that the null hypothesis for the treatment combinations must be rejected because the *p* value is significant at the 0.05 level. Thus, various factor combinations differ with respect to the percent of parts that exceed their respective due dates. Also, Table 4.11 shows that the interactions between tool policy and part selection rule are significant. This implies that the relative performance of tooling policy is dependent on the level of part-type selection rule. In addition, Table 4.11 shows that the *p* values for tool policy and selection rule are equal to 0.0001. This value is significant at the 0.05 level of significance.

Table 4.12 shows the Bonferroni comparisons. Tool migration and resident tooling are in the same letter group (A) for each part-type selection rule. This implies

Table 4.10. Percent of Parts Late and 98% Confidence Intervals

Tooling Policy	Selection Rule	Mean (%)	Lower 98% C.I.	Upper 98% C.I.
Bulk Exchange	LNT	0.4600	0.4522	0.4678
Bulk Exchange	SNT	0.4530	0.4456	0.4604
Bulk Exchange	EDD	0.4920	0.4834	0.5006
Tool Migration	LNT	0.5480	0.5355	0.5605
Tool Migration	SNT	0.5470	0.5400	0.5541
Tool Migration	EDD	0.6000	0.5930	0.6070
Tool Sharing	LNT	0.4220	0.4149	0.4291
Tool Sharing	SNT	0.4250	0.4174	0.4326
Tool Sharing	EDD	0.4830	0.4732	0.4928
Resident Tooling	LNT	0.5440	0.5348	0.5532
Resident Tooling	SNT	0.5410	0.5349	0.5471
Resident Tooling	EDD	0.6080	0.5981	0.6179

Table 4.11. Analysis of Variance Procedures for Percent of Parts Late

DEPENDENT VARIABLE: Percent of Parts Late

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.44467129	0.04042466	442.57	<.0001
Error	108	0.00986470	0.00009134		
Corrected Total	119	0.45453599			

R-Square	Coeff Var	Root MSE	Percent of Parts Tardy
0.978297	1.873071	0.009557	0.510242

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Tool Policy	3	0.36528762	0.12176254	1333.07	<.0001
Selection Rule	2	0.07596722	0.03798361	415.85	<.0001
Policy*Rule	6	0.00341645	0.00056941	6.23	<.0001

Table: 4.12. Multiple Comparisons Test for Percent of Parts Late

DEPENDANT VARIABLE: Percent of Parts Late

SCHEDULING RULE: Largest Number of Tools

Bonferroni (Dunn) *t* Tests for Percent of Parts Late

Bon Grouping	Mean	N	Tool Policy
A	0.548500	10	Migration
A	0.544100	10	Resident
B	0.459800	10	Bulk Exchange
C	0.422000	10	Sharing

SCHEDULING RULE: Smallest Number of Tools

Bonferroni (Dunn) *t* Tests for Percent of Parts Late

Bon Grouping	Mean	N	Tool Policy
A	0.546000	10	Migration
A	0.541300	10	Resident
B	0.452700	10	Bulk Exchange
C	0.425300	10	Sharing

SCHEDULING RULE: Earliest Due Date

Bonferroni (Dunn) *t* Tests for Percent Tardy

Bon Grouping	Mean	N	Tool Policy
A	0.608100	10	Resident
A	0.600200	10	Migration
B	0.492400	10	Bulk Exchange
B	0.482500	10	Sharing

that they are not statistically different from each other for all part-type selection rules. However, both policies are statistically different from tool sharing and bulk exchange for all levels of part-type selection rule. For the LNT and SNT selection rules, the bulk exchange is represented by group letter (B), and tool sharing is represented by group letter (C). For these rules, their means are statistically different. However, when the EDD is assigned priority, bulk exchange and tool sharing are not statistically different because they share the same letter group.

As illustrated in Figure 4.4, tool sharing produces the lowest percentage of late parts followed by the bulk exchange, for all part-type selection rules. There appears to be no significant difference between migration and resident tooling. (This was also shown in the multiple comparison tests.) Nevertheless, with the assignment of LNT and SNT rules, tool migration produces a slightly higher percentage of parts late than resident tooling. However, when priority is assigned to the EDD rule, tool migration produces a slightly lower percentage of parts late than resident tooling. When comparing part-type selection rules, the EDD rule produces the highest percentage of parts late for all tooling policies.

The reasons for parts not meeting their due dates depend on factors such as part processing times, robot unavailability, machine unavailability, and part release rates. For these reasons, bottlenecks occur within the FMS. The bottlenecks cause part delays. Although sharing and resident policies are based on group technology principles, their performance on part lateness does not depend on exploiting tool commonality. This is shown in Figure 4.4 by the separation of their respective value symbols for each part selection rule. For resident and migration tool policies, parts are being delayed resulting in a high percentage of parts not meeting their due dates. Using tool sharing, with LNT rule, will minimize part lateness.

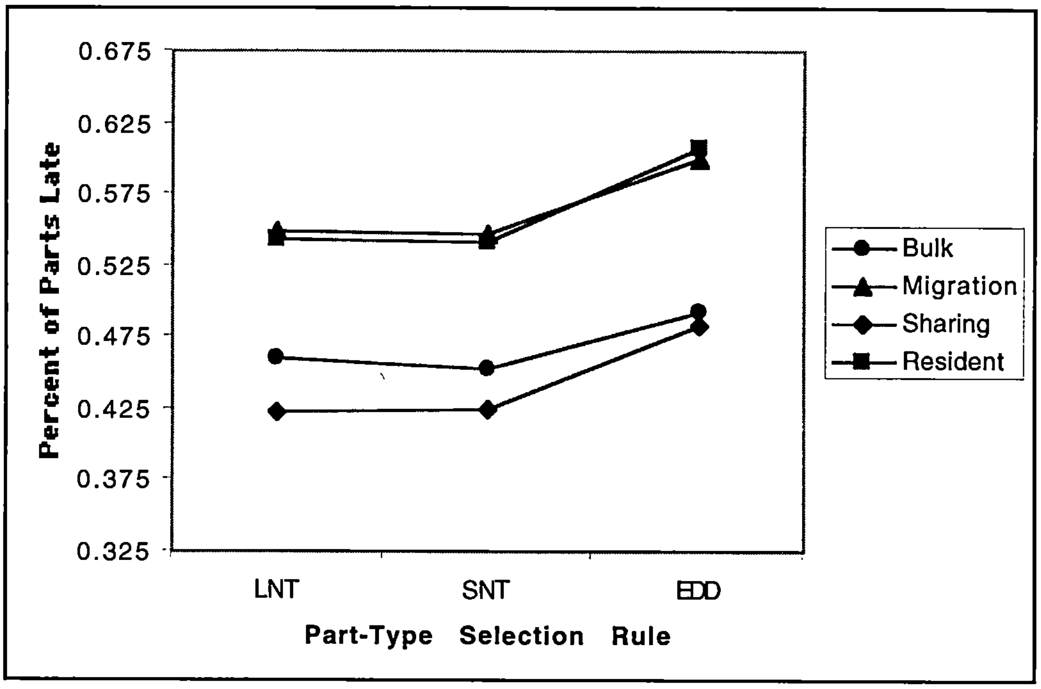

Figure 4.4. Graphical Comparison on Percent of Parts Late

4.6 MEAN LATENESS

The "mean lateness" is the dependant variable that measures the average late time for all parts that do not meet their due date requirements. The null hypothesis for the mean lateness performance measure is stated as follows:

H_o5: There is no difference in the mean lateness measure between the various treatment combinations of tooling policy and part-type selection rule.

Table 4.13 shows the 12 treatment combinations with their respective confidence intervals. Table 4.14 shows the ANOVA procedures for the treatment combinations, the main factor effects, and the factor interaction. The *p* value for the treatment combinations is equal to 0.0001, which is significant at the 0.05 level. Therefore, the null hypothesis must be rejected. We have statistical evidence that not all treatment combinations are equal with respect to mean lateness. Table 4.14 shows that both main effects and their interaction are significant at the 0.05 level. Therefore, comparison of the tooling policies must be made at each level of part-type selection rule.

Table 4.15 shows the Bonferroni comparisons of the four tooling policies at the three levels of part-type selection rule. For the LNT rule, three groups emerge. Resident tooling has group letter (A). Bulk exchange has group letter (C), and sharing and migration share group letter (B). Thus, tool sharing and tool migration are not statistically different. However, they are statistically different than both resident tooling and bulk exchange. The bulk exchange and resident tooling are significantly different because they do not share the same letter group. For SNT rule, all tool policies are statistically different because no policies share the same letter group. Likewise, for

Table 4.13. Mean Lateness and 98% Confidence Intervals

Tooling Policy	Selection Rule	Mean (hrs.)	Lower 98% C.I.	Upper 98% C.I.
Bulk Exchange	LNT	1.9800	1.9315	2.0285
Bulk Exchange	SNT	2.0100	1.9725	2.0475
Bulk Exchange	EDD	1.6000	1.5717	1.6283
Tool Migration	LNT	2.5500	2.5143	2.5857
Tool Migration	SNT	2.5400	2.5043	2.5757
Tool Migration	EDD	2.1700	2.1344	2.1344
Tool Sharing	LNT	2.7600	2.6330	2.8870
Tool Sharing	SNT	2.7700	2.6937	2.8463
Tool Sharing	EDD	2.0600	1.9941	2.1259
Resident Tooling	LNT	3.4800	3.4348	3.5252
Resident Tooling	SNT	3.3700	3.2270	3.5130
Resident Tooling	EDD	2.9000	2.8232	2.9768

Table 4.14. Analysis of Variance Procedures for Mean Lateness

DEPENDENT VARIABLE: Mean Lateness

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	36.26650250	3.29695477	307.94	<.0001
Error	108	1.15631000	0.01070657		
Corrected Total	119	37.42281250			

R-Square	Coeff Var	Root MSE	Mean Lateness
0.969101	4.116264	0.103473	2.513750

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Tool Policy	3	29.2420917	9.74140306	909.85	<.0001
Selection Rule	2	6.57608000	3.28804000	307.10	<.0001
Policy*Rule	6	0.46621333	0.07770222	7.26	<.0001

Table: 4.15. Multiple Comparisons Test for Mean Lateness

DEPENDANT VARIABLE: Mean Lateness

SCHEDULING RULE: Largest Number of Tools

Bonferroni (Dunn) *t* Tests for Mean Lateness

Bon Grouping	Mean	N	Tool Policy
A	3.48400	10	Resident
B	2.70900	10	Sharing
B	2.56500	10	Migration
C	1.98100	10	Bulk Exchange

SCHEDULING RULE: Smallest Number of Tools

Bonferroni (Dunn) *t* Tests for Mean Lateness

Bon Grouping	Mean	N	Tool Policy
A	3.37400	10	Resident
B	2.76900	10	Sharing
C	2.54200	10	Migration
D	2.01000	10	Bulk Exchange

SCHEDULING RULE: Earliest Due Date

Bonferroni (Dunn) *t* Tests for Mean Lateness

Bon Grouping	Mean	N	Tool Policy
A	2.89800	10	Resident
B	2.16900	10	Migration
C	2.06100	10	Sharing
D	1.60300	10	Bulk Exchange

the EDD rule, the Bonferroni comparisons show that all tool policies are significantly different because they do not share the same letter group.

The graphical chart in Figure 4.5 shows that the bulk exchange has the lowest mean lateness for all levels of part-type selection rules. Resident tooling produces the highest mean lateness for all levels of part selection rules. When priority is assigned to LNT and SNT rules, tool migration outperforms tool sharing; however, when the EDD rule is assigned, the average mean lateness is lower for tool sharing. When comparing part-type selection rules, the EDD produces the lowest mean lateness value for all tool policies.

4.7 AVERAGE TOOL INVENTORY

This section provides the results on the average cutting tool inventory per production period for each tool allocation strategy and part selection rule. For this study, tool inventory consists of the "start-up" tooling requirements that are needed to fabricate all part-types for a specific production period; these tools are needed at the beginning of each production period. The average tool inventory is the cumulative total of each production period's inventory divided by the total number of production periods. The tool management system includes provisions for maintaining an inventory of cutting tools for the flexible manufacturing system. Tool inventory is important because an inadequate tool provision system, due to insufficient tooling requirements, can reduce the efficiency of an FMS system. Also, cutting tools have a large impact on tooling cost. Each tool allocation strategy has a different effect on tooling cost because each strategy may require a different tooling inventory level. The cutting tools for an FMS are

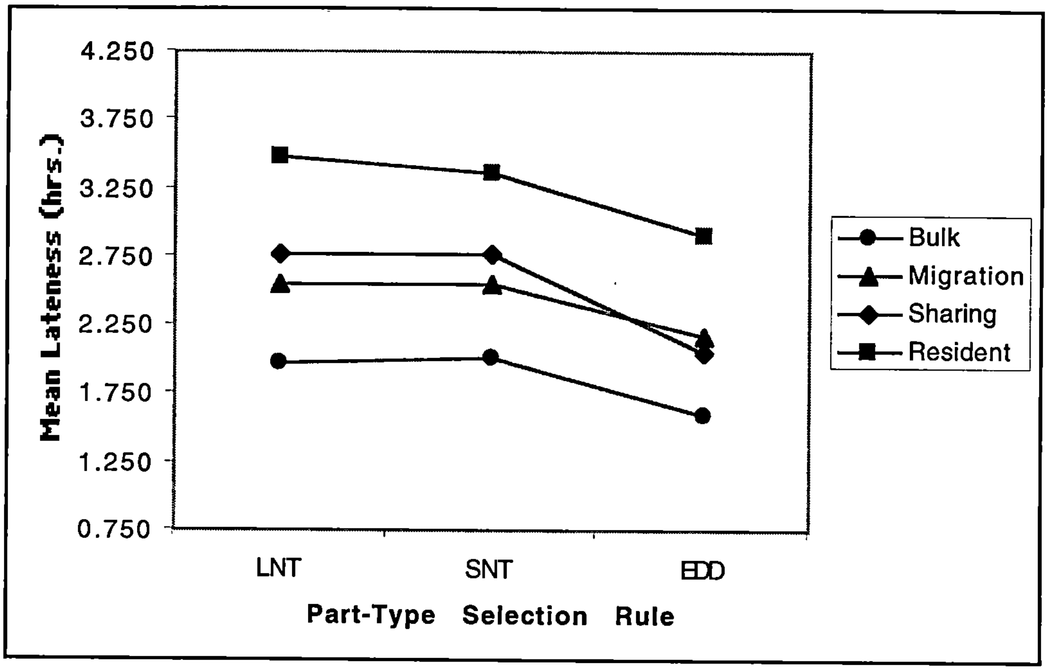

Figure 4.5. Graphical Comparison on Mean Lateness

relatively expensive in comparison to systems that lack flexibility. Therefore, excessive tool inventory may represent a significant cost. [14, 16, 19, 22, 28, 29]

For this study, with regard to the bulk exchange, each part has a unique toolkit. A toolkit contains a part's required cutting tools. During each production period, parts arrive in the system with their respective toolkit. The tool inventory for a production period consists of the total number of cutting tools for all toolkits. The average tool inventory per production period consists of the cumulative total of all cutting tools for each production period divided by the number of production periods. In this study, the production run consists of 150 production periods. For tool migration, like bulk exchange, parts arrive with their respective toolkits. The average tool inventory for tool migration is calculated the same as for the bulk exchange.

With regard to tool sharing, shared tools are made resident at each machine for the entire production run. The inventory for tool sharing consists of those tools that are made resident at the machines during the production period. The average tool inventory consists of the accumulative number of shared tools for each production period divided by the number of production periods.

With respect to resident tooling, a part arrives in the system with a partial toolkit. The part's remaining tool requirements are resident at the machine. The inventory for a production period consists of the total number of tools in each partial toolkit plus the tools that are made resident. The average inventory consists of the cumulative total of all cutting tools for each production period divided by the number of production periods. Table 4.16 shows the tooling inventory equations defined for each tooling policy.

Figure 4.6 shows a graphical comparison of the average tool inventory per production period for the tooling policies and part-type selection rules for 12 production periods. For all part-type selection rules, Figure 4.6 shows that bulk

Table 4.16. Inventory Equations for Tooling Policies

EQUATIONS FOR AVERAGE TOOL INVENTORY REQUIREMENTS PER PERIOD

Bulk Exchange:

$$\left(\sum_{i=1}^{P} \sum_{i=1}^{PT} Toolkit_j \right) / \, Number\ of\ Production\ Periods$$

Tool Migration:

$$\left(\sum_{i=1}^{P} \sum_{i=1}^{PT} Toolkit_j \right) / \, Number\ of\ Production\ Periods$$

Tool Sharing:

$$\left(\sum_{i=1}^{P} \sum_{i=1}^{M} Shared\ Tools_j \right) / \, Number\ of\ Production\ Periods$$

Resident Tooling:

$$\left(\sum_{i=1}^{P} \sum_{i=1}^{M} Partial\ Toolkit_j + Resident\ Tools_k \right) / \, Number\ of\ Production\ Periods$$

$Where:$

$$P = Production\ Period_i$$
$$PT = Part-Type_i$$
$$M = Machine_i$$

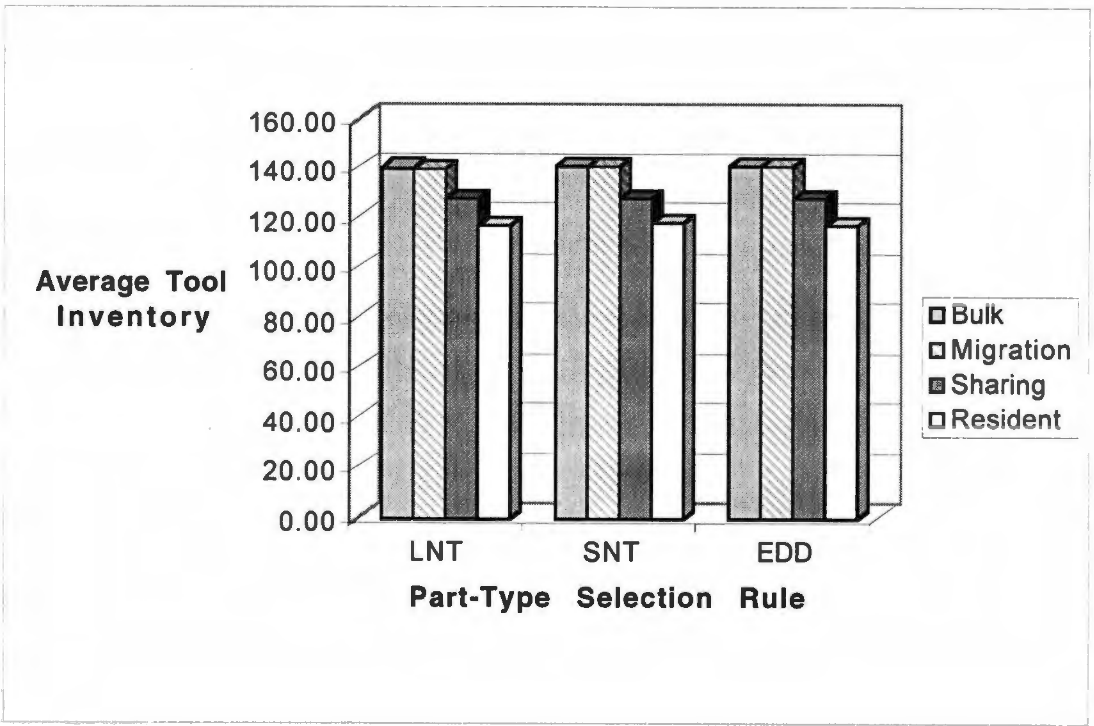

Figure 4.6. Average Start-Up Tool Inventory Per Period

exchange and tool migration have the highest average tool inventory per production period, followed by tool sharing and resident tooling, respectively. With bulk exchange and tool migration, cutting tools are being sent to the machines during the production period. These tools are not being shared between parts. Therefore, both strategies would require a higher average tool inventory when compared to sharing and resident tool policies.

The table also shows that resident tooling has a lower average tool inventory than tool sharing. Group technology was used to form part and tool families for each machine for resident tooling and tool sharing. There were a total of 128 cutting tools for tool sharing and a total of 38 cutting tools for resident tooling. The shared tool clusters, for a machine, consist of all tools needed for all parts assigned to that machine. No tools were duplicated for tool sharing.

The results of this study show that approximately 117 cutting tools are needed, on the average, during each production period for resident tooling. This is less than the 128 cutting tools that are needed for tool sharing during each production period. Since 38 cutting tools are made resident during each production period, there are approximately 79 cutting tools (117-38=79) being sent during each period. The 79 cutting tools is the average number of partial tools that are sent during a given production period.

With regard to the inventory levels for bulk exchange and tool migration, during a given production period, parts arrive with an average of 10 cutting tools. Since 14 parts enter the system during a given production period, the cutting tool inventory will be approximately 140 (10*14=140) for that period. Table 4.17 shows the cutting tool inventories for 12 production periods for each tool policy and part type selection rule.

Table 4.17. Inventory Levels

Production Period		1	7	15	30	45	60	75	90	105	120	135	150
Units Produced		14	98	210	420	630	840	1050	1260	1470	1680	1890	2100
LNT	Bulk	141.00	138.71	139.13	140.56	140.22	140.37	140.60	140.57	140.36	140.50	140.36	140.49
SNT	Bulk	141.00	138.54	140.06	140.86	140.85	140.96	140.82	140.73	140.72	140.65	140.63	140.63
EDD	Bulk	141.00	140.00	140.86	140.50	140.86	140.98	140.98	140.66	140.62	140.46	140.45	140.54
LNT	Migration	141.00	139.28	140.06	140.20	140.60	140.73	140.68	140.54	140.53	140.40	140.40	140.44
SNT	Migration	141.00	141.42	141.13	140.90	140.97	140.66	140.38	140.44	140.57	140.53	140.68	140.58
EDD	Migration	141.00	140.57	140.53	140.80	140.84	140.80	140.68	140.76	140.85	140.83	140.68	140.75
LNT	Sharing	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00
SNT	Sharing	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00
EDD	Sharing	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00
LNT	Resident	119.00	118.85	117.33	117.63	116.40	116.41	116.54	116.46	116.70	116.93	116.99	116.86
SNT	Resident	119.00	117.57	115.33	115.73	116.62	117.40	117.38	117.65	117.41	117.51	117.82	117.88
EDD	Resident	119.00	117.85	115.46	115.46	116.37	116.01	116.09	116.68	116.68	117.02	116.91	117.11

The results with regard to the average tool inventory show that randomly assigning parts to machines produces a higher average tool inventory per period. The bulk and migration policies provide a copy of each tool for each part visiting a machine. However, sharing and resident tooling, based on group technology, reduce cutting tool inventory by exploiting tool commonality, which reduces tool duplication. As a result of tool reduction, the cost for cutting tools is also minimized.

This section of the study only focused on the average tool inventory per production period. In the literature, the overall tool inventory consists of three duplicated tools for each cutting tool: a tool in the magazine, a backup tool, and a tool being refurbished [10]. This is consistent with conversations with metal cutting manufacturing companies and companies that provide cutting tools. The next section will show the results of the tool consumption rates per period for each tool allocation strategy and part-type selection rule.

4.8 TOOL CONSUMPTION RATE

This section will discuss the tool consumption rates for each tool allocation policy and part-type selection rule. For each tooling policy and part-type selection rule, the tool consumption rates were collected. For this study, the tool consumption rate is the average number of expired cutting tools per production period. The tool consumption rate is defined as follows, where P is production period (i):

$$\left(\sum_{i=1}^{P} Expired\,Tool_j \right) \Big/ \; Number\,of\,Production\,Periods$$

A tool must reach its useful life before being discarded. The tool life for each tool is 30 minutes. The objective is to utilize each tool to the extent of its tool life. This is generally true for most metal-cutting manufacturing environments. This is necessary because discarding a tool with adequate tool life remaining may be considered an improper, inefficient, and costly tooling practice. With proper table feed rates, spindle speeds, and adequate machine coolant, cutting tools may exceed their useful lives. For this study, when a cutting tool has reached or has exceeded 30 minutes, the tool is changed according to the tool allocation policy.

Because of the need to fully utilize each tool and because of the incremental tool usage per production period, the bulk exchange strategy shares toolkits between production periods. However, these toolkits are only used on their respective part-types (i.e., there is no sharing of tools between different part-types). Since all tools are removed at the end of the production period, the tool room operator or tool controller monitors the useful life of each tool.

Tool migration allows tools to be shared between production periods. These tools are also shared between part-types. Since tools are removed at the end of the machining cycle, the tool controller monitors the useful life of each tool.

Under the resident tooling policy, tools are shared between production periods. The tools that are made resident at a machine are shared between the part-types that are assigned to that machine. The expired resident tools are changed after the machining cycle. A tool controller checks the useful lives of the tools that migrate.

With regard to tool sharing, a machine's tool cluster is shared between the part-types that are assigned to that machine. Expired tools are changed at the end of the production period.

The following sub-sections will compare the tool consumption rates for the four tooling policies for each part-type selection rule. The assumption was that the results for each part-type selection rule would be similar since the variability in the number of tools per part-type is small; each part-type has 9, 10, or 11 tools. Each tool allocation policy and part-type selection rule has 2100 parts arriving in the system during the entire production run. Tables 4.18 and 4.19 show the tool consumption rates and the cumulative expired-tool usage for each tooling policy and part-type selection rule, respectively, for 12 production periods.

4.8.1 LARGEST NUMBER OF TOOLS

Figure 4.7 shows the results of the tool consumption rates for each tooling policy under the largest number of tools rule. Periods 1 through 15 show that the bulk exchange has the lowest tool consumption rates followed by tool migration, tool sharing, and resident tooling, respectively. After period 75, tool sharing and tool migration have the lowest consumption rates, followed by bulk exchange and resident tooling, respectively. After period 150, bulk exchange has the highest consumption rates, followed by resident tooling, tool migration, and tool sharing, respectively.

Resident tooling has the highest consumption rates from periods 1 through 75. This is expected because tools are being shared within and between production periods. The tools that migrate are shared with different part-types between production periods. Tools that are resident are shared only with specific part-types within each production period.

The bulk exchange has the lowest consumption rates from periods 1 through 45. This is expected because toolkits are only shared between production periods, and the toolkits are only shared with their respective part-types. After period 45, the bulk exchange experiences a gradual increase in the tool consumption rate per period. After period 60, the consumption rates for bulk exchange exceed those for tool sharing and tool

Table 4.18. Tool Consumption Rates

Production Period		1	7	15	30	45	60	75	90	105	120	135	150
Units Produced		14	98	210	420	630	840	1050	1260	1470	1680	1890	2100
LNT	Bulk	0.00	12.43	22.73	35.40	42.98	47.42	47.28	48.95	50.27	50.82	51.84	52.84
SNT	Bulk	0.00	12.29	21.73	34.47	41.51	45.88	48.16	49.87	49.93	50.96	51.39	51.84
EDD	Bulk	0.00	6.71	23.26	37.23	44.27	47.48	49.95	51.31	51.15	52.08	52.94	52.99
LNT	Migration	5.00	36.71	42.07	43.60	43.76	44.20	44.29	44.46	44.60	44.62	44.64	44.65
SNT	Migration	4.00	38.14	41.40	43.63	44.22	44.57	44.67	44.86	44.86	44.79	44.93	44.84
EDD	Migration	4.00	39.43	42.07	43.83	44.18	44.45	44.93	44.68	44.83	44.80	44.83	44.89
LNT	Sharing	11.00	39.57	43.13	43.50	43.91	44.18	44.17	44.08	44.11	44.28	44.26	44.18
SNT	Sharing	11.00	38.00	41.20	42.60	43.24	43.23	43.64	43.73	43.78	43.97	44.05	44.07
EDD	Sharing	11.00	37.00	41.60	43.10	43.58	43.57	43.75	43.94	43.94	44.06	44.17	44.15
LNT	Resident	13.00	44.00	46.80	48.50	49.20	49.37	49.37	49.44	49.77	49.88	49.92	50.09
SNT	Resident	13.00	43.43	47.00	48.40	49.20	49.66	49.75	49.87	50.10	50.23	50.19	50.23
EDD	Resident	13.00	44.00	47.93	48.90	49.96	49.98	49.99	50.04	50.26	50.16	50.30	50.38

Table 4.19. Cumulative Expired Tool Usage

Production Period		1	7	15	30	45	60	75	90	105	120	135	150
Units Produced		14	98	210	420	630	840	1050	1260	1470	1680	1890	2100
LNT	Bulk	0	87	341	1062	1934	2845	3546	4406	5278	6098	6999	7926
SNT	Bulk	0	86	326	1034	1868	2753	3612	4488	5243	6115	6937	7776
EDD	Bulk	0	47	349	1117	1992	2849	3746	4618	5371	6250	7147	7949
LNT	Migration	5	257	631	1308	1969	2652	3322	4001	4682	5354	6026	6697
SNT	Migration	4	267	621	1309	1990	2674	3350	4037	4710	5375	6065	6726
EDD	Migration	4	276	631	1315	1988	2667	3369	4021	4707	5376	6052	6733
LNT	Sharing	11	277	647	1305	1976	2651	3313	3967	4632	5313	5975	6627
SNT	Sharing	11	266	618	1278	1946	2594	3273	3936	4597	5276	5947	6610
EDD	Sharing	11	259	624	1293	1961	2614	3281	3955	4614	5287	5963	6623
LNT	Resident	13	308	702	1455	2214	2962	3703	4450	5226	5985	6739	7513
SNT	Resident	13	304	705	1452	2214	2980	3731	4488	5261	6027	6776	7534
EDD	Resident	13	308	719	1467	2248	2999	3749	4504	5277	6019	6791	7557

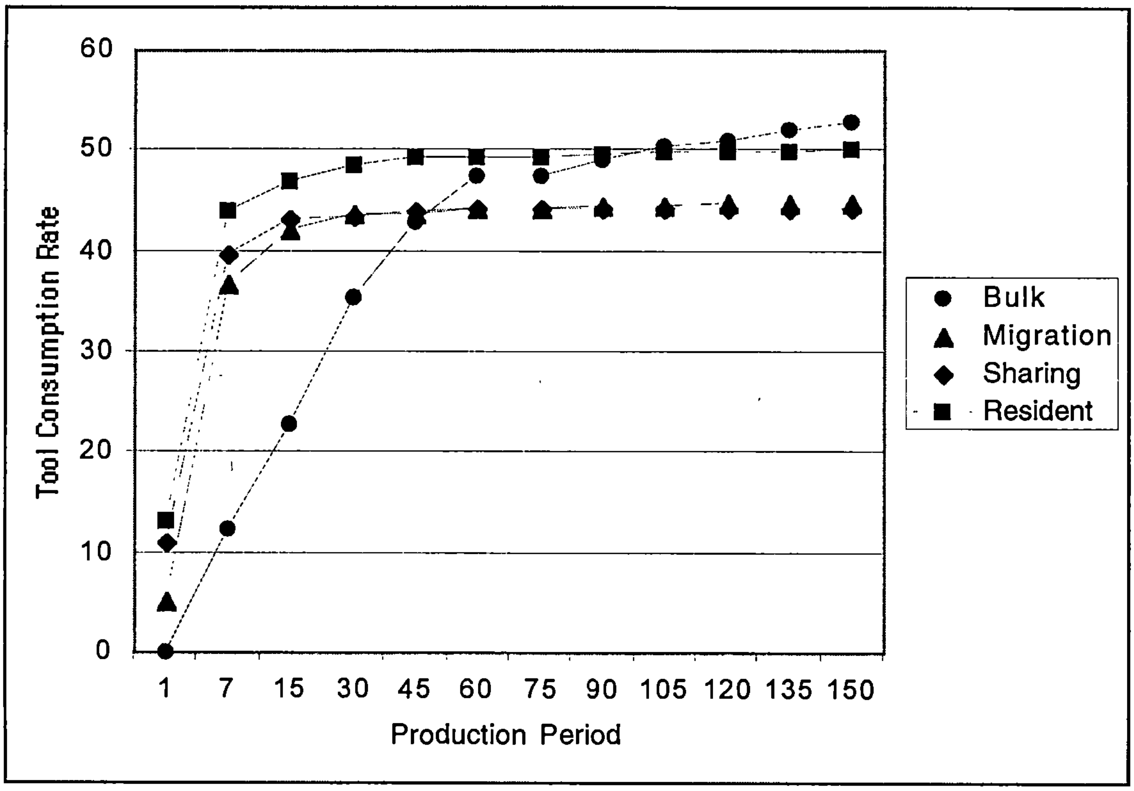

Figure 4.7. Tool Consumption Rates for Largest Number Tools Rule

migration. After period 120, the bulk exchange exceeds resident tooling. Since toolkits are not shared between part-types, the rate of tool consumption is lower during the early production periods. Each part-type has a toolkit. Part-types arrive in the system, and the tools in their toolkits are gradually incremented for usage. Since 14 of 25 part-types are being randomly selected, all 25 part-types are not able to visit the system during a given production period. So when part-types reappear during subsequent production periods, their toolkits are gradually incremented for tool usage.

All tools in the toolkit eventually expire. An expired toolkit is replaced with new tools for a respective part-type. As part-types frequent the machining center, a system develops; new toolkits, partially used toolkits, and toolkits on their last machining cycles are continually utilized until the end of the production run. As new toolkits are being used, other toolkits are in the process of expiring. This cycle continues until the end of the production run. Thus, over time, tool usage accumulates and subsequently expires. This explains the increase in tool usage with the bulk exchange during the middle and latter course of the production run. Therefore, during short production runs, the bulk exchange policy may be preferred over the other policies with respect to lowering tool consumption rates.

Since tool sharing and tool resident tooling share tools within a production period, higher consumption rates would be realized during the earliest production periods. This explains why tool sharing and resident tooling have higher consumption rates than tool migration and bulk exchange during the early production periods.

Tool sharing has the lowest consumption rates from periods 105 through 150. During these periods, the rates are slightly lower than for the rates for tool migration. This strategy appears to be preferred during these production periods. During production periods 1 through 15, bulk and migration policies produce the lowest consumption rates. With these policies, parts are randomly assigned to machines.

During these periods, tool sharing and resident tooling produce higher consumption rates; their policies are based on group technology to exploit tool commonality. Thus, randomly assigning parts to machines may produce low tool consumption rates during short production runs.

The trend for the consumption rates for resident tooling increases and then levels out after period 45. After this period, the tool consumption rates do not vary significantly. With regard to tool sharing, the trend increases and levels after period 60, with no significant variation between rates during subsequent periods. For tool migration, like tool sharing, the trend increases and then levels after period 60, with no significant variation between the remaining periods. The trend for bulk exchange increases to period 60 and then gradually increases until the end of the production run.

4.8.2 SMALLEST NUMBER OF TOOLS

Figure 4.8 shows the results of the tool consumption rates for each tooling policy under the smallest number of tools rule. Between periods 1 and 7, the bulk exchange has the lowest tool consumption rates, followed by tool migration, tool sharing, and resident tooling, respectively. After production period 75, tool sharing has the lowest consumption rates, followed by tool migration, bulk exchange, and resident tooling, respectively. After period 150, the bulk exchange strategy has the highest consumption rates and tool sharing has the lowest rates.

Resident tooling has the highest consumption rates from period 1 through period 75. The bulk exchange has the lowest consumption rates from periods 1 through 45. After period 60, the bulk exchange exceeds tool sharing and tool migration. After period 120, the bulk exchange exceeds resident tooling. Bulk exchange policy may be preferred during these early production periods. Tool sharing has the lowest consumption rates after periods 60 through period 150. This policy appears to be preferred during these

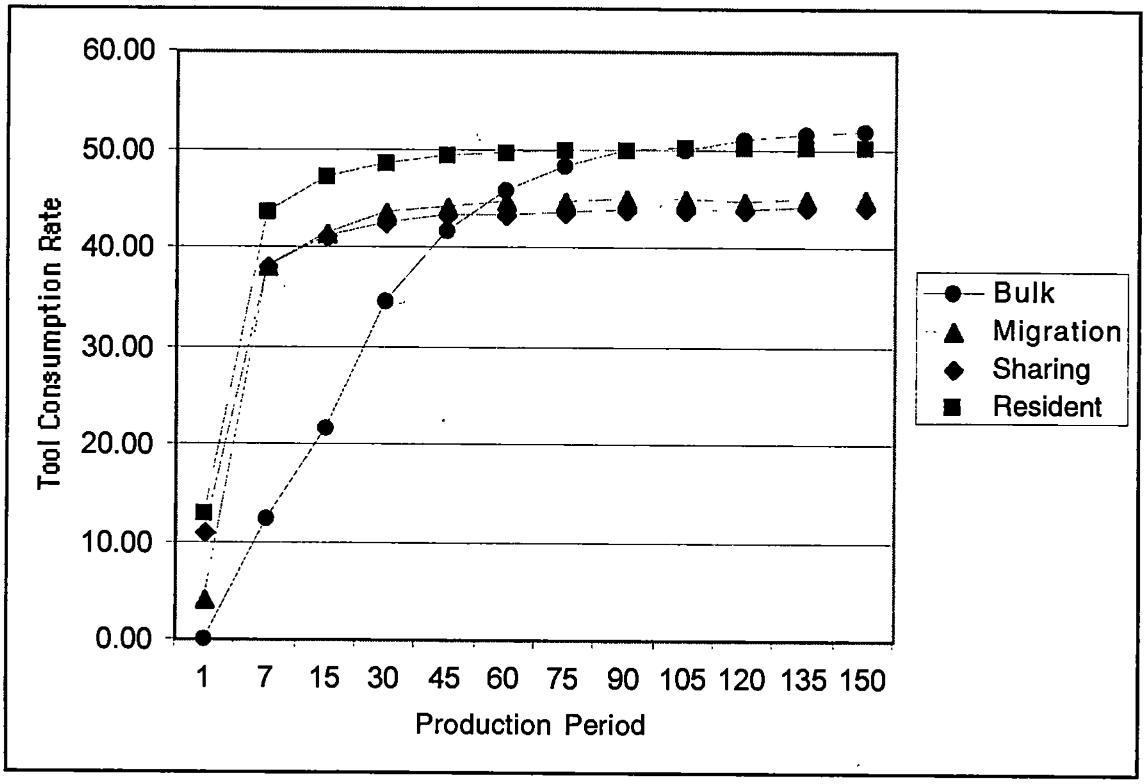

Figure 4.8. Tool Consumption Rates for Smallest Number Tools Rule

periods of production. During production periods 1 through 7, bulk and migration policies produce the lowest consumption rates. Like the LNT rule, randomly assigning parts to machines produces the lowest tool consumption rates during the earlier periods for this production. The consumption rate trend for resident tooling increases to period 60 and then remains steady until period 150. With regard to tool sharing, a steady tool consumption rate is met starting at 45. The trend for tool migration increases and then levels at period 45. The trend for bulk exchange increases sharply to period 90 and then gradually increases to period 150.

4.8.3 EARLIEST DUE DATE

Figure 4.9 shows the results for the tool consumption rates for each tool policy and earliest due date rule. The results show that the bulk exchange has the lowest tool consumption rates from periods 1 through 30. Resident tooling has the highest consumption rates from periods 1 through 75. However, after period 75, the bulk exchange produces the highest consumption rates. Tool sharing has the lowest tool consumption rates from periods 45 through 150. As shown in the Figure 4.9, the rates for tool sharing are slightly lower than the rates for tool migration during periods 15 through 150.

The tool consumption rate trends for sharing, migration, and resident tooling increase and level after production period 45. The consumption rate trend for the bulk exchange strategy increases until production period 90. Then, there is a gradual decrease, followed by an increase until the end of the production run.

With respect to the part-type selection rules, each rule produced similar results. The similar findings are primarily due to the small variation in the number of cutting tool requirements for each part-type.

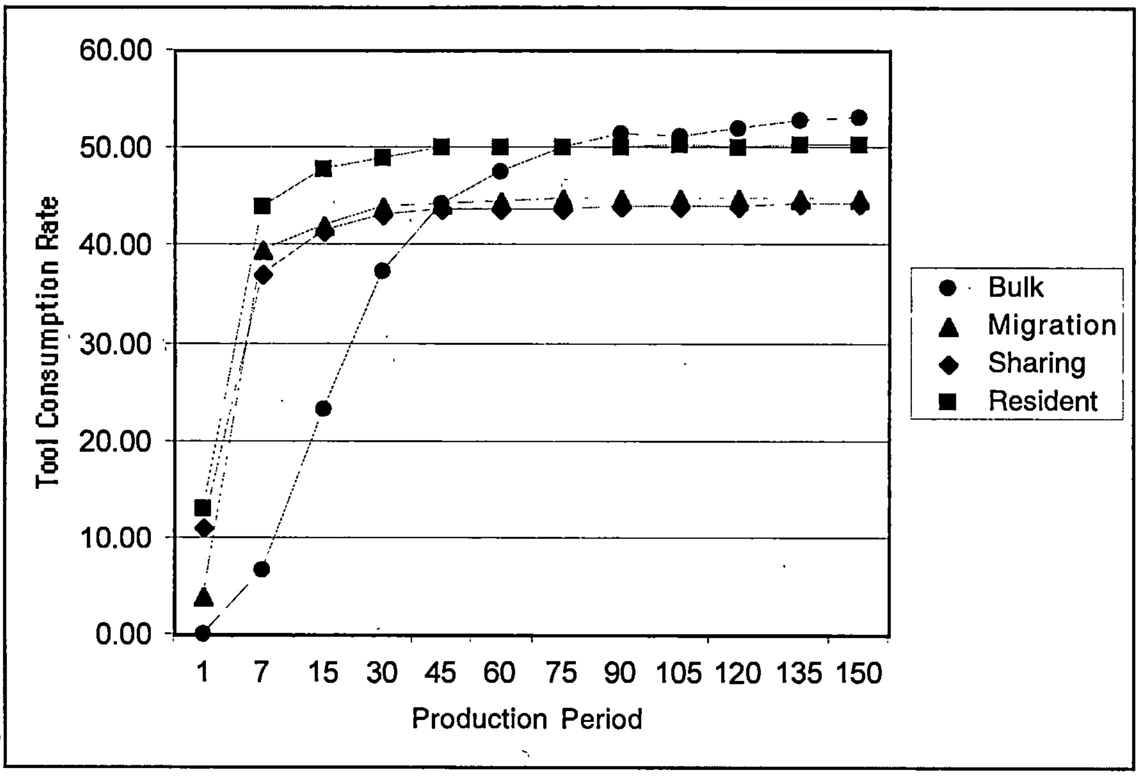

Figure 4.9. Tool Consumption Rates for Earliest Due Date Rule

4.9 SUMMARY, COMPARISON, AND DISCUSSION OF RESULTS

The section will provide a summary of the findings for each of the five performance measures, the average tooling inventory, and tool consumption rates. Also, this section will compare specific aspects of this study and the study that was conducted by Amoako et al. [3]. In that study, the average processing time was 8 hours with an average of 3 cutting tools per part-type. For this study, the average processing time is 2 hours with an average of 10 cutting tools.

Table 4.20 shows the significant levels of the factors and their interactions on the performance measures for this study and the study conducted by Amoako et al. [3]. Table 4.20 shows that tooling policy was significant on all performance measures for both studies. Prior research showed that part-type selection was significant on the percent of parts late and the mean lateness. For this study, the part-type selection rule was significant on all performance measures, except for machine utilization. With regard to factor interaction, prior research showed that factor interaction was significant only on the percent of parts late. For this study, factor interaction was significant on the percent of parts late as well as the mean lateness. [3]

4.9.1 MEAN FLOWTIME

A part's flowtime is affected by the part's processing time, release rate, and move time. With respect to the mean flowtime, tool sharing and the bulk exchange outperformed resident tooling and migration. There was no statistical difference between the average flowtimes for tool sharing and the bulk exchange for all levels of part-type selection rule. Tool migration had a lower mean flowtime than resident tooling. However, both policies resulted in high mean flowtime values because they require an increase in tool changing activities. Tools are changed at the end of a part's

Table 4.20. Summary of Significant Levels of ANOVA Procedures

Performance Measure	Tool Policy (A)		Selection Rule (B)		Interaction (A*B)	
	Prior Research	*This Study*	*Prior Research*	*This Study*	*Prior Research*	*This Study*
Mean Flowtime	0.001	0.05	NS	0.05	NS	NS
Machine Util.	0.001	0.05	NS	NS	NS	NS
Robot Util.	0.001	0.05	NS	0.05	NS	NS
Percent Late	0.050	0.05	0.050	0.05	0.05	0.05
Mean Lateness	0.001	0.05	0.001	0.05	NS	0.05

NS = not significant at 0.05 level

machining cycle. The tools migrate to allow new tools to be loaded in the tool magazine for new part processing. Because of the increased tool changing requirements, parts are delayed. Therefore, their flowtimes through the system are increased.

In the research conducted by Amoako et al. [3], the bulk exchange outperformed the other policies for all three levels of part-type selection rules. Also, for that study, tool migration outperformed tool sharing for all selection rules. For this study, the unanticipated findings show that the bulk exchange does not outperform tool sharing when utilizing an average processing time of 2 hours and increased tooling requirements. In addition, tool migration had a higher mean flowtime than tool sharing. For both studies, resident tooling had the highest mean flowtimes for all part-type selection rules. Also, when priority was assigned to the SNT, bulk, migration, and resident policies had slightly lower flowtimes when comparing part selection rules. Prior research [3] showed that part-type selection rules were not significant with respect to the mean flowtime. However, in this study, part-type selection rules were significant at the 0.05 level on the mean flowtime.

4.9.2 AVERAGE MACHINE UTILIZATION

Part processing times and the loading and unloading of parts affect a machine's utilization. Tool migration had the highest average machine utilization followed by bulk exchange, tool sharing, and resident tooling, respectively, for all part selection rules. Parts are randomly assigned to machines with bulk exchange and tool migration. Therefore, the machine utilization is evenly distributed between machines. The high machine utilization for these tooling policies is attributed to (1) the even distribution of the total part processing times between machines, and (2) parts being delayed at machines because of the unavailability of the material handling unit. The robot is busy changing tools or parts at other machines in the system. Machine utilization is low for tool sharing and resident tooling because of the need to exploit common tool usage. Part-types are routed to specific machines. The utilization between machines is not balanced because the total processing times between machines are not evenly distributed during the production period. Some machines are utilized more than other machines because their total part processing times are higher. [65]

Like this study, prior research [3] showed that tool migration produced the highest machine utilization [3]. However, unlike this study, the remaining three policies resulted in similar average machine utilization [3]. For both studies, the part-type selection rule and the interaction between the main effects were not significant at the 0.05 level.

4.9.3 ROBOT UTILIZATION

Robot utilization depends on part and tool loading and unloading activities. Tool sharing produced the lowest robot utilization for each part-type selection rule. Resident tooling had the next lowest robot utilization, followed by bulk exchange and tool migration, respectively. Tool activities are decreased with tool sharing because parts are routed to machines that contain all of their tooling requirements. Expired tools are changed at the end of the production period. Tool sharing, based on group technology principles, decreases the frequency of tool changing activities. The frequency of tool changing activities increases with resident tooling because partial toolkits and any expired resident tools are changed after the completion of a part. The difference between resident tooling and tool migration is that more tools are being loaded and unloaded with tool migration. The frequency of tool changing is greater for tool migration than for bulk exchange. With bulk exchange, tools are changed at the end of the production period. With tool migration, a part's tools are changed after part completion.

Amoako et al. [3] showed that with an average processing time of 8 hours and fewer tool requirements, bulk exchange and tool sharing produced the lowest robot utilization. For this study, however, with an average processing time of 2 hours and increased tooling requirements, tool sharing outperformed the other tooling policies.

4.9.4 PERCENT OF PARTS LATE

With regard to the percent of parts late, tool sharing produced the lowest percentages of late parts for all part-type selection rules. Tool sharing experienced the lowest percentage when priority was assigned to the LNT rule. Prior research [3] showed that the interaction between tooling policy and part selection rule was significant. Also, for that study, the bulk exchange had the lowest percentage of late parts for all part-type selection rules. For this study, the bulk exchange has the next lowest percentage of parts not meeting their due date requirements. However, the Bonferroni multiple comparison tests indicated that, with the EDD rule, tool sharing and bulk exchange are not statistically different. Tool migration and resident tooling produced the highest percentage of parts late. The Bonferroni comparison tests showed that they are not significantly different for all levels of part-type selection rules. When comparing part-type selection rules, the EDD rule produced the highest percentage of late parts for each tooling policy. Parts are experiencing delays due to part processing times, part release rates, and the unavailability of the material handling unit which is used for loading and unloading parts and tools.

4.9.5 MEAN LATENESS

With respect to mean lateness, the bulk exchange outperformed the other policies for all levels of part-type selection rules. Resident tooling produced the highest mean lateness for all selection rules. When priority is assigned to LNT and SNT rules, tool migration produces a lower mean lateness than tool sharing. However, when the EDD rule is assigned, the average mean lateness is lower for tool sharing. The Bonferroni comparisons show that tool sharing and tool migration are not statistically different when priority is assigned to the LNT rule. Also, the Bonferroni method shows that, with the EDD rule, bulk exchange and tool sharing are statistically different.

When comparing part-type selection rules, the EDD produced the lowest mean lateness value for all tool policies. Likewise, when comparing part-type selection rules, prior research showed that the EDD produced the lowest mean lateness value for all tool policies [3]. Also, prior researchers showed that the bulk exchange outperformed the other policies, and resident tooling produced the highest mean lateness [3], which is consistent with this study.

4.9.6 AVERAGE TOOL CONSUMPTION RATE

For all part-type selection rules, the bulk exchange produced the lowest tool consumption rates than the other tooling policies, between periods 1 through 45. Therefore, the bulk exchange would probably be preferred for short production runs. For all part-type selection rules, the bulk exchange and tool migration produced lower tool consumption rates than for sharing and resident tooling, during periods 1 through 5. This also suggests that randomly assigning parts to machines during short production runs may produce lower tool consumption rates.

For long production runs, tool sharing produced the lowest tool consumption rates during periods 105 through 150 for LNT, periods 60 through 150 for SNT, and during periods 45 through 150 for the EDD rule. This suggests that tool sharing is preferred for long production runs when the objective is to minimize tool consumption.

However, with tool sharing, expired tools are changed at the end of the production period. This may contribute to the low tool consumption rates because some tools are being used beyond their tool life before the end of the production period. Also, this could affect product quality because some parts are being machined with used or expired tools.

4.9.7 AVERAGE TOOL INVENTORY

For all part-type selection rules, resident tooling had the lowest average tool inventory per production period, followed by tool sharing. Bulk exchange and tool migration showed similar average tool inventory requirements. The results show that randomly assigning parts to machines produce a higher average tool inventory per period. The bulk and migration policies provide a copy of each tool for each part visiting a machine per production period. Therefore, both strategies would require a higher average tool inventory when compared to sharing and resident tool policies. Because they are based on group technology, sharing and resident tooling reduce cutting tool inventory by exploiting common tool usage. This reduces tool duplication and minimizes tooling cost.

4.9.8 DISCUSSION OF RESULTS

Tool migration and bulk exchange produced high machine and robot utilization. However, the machine utilization and robot utilization were low for tool sharing and resident tooling. The flowtimes for tool migration and resident tooling were higher than for bulk exchange and tool sharing because tools are changed after each machining cycle. Thus, parts are delayed in the system due to the frequency of tool changing activities. The flowtime for bulk exchange was not affected by the high machine and robot utilization because tools are changed at the end of the production period.

The increased tool changing activities affect the percentage of parts late. Tool migration and resident tooling had the highest percentages of late parts. Both polices require tools to migrate after each machining cycle. Since parts are contending for the materials handling unit with tool changing activities, their flowtimes increase. As a result, this increases the probability of parts not meeting their due dates. Therefore, tooling polices that require tools to migrate between machining cycles have a greater effect on the percent of parts not meeting their earliest due date requirements.

The mean lateness is higher for tool sharing and resident tooling. With tool sharing, minimizing flowtime does not minimize mean lateness. Tool sharing produced a low mean flowtime. However, tool sharing produced a higher mean lateness than bulk exchange (on all part selection rules) and tool migration on LNT and SNT rules. However, with EDD assigned priority, tool sharing produced a lower mean lateness than tool migration. Also, bulk exchange produced low mean flowtime values and the lowest mean lateness values. This implies that tooling policies that produce low part flowtimes may not necessarily produce parts with low mean lateness values.

Although tool sharing produced high mean lateness values, this tool allocation strategy produced the lowest percentage of late parts, followed by bulk exchange on all part-type selection rules. This suggests that the "low percentage of late parts" are experiencing longer delays at their machines. Since the robot utilization is low for tool sharing, this implies that the mean lateness values are attributed to uneven part distributions at machines. For example, under tool sharing and resident tooling, parts are routed to specific machines. Some machines receive more parts than other machines during the same production period. This creates an imbalance between machines because the cumulative processing times between machines are different. Some machines are still processing parts while other machines have completed part processing. The parts that are still in the system have an increased probability of not meeting their due date requirements. The additional time spent in the system increases the average lateness of all parts. The robot utilization for resident tooling is higher than for tool sharing. This suggests that the percent of parts late and the mean lateness are higher for resident tooling than for tool sharing. This study shows that resident tooling has the highest mean lateness values for all part-type selection rules. Therefore, uneven machine utilization affects the mean lateness

Cutting tool requirements and the rate of expired tool usage were used to determine tool inventory levels and tool consumption rates per production period, respectively. The average tool inventory per period for bulk exchange and tool migration was higher than for tool sharing and resident tooling. However, bulk exchange produced the lowest tool consumption rates during the early production periods. Tool sharing produced the lowest tool consumption rates during the middle and later production runs, followed by tool migration. Tool sharing and resident tooling produced high tool consumption rates during the short production runs. Resident tooling had higher tool consumption rates than tool sharing and tool migration. However, resident tooling had the lowest average tool inventory per period for all tool allocation policies.

Nevertheless, with respect to minimizing tool consumption, tool sharing would be appropriate for an FMS. Flexible manufacturing systems are automated batch-manufacturing systems that are primarily used for medium-volume batch production [10, 23, 74, 75]. These systems are also effective for high-volume production [77]. DeGarmo et al. [76] state that the annual production volume for an FMS is usually in the range of 3,000 and 10,000 parts. This implies that production periods are extended over periods of time. Therefore, tool sharing would be effective for an FMS over the long term when the objective is to minimize cutting tool consumption.

4.9.9 SUMMARY CONCLUSIONS

Table 4.21 shows the relative rankings of the four tooling polices on the five performance measures for all levels of the part-type selection rules. The rankings are

Table 4.21. Relative Ranking of Performance Measures

Policy	Flowtime			Mach. Util.			Robot Util.			% Late			Time Late		
	L	*S*	*E*	*L*	*S*	*E*	*L*	*S*	*E*	*L*	*S*	*E*	*L*	*S*	*E*
Bulk	1	1	1	3	3	3	3	3	3	2	2	1	1	1	1
Migration	2	2	2	4	4	4	4	4	4	3	3	2	2	2	3
Sharing	1	1	1	2	2	2	1	1	1	1	1	1	2	3	2
Resident	3	3	3	1	1	1	2	2	2	3	3	2	3	4	4

L = Largest Number of Tools

S = Smallest Number of Tools

E = Earliest Due Date

based on the analysis of the data and the results from Bonferroni statistical comparison tests. The ranking of 1 is best while the ranking of 4 is worst.

With respect to the five performance measures, the results of this study suggest that tool sharing is the preferred tooling policy, followed by bulk exchange, resident tooling, and tool migration, respectively. Tool sharing outperformed the other tool policies on two performance measures: robot utilization and percent of parts late. Resident tooling produced the lowest average machine utilization, followed by tool sharing. However, resident tooling did not outperform tool sharing with respect to flowtime. Tool sharing and bulk exchange produced the lowest flowtimes; they were not statistically different according to the Bonferroni comparison tests. Bulk exchange outperformed tool sharing on the mean lateness performance measure.

With respect to part-type selection rules, this study showed that no rule outperformed another on all performance measures. This result is consistent with the study conducted by Amoako et al [3]. With respect to the percentage of parts late, the LNT and SNT rules produced lower percentages of parts late than the EDD rule for all tooling polices.

Based on the pilot study results and a survey conducted by Ramesh et al. [7], meeting due dates was the most important scheduling criteria for FMS users. For this study, under the EDD rule, tool sharing produced the lowest percentage of parts late. In addition, for all tooling policies, the EDD rule produced lower mean lateness values than LNT and SNT rules. Tool sharing had the second lowest mean lateness value under this rule. For this study, the EDD for a part-type was equal to the part's arrival time into the system plus a random number that was generated using a uniform distribution from 120 minutes to 480 minutes: EDD = TNOW + UNIF(120, 480). The first value in the distribution is the average processing time for all part-types. The second value in the distribution is based on an 8-hour production period.

Resident tooling had the lowest average tool inventory per period followed by tool sharing. Bulk exchange produced the lowest tool consumption rates during the early periods of production. Tool sharing produced the lowest consumption rates during the middle and later periods of production. However, tool sharing would be more effective for an FMS over the long term because of the reduction in tool consumption rates. The overall results and analysis from this study suggest that tool sharing would probably be the preferred tool allocation policy. The prior research [3] showed that bulk exchange was the preferred tooling policy with longer processing times and fewer tooling requirements.

CHAPTER 5

CONCLUSIONS AND IMPLICATIONS

5.1 CONCLUSIONS

This chapter will present the main conclusions, managerial implications, limitations of this research, and suggestions for further research. This research was conducted to study the impact of four tool allocation strategies on five performance measures, contingent upon three part-type selection rules. In addition, the tracking of tools was also included to determine the average tool inventory and tool consumption rates for each tool allocation policy and part-type selection rule after each period of production. The four tool allocation policies consisted of bulk exchange, tool migration, tool sharing, and resident tooling. The five performance measures consisted of the average flowtime of parts, the average machine utilization, robot utilization, percentage of part late, and mean lateness.

The null hypotheses were stated for each performance measure. The analysis of variance was the statistical procedure used to evaluate the impact of the factors and their combinations on the selected performance measures. Graphical comparison charts and the Bonferroni multiple statistical comparison tests were used to compare and identify the differences between the tooling policies for each performance measure and part-type selection rule. The production period for this study was based on an 8 hour shift. The average processing time was 2 hours based on an Erlang distribution. Each part-type required an average of 10 cutting tools and 9 operations.

The results of this study showed that there were significant differences in the means of the treatment combinations for each performance measure. Therefore, each null hypothesis was rejected at the 0.05 level of significance for each performance measure. The results also show that all tooling policies were significant at the 0.05 level of significance. In addition, the part-type selection rules were significant on all performance measures except for machine utilization. Furthermore, the interaction was significant on the percentage of parts late and the mean lateness.

Given the evidence presented in Chapter 4, Results and Analysis, the conclusions drawn from this study suggest that clustering tools based on group technology is the preferred method for allocating tools to machines. Specifically, tool sharing was the preferred tool allocation strategy. Under this policy, a cluster of cutting tools is assigned to each machine's tool magazine. Part-types are routed to specific machines based on their commonality of tool usage. Tool sharing produced low part flowtimes, low machine utilization, and low robot utilization. Also, tool sharing produced the lowest percentage of late parts for all part-type selection rules. In addition, tool sharing produced the second lowest average tool inventory requirement per period. The benefits for using tool sharing outweigh the contributions of the other tooling policies.

The success of tool sharing is primarily attributed to the reduction in tool changing activities. The tool clusters are loaded in the magazine before the production period. The expired tools are changed at the end of the production period. After parts are processed, they exit the FMS without significant delays due to the reduction in tool changing activities.

The research conducted in this study extends the work of Amoako et al. [3]. The prior researchers showed that randomly assigning parts to machines was preferred with long processing times and fewer tool requirements. In that study, bulk exchange outperformed the other policies. Tools are changed at the end of the production period. In that study, the average processing time was 8 hours based on an Erlang distribution. Each part-type required an average of 3 cutting tools and 4 operations. Both studies were compared in Chapter 4, Section 4.9. The results differ with respect to the selection of a tool strategy. Their differences are primarily due to the different part processing times and tooling requirements.

Also, the following observations and findings were made in this study:

(1). Tooling allocation policies that require tools to migrate produce high part flowtimes. With tool migration and resident tooling, tools are changed at the end of the part's machining cycle. Parts are delayed in the system because of the frequent tooling changing activities. Parts must contend for the material-handling robot with tool loading and unloading.

(2). Tool allocation strategies based on tool clustering methods reduce the utilization of resources. Tool sharing and resident tooling produced the lowest average machine utilization and robot utilization. Parts are assigned to machines based on their commonality of tool usage.

(3). With respect to the tool consumption, randomly assigning parts to machines during short production runs produces lower tool consumption rates. This study shows that bulk exchange is preferred during early production periods because the rate of tool usage is minimized. During the middle and later production periods, tool sharing is the preferred tool allocation policy because this strategy produces lower tool consumption rates. Tool sharing would be more effective for an FMS over the long term because they are typically characterized as medium-volume to high-volume part production systems which require extended periods of production [74, 75, 76, 77].

(4). Although resident tooling produced the highest tool consumption rates, this policy produced the lowest average tool inventory per production period followed by tool sharing. This study concluded that grouping tools based on the commonality of tool usage results in a lower average inventory per production period.

(5). Uneven distribution of part-types to machine under tool clustering methods affected the average mean lateness of part-types. The mean lateness was high for tool sharing and resident tooling. However, tool sharing produced the lowest percentage of late parts for all part-type selection rules. Because robot utilization and machine utilization are low, this implies that that the mean lateness values may be attributed to uneven part distributions at machines.

(6). No part-type selection rule outperformed another on all performance measures. The EDD rule produced the lowest mean lateness values for all tooling policies. However, the EDD rule produced the highest percentage of late parts for all tooling policies and selection rules. These results are consistent with prior research [3]. For this study, under the EDD rule, tool sharing produced the lowest percentage of parts late for all tooling policies.

(7). Tool allocation policies that produce low mean flowtimes may not produce low mean lateness values. This depends on the chosen part-type selection rule. Tool sharing produced low flowtimes but high mean lateness values under LNT and SNT rules. However, tool sharing produced a low mean lateness value under the EDD rule. Bulk exchange produced the lowest mean lateness values for all part-type selection rules.

5.2 IMPLICATIONS

This section discusses some of managerial implications with respect to the results from this study. The results of the study have shown that forming tool clusters based on the part-types that share common tooling requirements is preferred. This method is preferred over randomly assigning part-types to machines, as with bulk and migration tooling policies.

Clustering tools based on the commonality of tool usage requires developing clustering algorithms to successfully assign parts to machines. This may require the purchase of computer software for tool and part assignments. This also facilitates tool inventory for sharing. Once the cluster of cutting tools is determined, the inventory level can be established. Gray et al. [10] stated that in general three tools are required for each cutting tool: one at the machine, one waiting to be used, and one being refurbished. This is consistent with interviews with manufacturing managers. This significantly minimizes the tool inventory requirements for tool sharing when compared to bulk exchange and tool migration. Also, tool sharing produced low tool consumption rates for periods of production that are more applicable for an FMS. Tool sharing is an effective tool allocation strategy to achieve a reduction in inventory and the associated cost [22, 38, 61].

The levels of control and inventory requirements are minimized with tool sharing. Hankins and Rovito [43] conducted a study of four tooling strategies and their tool inventory and control levels. In that study, tool sharing was the second tooling strategy that required less control and inventory requirements. The control refers to software for tool monitoring and tool allocation to machines [43].

With regard to magazine capacity, Amoako-Gyampah and Meredith [41] stated that a limited magazine capacity constrains the number of tools that can be mounted on the machine due to the limited number of tool slots. This is more applicable to tool strategies like bulk exchange because tools are not removed from the tool magazine until the end of the production period. Khator and Leung [22] stated that other tool allocation methods must be considered to address the limitations of tool magazine capacity. For tool sharing, the capacity of a machine's tool magazine is dependent upon the total number of tools in the tool cluster that are needed for that machine. Tool sharing reduces the number of tool slots needed because parts share tools. This reduces the need for a large tool magazine. Thus, cost savings would be realized because of the reduced magazine capacity requirements.

The results of this study show that tool sharing produced low machine and robot utilization. Some benefits for low machine utilization are as follows:

- New part-types may be introduced into the FMS. This increases the flexibility of the FMS.

- Parts may be re-routed to different machines because of machine downtime due to machine failure.

- Lower machine utilization will allow for pre-maintenance checks for calibration and other machine analysis.

The low robot utilization may be favorable for the following reasons:

- The maintenance cost for the materials handling robot is reduced.

- The frequency of tool changing activities is reduced. Therefore, part flow through the system is not delayed because of the unavailability of the material-handling unit.

- Low robot utilization may allow an additional CNC machine to be added to the cell to increase productivity.

Management must be concerned with the uneven distribution of parts to machines when using tool sharing. The cumulative processing times of parts between machines during a production period are not the same. Gray, Seidman, and Stecke [10] noted that balancing the utilization of machines or workloads may not be suitable for flexible manufacturing environments because this may reduce the system's flexibility. However, uneven machine utilization may affect the average mean lateness of parts. Tool sharing had the second lowest mean lateness value under the EDD rule. In addition, under the EDD rule, tool sharing produced the lowest percentage of parts late for all tooling policies. Based on conversations with metal cutting manufacturers and based on the survey conducted by Ramesh et al. [7], meeting due dates was the most important scheduling criteria for FMS users. The EDD rule produced the lowest mean lateness values with all tooling policies. Therefore, if tool sharing is utilized, then meeting due date requirements may be realized with part-selection based on the EDD rule.

5.3 OTHER LIMITATIONS OF THE STUDY

This section will discuss the limitations with respect to this study. The results of this research were determined by the configuration of the FMS modeled. Also, the results were dependent on the parameters under study. There were 12 simulation models developed. Each model represented the 12 treatment combinations of tooling policy and part-type selection rule. Also, the processing times of part-types were limited to an average of 2 hours. The processing times were based on an Erlang distribution.

Other limitations include the following:

- This study was limited to 30 unique cutting tools and 25 unique part-types. The variability in the number of unique tools and part-types was not evaluated in this study.

- A tool's magazine capacity was limited to 50 tool slots. Tool magazine capacity requirements are dependent on the manufacturing process and the flexibility of the FMS as well as cost considerations.

- The lifetime of a tool was limited to 30 minutes. The assumption was that during the machining process, adequate coolant, feed rates, and spindle speeds were utilized in order to maximize tool usage. A tool's usage was determined by a part's processing time divided by the number of tools required for that part-type. Tools were not monitored for premature breakage. Sometimes, during machine processes, cutting tools break due to tool defects.

- This study was limited to three part-type selection rules. Other part-type selection rules were not evaluated in this study.

- Machine downtime due to machine failure or machine maintenance was not evaluated in this study.

- The FMS modeled was a static and not dynamic system. New part-types were not introduced into the system during the production period. This decreases the flexibility of the flexible manufacturing system.

- The earliest due date (EDD) for a part was equal to the part's arrival time into the system plus a random number that was generated using a uniform distribution from 120 minutes to 480 minutes: EDD = TNOW + UNIF(120, 480). The random number range was limited to a minimum time of 120 minutes (2 hours) and a maximum time of 480 minutes (8 hours).

- According to researchers in the literature, under the tool sharing policy, tools are changed at the end of the production period [3, 38, 40, 41, 43, 65]. This could have an affect on product quality, especially if some cutting tools are being used beyond their expected tool life before the end of the production period.

5.3 RECOMMENDATIONS FOR FURTHER RESEARCH

This section will include the recommendations for further research and extensions to this study. The areas for further research include the following:

- Increase or decrease the variability of part-types, part processing times, and tooling requirements to determine the impact on performance measures on other FMS manufacturing environments.

- Develop different hybrids or mixtures of tool allocation strategies to determine their impacts on performance measures.

- Evaluate the FMS with respect to machine downtimes due to machine failures.

- Evaluate the FMS with respect to fixture changes during or after the production periods.

- Use different part-type selection rules such as longest processing time (LPT), shortest processing times (SPT), and first in first out (FIFO).

- Analyze the FMS system with the introduction of new part-types during the production period. For this study, the system was static such that part-types were determined prior to the beginning of the production period. A dynamic system will allow new part-types to be introduced into the system during the production period.

- Extend the minimum time limit for the EDD rule beyond 2 hours to determine the affect on the "percent of parts late" performance measure. As illustrated in Figure 4.4, located on page 105, the percent of parts late is higher under the EDD rule than for the LNT and SNT rules. Extending the minimum EDD limit will increase the average EDD time and reduce the percent of parts late. This change is expected to result in the EDD rule being comparable with the LNT and SNT rules.

- Change expired tools, for tool sharing, after each machining cycle to determine the affect on tool consumption rates for the entire production run. Compare the results with other tool allocation policies with respect to tool consumption.

REFERENCES

REFERENCES

[1] Carrie, S., Adhami, E., Stephens, A., and Murch, C., "Introducing a flexible manufacturing system," International Journal of Production Research, 1984 Vol. 22, No. 6, pp. 907-916.

[2] Tomek, P., "Tooling strategies related to FMS management," FMS Magazine, 1986, Vol. 4, pp. 102-107.

[3] Amoako-Gyampah, K., Meredith, R., and Raturi, A., "A comparison of tool management strategies and part selection rules for a flexible manufacturing system," International Journal of Production Research," 1992, Vol. 30, No. 4, pp. 733-748.

[4] Stecke, K. E., "Formulation and solution of nonlinear integer production planning problems for the flexible manufacturing systems," Management Science, 1983, Vol. 29, pp. 273-288.

[5] Rajagopalan, S., 1986, "Formulation and heuristic solutions for parts grouping and tool loading in flexible manufacturing systems," Proceedings of the Second ORSA/TIMS Conference on flexible manufacturing systems: Operations research Models and Applications, Stecke, K. E. and R. Suri (eds.), pp. (311-320).

[6] Hwang. S., "A constraint-directed method to solve the part selection problem in flexible manufacturing systems planning stage," Proceedings of the Second ORSA/TIMS Conference on flexible manufacturing Systems: Operations research Models and Applications, Stecke, K. E. and R. Suri (eds.), pp. (297-309).

[7] Ramesh, R., Smith, M. L., Dudek, R. A., and Blair, E. R., 1986, "Characteristics of U.S. flexible manufacturing systems: a survey," Proceedings of the Second ORSA/TIMS Conference on flexible manufacturing Systems: Operations research Models and Applications, Stecke, K. E. and R. Suri (eds.), pp. (477-486).

[8] Whitney, C. K., and Gaul, T. S., "Sequential decision procedures for batching and balancing in FMSs," Annals of Operations research, Vol. 3, pp. 301-316.

[9] Suri, R., and Whitney, C. K., "Decision support requirements inflexible manufacturing," Journal of manufacturing systems, Vol. 3, pp. 61-69.

[10] Gray, A. E., Seidmann, A., Stecke, K. E., "A synthesis of decision models for tool management in automated manufacturing," Management Science, Vol. 39, No. 5, May 1993.

[11] Cummings, S., "Developing integrated tooling systems: A case study at Garrett Engine Company," Proceedings of the Fall Industrial Engineering Conference, Boston, MA, 1986.

REFERENCES (Continued)

[12] Stecke, K. E., and Kim, I., "A flexible approach to part type selection in flexible flow system using part mix ratios," International Journal of Production Research, Vol. 29, No. 1, 1991, pp. 53-57.

[13] Tomek, P., "Tooling strategy related to FMS management," The FMS Magazine, Vol. 5, 1986, pp. 102-107.

[14] Graver, T. and Mc Ginnis, L., "A tool provisional problem in an FMS," The International Journal of Flexible Manufacturing Systems, 1989, pp. 239-254.

[15] Chan, B. W., "Tool Management for Flexible Manufacturing," International Journal of Computer integrated manufacturing, 1992, Vol. 5, No. 4&5, pp. 255-265.

[16] DeSouza, R., "Tool-provisioning strategies for flexible manufacturing systems," Robots and Computer integrated Manufacturing, 1997, Vol. 13, No. 1, pp. 31-39.

[17] Hedin, S. R., Philipoom, P. R., and Malhotra, M. K., "A comparison of static and dynamic tooling policies in a general flexible manufacturing system," IIE Transactions, 1997, Vol. 29, pp. 69-80.

[18] Coleman, P., Ozbayrak, M. and Bell, R., "Tool management and job allocation in flexible machining cells. Part 1: Work-oriented strategies," Proceedings of the Institution of mechanical Engineers, Vol. 210, pp. 405-415.

[19] Coleman, P., Ozbayrak, M. and Bell, R., "Tool management and job allocation in flexible machining cells. Part 2: Tool-oriented strategies," Proceedings of the Institute of mechanical Engineers, Vol. 210, pp. 417-427.

[20] Hankins , S. L., Rovito, V. P., "The impact of tooling in flexible manufacturing systems," Second International Machine Tools Conference, 1984, pp. 1.175-1.198.

[21] Eversheim, W. , "Tool management: the present and the future," Annals of CIRP, 1991, Vol. 40, No. 2, pp. 631-639.

[22] Khator, S. K., and Leung, L. C., "Intermediate tooling Requirements Planning for FMS," Journal of Manufacturing Systems, 1994, Vol. 13, No. 1, pp. 9-19.

[23] Chung, C., "Planning tool requirements for flexible manufacturing systems," Journal of Manufacturing Systems, 1991, Vol. 10, No. 6, pp. 476-483.

[24] Hankins, S. L., and Rovito, V. P., "The impact of tooling in flexible manufacturing systems," Second Biennial International Machine Tool Conference, September 1984, pp. 5-13.

[25] Vollmann, T. E., Berry, W. L., and Whybark D. C. (1998). Manufacturing Planning and Control Systems. Irwin, Homewood, Illinois, Second Edition, pp. 115-159.

[26] Pyung-Hoi, K., Tanchoco, M. A., and Talavage, J. J., "Tool requirements in manufacturing systems under dynamic tool sharing," Computers and Industrial Engineering, 1996, Vol. 33, Numbers 3 & 4, pp. 537-540.

[27] Pyung-Hoi, K., Tanchoco, M. A., and Talavage, J. J., "Estimation of Tool Requirements in Manufacturing Systems," International Journal of Production Research, 1998, Vol. 36, No. 6, pp. 1699-1713.

[28] Kumar, K., Mohamed, Z., Motwani, J., and Youssef, M., "A dynamic tool requirements planning model for flexible manufacturing systems," The International Journal of Flexible Manufacturing Systems, 1997, Vol. 9, pp. 307-342.

[29] Berr, A. and Falkenburg, D. R., "Tool management for flexible manufacturing systems," Annals of the CIRP, 1984, Vol. 34, No. 1, pp. 387-390.

[30] Kusiak, A., "Parts and tool handling systems," In Modeling and Design of Flexible Manufacturing Systems," 1986, A. Kusiak ed., Elsevier Science Publication, Amsterdam, pp. 99-109.

[31] Mohamed, Z., M., and Bernardo, J. J., "Tool planning models for flexibility manufacturing systems," Europeans Journals of Operations Research, 1997, Vol. 103, pp. 497-514.

[32] Smolink, D. (1983), Materials Requirement of Manufacturing, New York, Van Nostrand Reinfield Company.

[33] Mohamed, Z. M., and Bernado, J. J., "The relationship between part type demand and FMS loading police," International Journal of Production Research, 1995, Vol. 33, No. 8, pp. 2197-2211.

[34] Stecke, K. E., "Formulation and solution of nonlinear integer production planning problems for flexible manufacturing systems," Management Science, March 1983, Vol. 29, No. 3, pp. 273-288.

REFERENCES (Continued)

[35] Veeramani, D., Upton, D. M., and Barash, M. M., "Cutting tool management in computer integrated manufacturing," The International Journal of Flexible Manufacturing Systems, 1992, Vol. 3, No. 4, pp. 223-230.

[36] Leung, L. C., and Khator, S. K., "Tool automation in computerized manufacturing systems," Material Flow Systems in Manufacturing, 1994, Chapman and Hall, London, pp. 335-367.

[37] Mason, F., "Computerized cutting tool management," American Machinist and Automated Manufacturing, May 1986, Vol. 103, No. 5, pp. 105-132.

[38] Kashyap, A. S. and Khator, S. K., "Analysis of tool sharing in an FMS: A simulation study," Computers in Industrial Engineering, 1996, Vol. 30, No. 1, pp. 137-145.

[39] Gaalman, G. J. and Nawijn, W. M., "Tool sharing in parallel part production," International Journal of Production Economics, 1996, Vol. 46-47, pp. 521-533.

[40] Tsukada, T, K. and Shin, K. G., "Distributed tool sharing in flexible manufacturing systems," IEEE Transactions on Robotics and Automation, June 1998, Vol. 14, No. 3, pp. 379-389.

[41] Amoako-Gyampah, K. and Meredith, J. R., "A simulation study of FMS tool allocation procedures," Journal of Manufacturing Systems, 1996, Vol. 15, No. 6, pp. 419-431.

[42] Cuppan, B. C., "Tool management considerations for cells and FMS," Present at Session O6B: Cutting Tool Management: 3rd Biennial International Machine Tool Technical Conference, September 1986, pp. 6-71 - 6-82.

[43] Hankins, S. L. and Rovito, V. P., "The impact of tooling and flexible manufacturing system," Second Biennial International Machine Tool Technical Conference, September 5-13, 1984.

[44] Bell, R. and DeSouza, R., "A tool cluster based strategy for the management of cutting tools in flexible manufacturing systems," Journal of Operations Management, January 1991, Vol. 10, No. 1, pp. 73-90.

[45] King, J. R., "Machine-components grouping in production flow analysis: An approach using a rank order clustering algorithm," International Journal of Production Research, 1980, Vol. 18, No. 2, pp. 213-232.

[46] Macchiaroli, R. and Riemma, S., "Clustering algorithms to optimize the tool handling system management in an FMS," The International Journal of Flexible Manufacturing Systems," 1996, Vol. 8, pp. 183-201.

[47] Atan, T. S. and Pandit, R., "Auxiliary tool allocation in flexible manufacturing systems," European Journal of Operational Research, 1996, Vol. 89, pp. 642-659.

[48] Saran, S. C. and Chen, C. S., "The machine loading and tool allocation problem in a flexible manufacturing system," International Journal of Operations Research, 1986, Vol. 25, NO. 7., pp. 1081-1094.

[49] Berrada, M. and Stecke, K., "A branch and bound approach for machine and load balancing in flexible manufacturing systems," Management Science, 1986, Vol. 32, No. 10, pp. 1316-1334.

[50] Akturk, S. M. and Avci, S., "Tool allocation and machining conditions optimization for CNC machines," European Journal of Operational Research, 1996, Vol. 94, pp. 335-348.

[51] Agnetis, A., Alfieri, A., Brandimarte, P. and Prinsecchi, P., "Joint job and tool scheduling in a flexible manufacturing cell with no on-board tool magazine," Computer Integrated Manufacturing Systems, 1997, Vol. 10, No. 10, pp. 61-86.

[52] Katayama, H.,"FMS tool change schemes and their characteristics," Computers in Industrial Engineering, 1994, Vol. 27, Numbers 1-4, pp. 75-80.

[53] Melnyk, S. A., "Tool management and control: An introduction," Tool Management and Control: Conference Proceedings, A Two Day Conference on Manufacturing's Ignored Resource, October 12-13, 1998

[54] Veeramani, D., Upton, D. M. and Barash, M. M., "Cutting tool management in computer-integrated manufacturing," The International Journal of Flexible Manufacturing Systems, 1992, Vol. 3, No. 4, pp. 237-265.

[55] Boyle, C., "Using group technology for tool inventory control," Presented at Session 06B: Cutting Tool Management, 3rd Biennial International Machine Tool Technical Conference, September 3-10, 1986, pp. 6-111-6-120.

[56] Martin, J. M., "Managing tools makes the cell click," Manufacturing Engineer, April 1986, pp. 59-62.

REFERENCES (Continued)

[57] Maropoulos, P. G., "Review of research in tooling technology, process modeling and process planning part I: Tooling and process modeling," Computer Integrated Manufacturing Systems, 1995, Vol. 8, No. 1, pp. 5-12.

[58] Tanchoco, J. M. A. (1994). Material Flow Systems in Manufacturing. Chapman and Hall, London.

[59] Co, H. C., Biermann, J. S., and Chen, S. K., " A methodical approach to the flexible manufacturing batch, loading and tool configuration problems," International Journal of Production Research, 1990, Vol. 28, No. 12, 2171-2186.

[60] Macchiaroli, R. and Riemma, S., "Design of tool management system in a flexible cell," The International Journal of Production Research," 1996, Vol. 34, No. 3, pp. 767-784.

[61] Rahimifard, S. and Newman, S. T., "Simultaneous scheduling of workpieces, fixtures and cutting tools within flexible machining cells," International Journal of Production Research, 1997, Vol. 35, No. 9, 2379-2396.

[62] Jaikumar, R. "Flexible manufacturing systems: A managerial perspective," Working Paper No. 1-784-078, Harvard Business School, 1986.

[63] Jaikumar, R. "Postindustrial manufacturing," Harvard Business Review, November-December, 1986, pp. 69-76.

[64] Motz, P. D., Petticrew, G. L., and Somoza, P. A., "FMS scheduling and control: LTV aircraft products case study," CAD/CAM Management Strategies, Auerbach Publishers, 1986, Vol. 1, S53.

[65] Amoaka-Gyampah, K., "An examination of the impacts of tooling policies in flexible manufacturing environments," The University of Cincinnati, 1990.

[66] Kelton, D., Sadowski, R., and Sadowski, D. (1998). Simulation With Arena. WCB McGraw-Hill, Boston, Massachusetts.

[67] Milton, J., Arnold, J. (1990). Introduction to Probability and Statistics: Principles and Applications for Engineering and the Computing Sciences. Second Edition, McGraw-Hill.

[68] Pegden, D., Sadowski, R., and Shannon, R. (1995). Introduction to Simulation Using SIMAN. Second Edition, McGraw-Hill.

[69] McHaney, R. (1991). Computer Simulation: A Practical Perspective. Academic Press, London.

[70] Knepell, P., and Arangno, D. (1993). Simulation Validation: A Confidence Assessment Methodology. IEEE Computer Society Press, California.

[71] Hsu, J. (1996). Multiple Comparisons: Theory and Methods. Chapman & Hall, London.

[72] Toothaker, L. (1991). Multiple Comparisons for Researchers. SAGE Publications, London.

[73] Klockars, A., and Sax, G. (1986). Multiple Comparisons. SAGE Publications, London.

[74] Schall, S., and Chandra, J., "Evaluation of alternative tool combinations in a flexible manufacturing system," Computers Industrial Engineering, 1994, Vol. 26, No. 4, pp. 633-645.

[75] Reddy, E., Chetty, K., and Chaudhuri, D., "A petri net based approached for analyzing tool management issues in FMS," International Journal of Production Research, 1992, Vol. 30, No. 6, 1427-1446.

[76] DeGarmo, P., Black, T., and Kohser, R. (1998). Materials and Processes in Manufacturing. Macmillan Publishing Company, New York.

[77] Venkatesan, R., "Cummins Engine flexes its factory," Harvard Business Review, March-April 1990, pp. 120-27.

APPENDICES

APPENDIX A: TOOL MANAGEMENT/PRODUCTION OPERATIONS FORM

TOOL MANAGEMENT AND PRODUCTION OPERATIONS FORM

*The information acquired for this study will be held confidential. The Company's name and production information will not be disclosed to any other company or to the general public. The data acquired from the study will be used only to develop a model to analysis the impact of tooling policies on performance measures. This research is for The University of Tennessee, Industrial Engineering Department, only.

PART A: GENERAL CUTTING-TOOL MANAGEMENT QUESTIONS

WHICH TOOL ALLOCATION POLICY BEST DESCRIBES YOUR PRODUCTION PROCESS?

____ Bulk Exchange:

At the beginning of a production period or schedule, cutting tools for each job are allocated to the machines. After the production period, the cutting tools are removed from the machine and sent to the tool room. A new set of cutting tools replace the prior set for the next family of parts.

____ Tool Migration:

Tools do not remain in the tool magazine during the whole production period. When the production run of a particular part-type is completed, only those tools that are unique to that part-type are removed from the tool magazine. Their removal permits the loading of tools for the next part-type.

____ Tool Sharing:

Different part-types may have common tooling requirements. Part-types that have common tooling requirements are transported to a machine. The machine's tool magazine contains the commonly used tools. At the end of the production period, the tools are replaced by those needed for the next production period or schedule.

____ Resident Tooling:

Tools that are frequently utilized are made resident to the machine. When the useful life of a tool has been reached, the tool is replaced. The remaining tool slots may be used for tools that migrate.

____ Others? Please explain.

WHO MAKES THE TOOLING DECISION?

____ Machinists
____ Design engineers
____ Production engineers
____ Manufacturing engineers
____ Tool crib personnel
____ CNC Programmers
____ Others? Please explain.

THE POINT IN TIME WHEN TOOLING DECISIONS ARE MADE?

____ Product design stage
____ Floor level
____ Machine level
____ Others? Please explain.

THE PRIORITIES CONSIDERED IN MAKING TOOLING DECISIONS?

____ Tool material
____ Machine horsepower
____ Tool life
____ Tool availability
____ Time constraints
____ Part geometry
____ Part Material
____ Tooling Cost
____ Machine flexibility
____ Part quality
____ Throughput time for parts
____ Others? Please explain:

WHAT ARE THE CONSTRAINTS THAT INFLUENCE TOOLING DECISIONS?

____ Tooling Cost
____ Part material
____ Tool availability
____ Machine capability
____ Tool life
____ Size of tool
____ Part design
____ Tool design
____ Others? Explain.

PART B: **PLEASE ANSWER THE FOLLOWING QUESTIONS FOR ONLY ONE FAMILY OF PARTS DURING ONE PRODUCTION PERIOD OR SCHEDULE.**

1. What is the production schedule or period?

____ 1 Hour
____ 24 hours
____ 1 Week
____ 1 Month
____ Others? Please explain.

2. Total number of parts produced? ____.

3. Number of different part-types produced? ____.

4. Are parts processed according to earliest due dates?

____ Yes
____ No
____ Others? Explain

5. How many CNC machines are used? _____

6. How many tool-slots per machine?

____ 12
____ 30
____ 60
____ 80
____ 120
____ Others? Please explain.

7. Can machines manufacture all the different part-types?

____ Yes
____ No
____ Others? Please explain.

8. Do you have single machine set-ups for all operations?

____ Yes
____ No
____ Others? Please explain.

9. What is the average downtime per machine due to maintenance?

____ Hours? How many hours? ____
____ Days? How many days? ____
____ Others? Please explain.

10. Automatic part/tool loading robots in the system?

____ Yes
____ No
If Yes, how many? _____

11. Number of different types of tools used for the entire production period?

____ 1-10
____ 10-20
____ 20-30
____ 30-40
____ Others? Please explain

12. Number of operations per part?

____ 1-4
____ 4-8
____ 8-12
____ Others? Please explain.

13. Average processing time per part?

____ Minutes, How many minutes? ____
____ Hours, How many hours? ____
____ Others? Please explain.

14. Average tool life?
____ 30 minutes
____ 100 minutes
____ 10 parts per tool
____ 25 parts per tool
____ 100 parts per tool
____ Others? Please explain.

15. Number of different unique tools per part?

____ 1 - 5
____ 5 - 10
____ 10 - 15
____ 15 - 20
____ Other? Please explain.

16. Number of common tools used per part?

____ 1 - 3
____ 4 - 7
____ 8 - 12
____ 13 - 16
____ Others? Please explain.

APPENDIX B. PILOT STUDY RESULTS

Table B1. Results of Company On-Site Interviews

Activities	Companies										
	A	B	C	D	E	F	G	H	I	J	K	Avg.
Bulk Exchange	No	No	No	No	No	No	No	No	No	No	No	n/a
Migration	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	No	No	n/a
Resident Tooling	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	n/a
Sharing	No	No	No	No	No	No	No	No	No	No	No	n/a
Production period	Week	Week	Month	8 Hours	Month	Month	Week	Day	Week	Week	Month	n/a
Number of parts produced	42000	46000	400	2000	1650	40	35	300	400	200	960	8544
Number of part-types	1	1	20	1	71	2	20	300	3	3	40	42
Production criteria	EDD	EDD	EDD	EDD	EDD	EDD	EDD	EDD	NO	NO	EDD	n/a
CNC machines/cell	8	5	4	6	4	1	4	37	1	1	5	7
Tool slots/machine	20	20	30	11	30	12	30	80	2	2	30	24
Machine all part-types	yes	yes	yes	yes	90%	yes	No	yes	yes	yes	yes	n/a
Single machine set-up	100%	100%	100%	100%	100%	85%	100%	95%	100%	100%	100%	98%
Downtime/machine (Hrs.)	3.5	3.5	24	0.5	1	2	4	2	0.5	0.5	24	6
Auto part/tool loading	part	part	none	p/t	none	none	none	p/t	none	none	none	n/a
Number of robots	0	0	0	6	0	0	0	6	0	0	0	n/a
Unique tools in system	9	12	12	11	27	4	11	25	1	1	29	13
Unique tools/part	9	12	12	8	3	4	11	30	1	1	24	10
Common tools/part	n/a	n/a	6	n/a	5	3	2	15	1	1	29	8
Operations/part	8	10	20	4	3	9	13	3	1	5	24	9
Mean processing time (hrs)	0.02	0.05	2.5	0.33	2	0.12	7	3	0.02	0.05	2	1.55
Mean tool life (parts/tool)	1500	1000	25	150	25	40	6	n/a	60	n/a	25	315

VITA

Kevin M. Smith was born in Dayton, Ohio where he graduated from Kiser High School in July of 1976. After graduation, he joined the United States Navy and received an honorable discharged in March of 1980. In August of 1981, he was employed as a machinist for Martin Marietta Energy Systems (Department of Energy) located in Oak Ridge, Tennessee. In January of 1989, he enrolled in the Industrial Engineering Department at the University of Tennessee, Knoxville where he received a Bachelor of Science degree and Master of Science degree in 1991 and 1993, respectively. In August of 1995, Kevin entered the Ph.D. program at the University of Tennessee in the Industrial Engineering Department. In December of 2000, he received his Ph.D. with a concentration in manufacturing.