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Chapter 35: Flexible Manufacturing Systems

Engineering Handbook

Flexible Manufacturing Systems

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Chapter 35: Flexible Manufacturing Systems

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Flexible Manufacturing Systems are an evolutionary process from numerical control (NC), then computer numerical control (CNC), to manufacturing systems. Numerical control provides the ability for a machine to use a program to process a part. Computer numerical control provides the ability to store multiple programs and interchange these programs for a machine. CNC controlled machines combined with a pallet changing device provides the ability to process a mixture of parts without setup. FMS combine multiple CNC controlled machines with pallet handling systems, pallet load/unload stations and a supervisory computer control.

The first FMS appeared in the late 1960s; no two were the same. These early systems incorporated CNC controlled machines with a variety of pallet handling systems which included two chains, non-synchronous conveyors, lift and carry devices, gantry cranes, and rail guided vehicles. The supervisory computer controlled the used customized software. The development and debugging of the supervisory control software required that all of the hardware be operational, which made it the least reliable components of the early FMS.

35.1 FMS Definition

Any manufacturing operation with five or more part numbers sharing the same process equipment qualifies as a flexible manufacturing system—provided that there is no setup required when processing one part to another. The elimination of setup is the primary characteristic that differentiates a flexible manufacturing system from any production system.

No Setup

The elimination of setup does not mean that there are no delays when processing one part to the next; setup is eliminated or replaced with changeover. Changeover involves the reconfiguration of some component of the flexible manufacturing system without stopping the system from operation. That is, the changeover must be internal to the normal operation. A guideline for any changeover is the time required to reconfigure a component is no longer than a typical process cycle time. A changeover might reduce the production rate (throughput) temporarily but output is restored quickly after the changeover event.

Work-In-Process Level

All FMS operate with low work-in-process (WIP) inventory. The amount of inventory contained within the FMS could be considered at just-in-time levels. The WIP comprises a pallet that provides uniform material handling for the variety of parts. The handling of these pallets is done though a mechanical system. These pallet systems are closed; there are a fixed number of available pallets. This means that the WIP level in an FMS is fixed as well. The pallet handling system can range from operators sliding a pallet along a rolling conveyor to fully automatic multi-level cranes. It is not necessary for an FMS to have fully automatic pallet handling system however, each FMS has a pallet handling system with a fixed WIP level.

Alternative Paths

Another common characteristic of FMS is that a part can have alternative paths to complete a sequence of operations. A path is defined as a combination of part number, pallet number, fixture, machine, and tool set. All available paths for a part number can be on-line (requiring no setup) or require a changeover to make it available. Also, on-line paths are always available anytime during the FMS operation. Changeover to provide an alternative path for a part number is allowed as long as the change over time is less than the typical process cycle time. These alternative paths are useful to offset the negative impact on production rate due to low and fixed WIP characteristics of the pallet handling system. The use of these alternative paths, which add flexibility, are to benefit FMS performance which is presented in section 35.2

Types of Flexibility

Part number. The components of a path define the specific types of flexibility utilized in FMS. Part Number flexibility allows different part numbers to share the same pallet, fixture, machine and tool set. The collection of part numbers into a part family allows the production of any family members without setup or changeover. Each part number receives a unique numerical control (NC) program and these will be automatically engaged using the CNC features.

Pallet. Another type of flexibility in FMS is pallet flexibility which allows multiple pallets to process the same part number using identical fixtures, the same set of machines, and the same tool sets. The differences of each pallet are adjusted using pallet offsets to provide for alternative paths.

A fixture is the part-specific tooling attached to the pallet which positions the part-specific orientation for each operation. Fixture flexibility is the ability to interchange fixtures to fit multiple pallets. Fixture offsets can be used to adjust for the differences between where the fixture is placed on the pallet, moving the fixtures from one pallet to another would be considered a changeover event.

Machine. Machine flexibility is the most obvious type of flexibility in an FMS. Most FMS contain multiple machines that have identical characteristics. Because of the similarities of the machines, it is assumed any machine can process any part. This is true in theory but in practice it involves tool sets, NC programs, and pallet offset. Each alternative machine defines a new path that must be qualified and use the same NC program with adjustments limited to offsets. The biggest misconception of FMS is that any machine can process any part. In reality, machine flexibility in an FMS is one of the least utilized types of flexibility.

The reason for this limited usage is the amount of data and planning that is required to support multiple FMS paths. Pallets and fixtures have subtle differences when located at one machine to the next. These differences are often adjusted within the NC program thus making a special program for each path. This special set of data requires special scheduling and tracking that eliminates on-line flexibility. Pallet to machine adjustments can only be accounted for using pallet offsets. In order to quality multiple paths using pallet offset alone requires extensive planning and coordinated data management.

Tool sets. The last type of flexibility in an FMS is the tool sets. All machines have a finite tool capacity. For multiple paths, machines must have the same set of tools. However, as new parts are added, tools are added to specific machines. Eventually, tool positions fill up and prohibit multiple paths because they do not fit tools sets on multiple machines. Tool set constraints are recognized as one of the limits to on-line flexibility and a variety of solutions have been tested and implemented. Today most of these solutions are as complicated as the FMS itself has limited applications. The best solution is a well-designed tool plan as a component of the flexibility plan described in section 35.5 below.

Degree of Automation

Traditionally, automation and FMS have been synonymous, but they need not be. Automation in an FMS exists for the sole purpose to manage on-line paths. Consider the situation of four identical machines located near one another in a factory. A variety of parts can be processed on these four machines but moving one part to another machine requires the transportation of the fixture between machines. The actual transportation is not the issue; when to move the fixture and to which machine to move it to are the issues. The control system in the automation provides these management decisions. It is the timing of these decisions that manage the alternative paths which become the flexibility in the system. The Toyota Production System is an application of FMS that utilizes the flexibility of labor without need for automation. See section 35.3 for further explanation.

35.2 FMS Performance

The original expectation of FMS was they would be 100% efficient and exceed the output of stand-alone machines. However, this has not been the case. One of the most disappointing characteristics of FMS is its low utilization of capacity. A typical FMS operates from 55-65% of its capacity. This applies to fully automatic machine systems to labor limited U-lines. This underutilization of capacity does not mean the FMS is not cost effective. In most cases, it is the lowest cost solution. The biggest issue with under-utilization of capacity is resulting from lack of alternative paths. It is expected that FMS will out-perform any other production system and the adjustment from expectation to reality is the primary reason for negative views of FMS.

Low Inventory–High Mix

Most FMS are applied in the low inventory–high mix production configuration. Low inventory comes from the closed pallet system required in an FMS and high mix is due the variety of part families that are processed with no setup in an FMS. This combination of low inventory–high mix is the most complex of production configurations. The FMS is an ideal solution for low inventory–high mix production but high utilization of capacity is achieved only with a thorough plan and execution. Following is a description of the complexity of FMS performance.

Low WIP Inventory has Negative Impact on Performance

Work-in-process inventory is good for the performance of a production system. This is reflected in Little's Law: Production equals Inventory divided by Flow Time [P=I/F]. Inventory is directly proportional to production and as inventory increases so does production. Inventory can be increased to a level that will eventually maximize the capacity that can be utilized in the production system. In the same sense, as inventory decreases, so does production. Thus, lowering inventory has a negative impact on production. For FMS to have high utilization of capacity, it must find something to offset the negative impact of low WIP.

Balancing an FMS

The theory of constraints and bottleneck understanding provide an explanation of why balancing in a low inventory–high mix production situation does not benefit the utilization of capacity. According to the theory of constraints, the bottleneck determines the production of a system. In an unbalanced system, the bottleneck remains in one process or machine. In a balanced system, the bottleneck dynamically moves as the production system operates. Production losses occur when a process or machine becomes the bottleneck and is not able to operate due to inventory shortage. The combination of moving bottlenecks in balanced systems and low WIP explains the low use of capacity in balanced FMS.

A natural reaction to offset the negative impact of low WIP was to balance the process. This technique works well in transfer and assembly lines to achieve high utilization of capacity. Balancing an FMS is not quite as easy due to the high mix and variety of operations. As it turned out, a balanced FMS had a lower unitization of capacity than did an FMS that was unbalanced.

Role of Flexibility

Flexibility through the use of alternative paths will increase utilization of capacity in an FMS. Consider the hypothetical FMS where any part can travel to any work center to accomplish any process. In this FMS, utilization of capacity would be optimal without concern for inventory or balance, provided a minimum inventory was present, so flexibility is the substitute for inventory and balance in a production system.

However, flexibility is not a natural occurring characteristic of FMS. The definition of paths, the qualification of paths, and the minute-by-minute management of paths require considerable planning and execution. Without the use of flexibility in an FMS, utilization of capacity will be lower than that of stand-alone equipment. But this does not mean that FMS is not cost effective.

Machine Flexibility. The benefit of flexibility is observed through the elimination of interruptions in the operation of the bottleneck. The selection of paths must address the possible bottlenecks in the process. The first observation is to determine whether the process is machine or labor limited. If the process is machine limited, the production is determined by the utilization of the machines. When this is the case, alternative paths using machines is the essential form of flexibility. Having flexible labor in a machine limited process offers no benefits to the operation of the bottleneck.

Labor Flexibility. Labor flexibility provides benefit to the labor limited FMS. This is the underlying principle behind the Toyota Production System method of manufacturing. In labor limited FMS, the number of operators is kept low to ensure the output is directly related to the labor work hours. Excess machines are included in the FMS to keep labor as the constraint.

In such FMS, the use of flexible labor provides for the optimal use of labor capacity. Implementing flexible labor does not require costly automation or complex control systems to manage paths. Training, insight, and cooperation toward a single objective by the operators deliver sufficient flexibility to provide optimal use of capacity in low inventory high mix production.

A combination of inventory, balance, and labor or machine flexibility does not mean that it is the least cost solution to all production. There are a variety of conditions that comprise production mean a variety of FMS will provide the lowest cost solution. Low cost FMS configurations can range from two operators running three stand-alone machines to a fully automatic eighty pallet handling system with eight machines.

35.3 Applications

As the name indicates, Flexible Manufacturing Systems have a wide range of applications. These range from flexible labor with no automatic controls to fully automatic robotic loading of pallet handling machine systems. It is the use of flexibility (i.e., the management of alternative paths) that provides a common thread of FMS.

Toyota Production Systems

Most engineers do not consider Toyota Production Systems (TPS) as a member of FMS. However, it is the use of flexibility that is the backbone of the benefit of TPS. TPS have been effective given the restrictive nature of its applications. TPS is best applied to labor-limited production. While it has been applied to machine limited production, its benefits have been constrained and usually not any better than work-order based applications. When production is limited by labor such as assembly lines, fabrication areas, welding lines, and office operations, TPS delivers significant benefits to low cost and utilization of capacity. The key to these benefits is the use of flexibility as an offset to inventory and balance.

Conversely, TPS applied without labor flexibility will not deliver benefits over other production methods. As soon as labor decides not to share work it is reassigned to the bottleneck or tries to cooperate to reach a common objective; then flexibility and benefits will also disappear.

Flexible Fabrication Systems. Flexible Fabrication Systems (FFS) comprise of laser or plasma cutting machines (sometimes more than one) with a sheet steel handling system. These systems can process a variety of material types without setup. A variety of parts and quantities are “dynamically nested” to a single material sheet. The NC program processes this sheet which is dynamically generated and the parts are automatically produced.

The flexibility of FFS is in its ability to process a high mix of parts in a variety of quantities. The paths mingle parts with other parts for optimal use of material and capacity. The paths are managed through the nesting software and automatic generation of NC programs and automatic handling of material. The flexibility provides the strategic benefit to implement product-focus over part-focus operation. The nesting of product components in the correct mix simplifies the scheduling requirements.

Flexible Welding Systems. Flexible Welding Systems (FWS) comprise a line of weld robots each performing a specific task along a production line. The parts are transported automatically and fixed to a specific orientation. The robots perform tasks from NC programs.

The flexibility of FWS is in the ability to process a part family along the welding line. Not every part requires the exact same processes and the NC programs can be adapted to the mix of parts as they arrive to the weld robot. The paths allow parts to skip process steps and vary the process step as needed. These lines remain unbalanced and use flexibility to manage the use of capacity.

Flexible Machining Systems. Flexible Machining Systems (FMS) are the most common and recognized member of flexible manufacturing systems. It evolved in the 1960s from NC, to CNC, to the FMS which founded the flexible manufacturing system. FMS comprise a set of machines: a pallet handling system, manually or robotically operated pallet load stations, and supervisory control system. Over their evolution, the component has moved away from specialized equipment to more standard components. This standardization was first introduced by Japanese machine builders and applied to general production. FMS are most applied in horizontal machining applications.

The flexibility of Flexible Machining Systems can utilize any of the forms for flexibility (part, pallet, fixture, machine, or tools). In most FMS, the availability of flexibility is vastly under-utilized. It is quite common that FMS use no alternative machine paths, no pallet alternatives, or tool sets. They use only the part flexibility in their scheduling. Because of the under-utilization of flexibility, the FMS offers vast opportunities to reduce cost through an increase in the utilization of capacity.

Flexible Assembly Systems. Flexible Assembly Systems (FAS) are robot-operated stations located along a line. The parts are transported using pallets. In FAS, the robot usually removes the part from the pallet and then attaches some component(s) and then places the part back to the pallet. A gantry handling system that allows parts to by-pass process steps and visit only those that are needed.

The flexibility of the FAS is in the form of part flexibility. A mix of parts can be processed simultaneously without setup. Applications were products that have a variety of optional configurations are best suited for FAS.

35.4 Justification and Design

Justification of an FMS comes down to the automation and control systems versus additional capacity. Typically a two machine railcar system costs about the same as three stand-alone machines. Why purchase two machines for the price of three machines? The answer is the two machine FMS will outperform the three stand-alone machines provided the FMS utilizes the flexibility available with computer controlled, managed paths. Performance measurement is the total number of machine hours compared over the same time period. The outcome of a justification is to determine how many more machine hours the FMS must produce in order to be a lower cost solution.

Return on Investment Based on Future Cost

Return on Investment (ROI) is a method to compare capital investment to the return (savings) that the investment provides. In the case of the FMS, ROI compares the cost to manufacture a part in the current process to that of using an FMS to process the part. This part cost is based on two components: standard cost and process hours. Standard cost is derived from an accounting review (quarterly or annually) that uses the total expenditures including depreciation during the period and total process hours recorded during the same period. The total expenditure is divided by the total hours and this provides a “standard cost for each process hour”. To determine the specific cost of a part, the standard cost is multiplied by the part’s total process hours. This is the standard cost of each part and provides the comparison basis for ROI evaluations.

In the case of FMS, the total number of process hours is the total machine hours needed to manufacture the part. Its standard cost is the total machine hours multiplied by the hourly standard cost. Using these cost components, the most obvious means to reduce a part’s cost is to reduce the machine hours needed to manufacture the part. This approach of reducing the total machine hours in part has been the most common means to justify FMS. New manufacturing processes require fewer machine hours due to advances in technology. Most FMS were justified because of the advancement in machine technology and the standard cost only determined how many reduce machine hours were needed to provide the savings needed. However, advancements in machine technology have been diminishing and the capital cost of machine has been increasing. That is, it is becoming more difficult to simply reduce machine content in to justify the FMS manufacturing solution. It is necessary to investigate the other component to part cost: standard hourly cost.

Standard hourly cost is calculated by dividing the total expenditures of the operations by the total hours produced. Typically, the standard cost is calculated once per year and set for next year operation. This cost reflects the total expenditures for past operations. This includes depreciation, under use of capacity, and inefficiency. All of these negative characteristics are carried forward and are reflected in the past operation.

Not only is it difficult to reduce machine content in a part given the accumulation of these costs over several years, but also, standard cost increases to such a high level that the number of process hours needed prohibits any ROI. A different cost is needed. This is the cost of operating in the future. This future cost must be based on the same expenditure components including depreciation, use of capacity, and efficiency but must reflect how the FMS will operate in the future; it cannot be assumed that it will operate at efficiency levels observed in the past.

Cost Benefits of Flexible Manufacturing

Flexible manufacturing is the least cost solution when producing a variety of parts using the same equipment. The cost benefits range from high utilization of capacity to improved quality and low work-in-process inventory. Following is the list of cost benefits.

Increased machine hours per man per year. Machine hour is the time when a machine is in operation and adding value to a part. Standard machine hour is the planned or expected time of processing a part. For each part completed, standard machine hours are "earned" and the total of these hours in 24 hours is the number of machine hours per machine per day. When the part remains at the machine for longer than the standard time, usually due to fault condition, prove out, or quality checks, this time defines the actual time. The actual time when a part is at a machine will equal the standard time when the process completes without interruption. A machine can appear to be occupied for an entire 24 hour period but only its standard machine hours are important for cost.

A variety of machine cell configurations shown in Table 1 can be compared for their potential cost benefit in terms of machine hours per day. This comparison includes labor into the cost evaluation. The measurement used to compare one cell configuration to another is the number of machine hours per man per year. Labor is included because of the opportunity for one man to operate multiple machines. Also, including labor provides a means to compare machine cell operation in different labor cost markets.

Table 1: Machine Hour Configurations

Machine Cell Configuration	Labor Hours Available per shift per Year	Machine Hours Available Per Year	Utilization	Machine Hours per Man/Year	Total Machine Hours per Year
	(250 days x 8 hours)	(250 days x 24 hours)			
One Man - One Machine	2000	6000	50%	1000	3000
One Man - Two Machines	2000	12000	45%	1800	5400
One Man - Two Machine FMS	2000	12000	85%	3400	10200
One Man - Three Machine FMS	2000	18000	85%	5100	15300

A standard work year is five days per week and fifty weeks per year and this is used as the basis for comparison of the cell configurations. Each man works one shift (eight hours) each day and each machine is operated for three shifts. (The number of days available in a year and its impact on cost is reviewed in a following section.) The one man–one machine configuration provides a potential of 3000 machine hours per year and 1000 machine hours per man. (60% utilization is due to operator breaks, setup, process interruptions, quality, etc). Assuming that each machine hour can be billed at $100, this generates $300,000 of revenue per year and $100,000 of revenue per man per year. With a labor wage of $20 per hour, the annual labor cost is $40,000 or 40% the total revenue of the machine. The one man – one machine configuration is only profitable in low cost labor markets.

The common migration is from a one machine cell to the one man, two machine cell configurations. Using the same cost basis as used in the one man, one machine cell provides for total revenue per man per year of $180,000 with the same labor cost. Thus, labor cost is 22% of revenue. However, machine capacity is lost due to the interference of labor. This cost of lost capacity must be compared to the lower labor cost to determine if this is a least cost solution.

The one man, two machine FMS offers a potential of 3200 machine hours per man per year. This increased utilization to 85% is due to the elimination of setup, automatic handling, and computer based scheduling. This cell can generate $340,000 of annual revenue and labor cost is now 12.5%. The one man, three machine FMS offers a potential of $510,000 of annual revenue with labor cost at just 8%.

Increased machine hours of capacity per year. Referring to the cell configuration table, the average machine has potential of 3000 hours of capacity per year. Within the FMS, this capacity increases to 4800 hours per year. This is a 60% increase in the number of hours that can generate revenue. This increase in revenue must be compared to the additional capital cost of the FMS configuration.

A simple comparison is that the cost of the FMS configuration is about the same cost of one machine. That is the cost of a two machine FMS is about the same as three stand-alone machines. The three stand-alone machines have potential capacity of 9000 hours per year and the two machine FMS has capacity of 10200 hours per year. This benefit depends of utilization differences between stand-alone machines and FMS. When an FMS operates at utilization below 70%, its cost benefits over stand-alone machine are eliminated. The following sections on implementation and operation describe the steps necessary to maintain high utilization of FMS capacity.

Reduce ratio of labor hours to machine hours. The FMS requires fewer labor hours in order to produce the equivalent number of machine hours in alternative cell configurations. By reducing this ratio, the labor content of all parts processed in the FMS is lowered. Reducing labor content will lower the standard cost of the part.

Because of the automated handling, the FMS has a potential to operate during an “unmanned period” of time. Usually this period is between shift changes, a third shift, or weekend days. These unmanned periods do not reduce the labor content but instead provide for non-synchronization of the labor hours to the machine hours. That is, labor hours can occur somewhat independent of machine hours and in some cases, offer a higher utilization of labor.

This decoupling comes at a cost of higher work-in-process level. More active pallets are needed to sustain machine operation during unmanned labor periods. The cost of these additional pallets and higher WIP must be compared to the increased labor utilization to determine least cost solution. When labor utilization is not increased due to unmanned periods, then there is no cost benefit because of the cost associated with operating at higher work-in-process levels.

Lower inventory reduces scrap and increases quality. This relationship of inventory to quality is not unique to FMS and has been a proven characteristic in all forms of manufacturing. FMS takes advantage of this characteristic by operating in a low work-in-process inventory environment. Its low inventory occurs because of the pallet-fixture handling system and definition of paths. Each part must be processed on a proven path that can be monitored and recorded.

The tracking of material in an FMS is essential for the quality plan. Each part in an FMS receives a serial number which records the specific path that this part used for processing. The internal/data serial number is then transferred to the part using a marking method. The marking method can range from scribing alpha-numeric characters while the part is in the machine, marking the part at unload, pin printing on the part, or attaching a customized label. No matter the method for marking, each part has a record of its specific path used in its process.

Regular inspection frequencies of these paths provide a chronological review of the manufacturing process. When quality issues arise, only those parts since the last inspection are quarantined. Quarantined parts are easily identified due to the serial number tracking of all parts processed between inspections using the same path.

Root cause of quality issues can be identified. Chronic quality problems disappear because problems can be traced to fixture, pallet, machine, or tool characteristics. Quality adjustments can be implemented to specific paths and will not impact other paths. Continuous improvement of quality occurs naturally in FMS provided material is serial numbered and inspection signals are based on paths.

Accurate reporting of actual machine hours. “If you can’t measure it, you can’t manage it” applies to all manufacturing. Measurement of a manufacturing process is based on standard hours that are derived directly from production counts. Every time a part is completed, its standard hours are earned by labor and machines. The time it actually took to process the part is not recorded and lost. The FMS uses its computer monitoring to record actual process times.

Each part has a serial number and has its specific path tracked by the control system. When the part completes its path, it can be assigned to fill a specific order. These orders are the work orders issued by the factory computer system to manage factory operations. When the order is filled, the FMS can report the quantity of parts used to fill the order, the total standard hours by multiplying the standard hours by the quantity, and the actual machine hours. The actual machine hours are the cumulating of the actual time each part occupied a machine. This time includes fault conditions and any other interruption in normal machine operation.

Reporting each work order contains the standard machine hours and the actual machine hours. To compare the actual hours to the standard hours provides a measure of the efficiency of the manufacturing process. This efficiency can be used to understand actual cost and influence management decisions regarding manufacturing operations. The reporting of actual hours can provide the feedback that is lacking in management of manufacturing operations.

Allocation of flexible capacity to fit demand. Most factory scheduling is based on having a known capacity and then prioritizing demand to best utilize capacity. The FMS offers the opportunity to reverse this scheduling basis and consider demand fixed and adjust capacity. Allocation is the method of adjusting capacity to fit demand.

Because capacity is comprised as a set of paths in the FMS, these paths can be allocated as needed to meet demand. Each path defines a subset of the overall capacity and demand can be assigned to each. Once the paths are allocated, computer control can manage these paths simultaneously for efficient operation. The automated handling system facilitates the simultaneous operation of multiple paths. Implementation section below discusses how much flexibility is needed and the timing of when to reallocate flexibility.

Simulation Based Design and Future Cost

Justification of FMS cannot be based on how manufacturing operated in the past, but must be based on how manufacturing will operate in the future. Computer simulation provides the analytic means of how a manufacturing process will operate in the future. Please refer to Chapter 33 for the essentials of computer simulation.

Computer simulation models contain the process definition, part to pallet relations, fixture requirements, machine assignments, labor assignments, automated material handling layout, timings, and component reliability. Using these model definitions, simulation will measure the interactions of all the FMS components and provide a net performance result. Traditional simulation outputs such as production rates, machine utilization, and labor utilization, material handling utilization, inventory level and flow times provide the measure for how the FMS will operate in the future. This future operation must be translated into how much a part will cost to manufacture in the future.

Determining how much a part will cost to manufacture in a future FMS utilizes an actual cost model. This actual cost model is based on the following total cost per part equation in Equation 1:

Equation 1: Total Cost

$$\boxed{\text{Total Cost per Part} = \text{Station Cost} + \text{Labor Cost} + \text{Handling Cost} + \text{Overhead Cost}}$$

Machine cost per part is determined by cumulating the process cycle time multiplied by the actual hourly cost of machines used for each process. The actual hourly cost of a machine shown in Equation 2 is based on the annual depreciation / replacement cost, consumable costs, and its actual utilization. The utilization of each machine is taken directly from the output of the simulated operation.

Equation 2: Machine Cost

$$\boxed{\text{Actual Machine Cost per hour} = \left(\text{Machine Cost per Hour} + \text{Operating Cost per hour} \right) / \text{Actual Utilization}}$$

Labor Cost per part is determined by cumulating the labor time multiplied by the actual labor cost per hour. The actual labor cost shown in Equation 3 is based on the hourly wage multiplied by the actual utilization. The utilization of labor is taken directly from the output of the simulated operation.

Equation 3: Labor Cost

$$\boxed{\text{Actual Labor Cost per hour} = \text{Wage per Hour} / \text{Actual Utilization}}$$

Handling Cost per part is the cost hourly cost of automation. The hourly handling cost is the total purchase cost of the handling system, pallets, fixtures, and computer control divided by the expected hours of service. The actual handling cost per part shown in Equation 4 is the handling cost per hour multiplied by the handling time taken directly from the simulation.

Equation 4: Handling Cost

$$\boxed{\text{Actual Handling Cost per hour} = \left(\text{Total Cost of Automation} / \text{Total Hours of Expected Service} \right) / \text{Actual Utilization}}$$

Overhead cost per part shown in Equation 5 is the annual cost of each overhead cost component divided by the total annual production. The total annual production is taken directly from the simulation results. Each part has the same overhead cost. The actual costing offers the option to select specific cost components that apply to the FMS. Overhead items that are not utilized by the FMS should not be included.

Equation 5: Overhead Cost

$$\boxed{\text{Actual Overhead Cost per Part} = \text{Sum of Annual Costs} / \text{Actual Production}}$$

Capacity vs. Overall Equipment Effectiveness (OEE)

The actual cost model described above utilizes actual utilization of manufacturing components. The higher the utilization, the lower the actual part cost. This differs from standard cost in that standard cost is mostly influenced by process cycle time. Utilization of capacity is included in the standard hourly cost and based on past performance. Actual cost uses the future utilization of capacity to determine the cost to manufacture a part.

Another cost driver in the actual cost equation is capacity. Capacity is defined as the number of hours available. It the example above, the capacity is 6000 hours per year defined from 24 hours per day and 250 days per year. However, a full year has 8,760 hours. In the actual cost model, the hours available per year can be increased to six days per week to 7200 hours. This will reduce the hourly cost of machines. With the same part demand, the utilization will drop and the station cost per part will remain the same and labor cost will increase due to the added hours of operation. However, if the number of machines is reduced by expanded hours of operation then the actual cost will equal the reduced station cost to the increase in labor cost. Actual cost per part provides a common means to compare manufacturing alternatives and determine least cost methods.

The manufacturing industry has attempted to establish a standard measure for utilization of capacity. This measure is called Overall Equipment Effectiveness (OEE). OEE is the measurement of standard/ earned hours divided by operating hours. The use of this industry standard measure is to determine whether alternative manufacturing operation is reduced due to the opportunity to define operating hours. Operating hours can exclude unmanned periods, maintenance, prove-out time, some setup, and unallocated time. Comparing one machine's cells OEE to another is subject to interpretation of its operating hours.

Return on Investment Analysis. A variety of cell configurations with varying degrees of automation can be modeled and simulated. The utilizations and production rates can be used in the actual cost model to determine a future manufacturing cost per part. Having a future cost per part not only allows for comparison among cell configurations, but it also provides the basis for a ROI evaluation shown in Equation 6.

Equation 6: Return on Investment

$$\text{ROI} = \text{Total Investment} \; / \; \text{Total Savings per Year}$$

Return on investment is equal to the total capital investment divided by the total savings generated per year from the investment. ROI units are the number of years for the investment to break even (or return the investment). The total investment is the capital cost to purchase and install the capacity.

Equation 7: Total Savings

$$\text{Total Savings per Year} = \text{Sum over all Parts} \; \{ \; (\; \text{Standard Cost per Part} - \text{Actual Cost per Part} \;) \; \text{x} \; \text{Annual Demand of Part} \; \}$$

Part savings is the difference of the current cost and its future cost multiplied by the annual demand for the part. This savings is then summed for all parts to determine the total savings per year shown in Equation 7.

This method of determining an ROI provides some specific performance objectives of the FMS. The return (savings) is derived from a future part cost that is based on capacity and utilization. In order for the FMS to deliver the savings, it must operate at these planned levels of performance. Accomplishing these performance objectives requires a well-designed and executed implementation plan.

35.5 Implementation

Implementation is by far the most difficult component in an FMS project. Most FMS are planned, justified, and designed with specific performance criteria but very few FMS operate at these performance levels. The reason for this under-performance can be directly related to its implementation.

How Much Flexibility is Necessary?

Flexibility in an FMS can range from no alternative paths to hundreds of alternative paths. Having no alternative paths requires the least time for prove-out and simplest inspection signaling. Hundreds of alternative paths require extensive time for prove-out and complex quality plan based on part marking and inspection signals for each path. For an FMS to meet its performance criteria some alternative paths are needed but a hundred different ways to produce a set of parts is not needed either. What is the appropriate amount of flexibility needed in an FMS?

Determining the amount of flexibility needed in an FMS starts with the calculation of total machine hour demand. Total machine hour demand shown in Equation 8 is the sum over all parts of demand multiplied by cycle time.

Equation 8: Total Demand

$$\text{Total Machine Hour Demand} = \text{Sum over all Parts} \; \{ \; \text{Part Demand} * \text{Machine Cycle Time} \; \}$$

Total machine hour demand is determined for a specific time period. The time period must be at least one month and can be as long as one year. Consistency in the production mix determines the appropriate time period. Constantly changing production mix will have a one month time period and stable production mix can have an annual time period.

The rule of how much flexibility is needed is that 25% of total machine hours must have an alternative path. Ranking the parts from highest to lowest total machine hours determines which parts need an alternative path. In the case where only a few part numbers contribute 25% of the total hours, only a few alternative paths are needed to implement sufficient flexibility. Even FMS applications with a wide variety of parts, no more than twenty alternative paths are typically needed. This rule helps bind the implementation plan, yet sets sufficient flexibility to support daily scheduling.

Flexibility plan. The success of an implementation begins with a plan. Very few FMS implementations have a plan so the implementation becomes a long meandering sequence of decisions and outcomes. One under-performing outcome limits the decision for the next. For example, most FMS are planned so that parts will have multiple paths (combination of pallet, fixture, and machine). But when the pallet offsets are not managed and planned properly, it requires substantially more work to add a second path once one path is qualified. In many cases, a second path requires customized data and programs from the first path and this substantially limits the on-line flexibility. All of these issues can be avoided with a proper implementation plan called a flexibility plan. Figure 1 outlines the plan and each of the plan’s components is described below.

Figure 1: Flexibility Plan Outline

Flexibility Plan Outline

1. FMS Configuration
    a. Parts
    b. Machines
    c. Pallets
    d. Tool List
    e. Part Programming
    f. Paths
    g. Prove Out Procedure
2. Labor Assignments
    a. Load Unload Operator
    b. Machine / Tooling Operator
    c. Finish Operator
    d. Quality Operator
3. Part Tracking and Quality Plan
    a. Marking Parts
    b. Inspect Paths
    c. Close Loop Inspection Data
4. Daily Scheduling and Order Tracking
    a. Import Work Orders
    b. Allocation Algorithm

    - c. Download Routing Instructions
    - d. Report Production Counts, Actual Hours, Standard Hours
5. Work Instructions
    - a. Load Station Instructions
    - b. Inspection Triggers
6. Performance Monitor
    - a. Daily Production Counts
    - b. Machine Cycle Monitor
    - c. Pallet Cycle Monitor
    - d. OEE
    - e. Work Order Fulfillment

FMS Configuration

The flexibility plan begins with the list of part numbers that will be processed in the FMS. Due to the nature of the FMS, committing parts to be processed in the FMS is reserved and not committed until implementation has begun. Once a part is committed to the FMS, the simulation model is updated and the pallet number, fixture, and machine assignments are defined. It is important to define these paths so tool lists can be planned for each machine. When paths are not planned and added ad hoc to machines as the need arises, the tool configuration in each machine will be inconsistent. This inconsistency will limit opportunities to add on-line paths.

Capacity planning and simulation will help evaluate alternative path configurations. These alternatives can be compared to balance load machines, pallets and fixtures. Knowing the capacity of each path is an essential component of the flexibility plan. Once the number of paths is determined, then a well-planned prove-out procedure is needed.

The prove-out procedure is the sequence of steps to add process capability for a part and all of its paths. The prove-out procedure begins with tools added to machine tool magazine, fixture definition, part programming, definition of offsets, and many steps in debugging with quality acceptance. Some prove-out procedures involve more than twenty steps with several engineers and operators involved in individual steps. A tracking system is needed to communicate the progress and status of each path among the prove-out team. Many prove-outs will be underway simultaneously and the ability to coordinate decisions is essential for the delivery of the flexibility plan.

Labor assignments. Assigning labor to the FMS begins with a list of all labor activities. This list begins with handling raw material, in-process material, and completed materials. Other tasks include loading and unloading pallets, machine fault response, tool replacements, tool setting, deburring and other finish operations, and part inspections. Capacity model and simulation can be used to balance-load the individual operators and assign specific tasks to each.

Labor assignments can range from load station only to machine only to each operator having a load station and set of machines assigned. No single labor configuration is better than another. What is important is that each operator has a set of assigned tasks and these tasks are fair. Leaving the operators to self-assign to the tasks will not result with a fair solution that will become a constraint in the FMS achieving its performance objectives.

The labor assignments can be practiced as implementation progresses. These assignments can be tuned as needed. This evolutionary procedure will result with an effective labor role that supports the flexibility plan. If the specific assignments are not perfectly balanced, then rotating operators through the various assignments will alleviate the issue. Just as we need flexibility in the machine process, some flexibility in labor assignments is also needed. Sharing tasks is one way to accomplish this but a specific procedure (or rule) is needed on when and how a task is share. Simulation can help define the rules for labor to share tasks.

Part tracking and quality plan. The most common under-performing feature of an FMS implementation is the lack of alternative paths. Without a part marking method, there will not be any alternative paths in the FMS operation. Implementing alternative paths begins with a part tracking procedure. The FMS control will use an internal tracking method as it automatically routes pallets through the designated process. The essential task is to link this data tracking with the physical part itself. A variety of techniques can be used to establish this link.

Once the part is marked that links it to the tracking data, it can be signaled through the quality plan. The quality plan contains a set of inspection types and frequencies for each path. Inspection types can range from single dimensional checks to Coordinate Measure Machine (CMM) inspections. Each type can be assigned to all paths or specific to a subset of paths. The control system counts all paths and signals for inspections based on frequency count and/or elapsed time duration. The signal is a notice provided during the unload process.

The data collected in the inspection process is linked to the part and serial number. For example, if a CMM inspection is required after every tenth occurrence of a path, the sequence of CMM reports can be reviewed for each path. This provides an opportunity to observe trends and root cause quality issues. Sequence of inspection reports can be compared for other paths to compare results and isolate issues. The review of sequential inspection reports over multiple paths contributes to improved quality and reduced scrap.

Daily scheduling and order tracking. Adjusting schedules to daily demand is the most under-utilized feature of FMS. FMS, with its multiple paths and elimination of setup, can adapt to constantly changing demand however it is seldom implemented. Two barriers contribute to the limited use of daily scheduling in FMS.

The first barrier is the amount of data needed to implement a schedule in an FMS. The data needed includes fixture, pallet, machine, part program, and demand quantity for each path. It is impossible for an operator or supervisor to enter this amount of data daily and ensure its 100% accuracy. Daily scheduling in an FMS becomes the establishment of a permanent schedule for each path with the production quantity set to a large number usually 1000. Scheduling becomes the process of “un-holding” and “holding” the pallet associated with the path. This labor intense method requires no changes to the schedule data and results with under-loading of machine capacity.

The second barrier to daily scheduling is not having a capacity plan that allocates paths based on current production mix. Review of the demand for the next few days will provide a method of when and what paths are best activated for the current demand. A set of rules or playbook is needed (see below).

The barrier to the amount of data needed can be overcome using control software that downloads the schedule data needed to the cell control. Once the software is debugged it will provide 100% accurate and timely data to the control. The second barrier can be overcome with regular capacity planning and development of a playbook.

Daily scheduling in an FMS begins with the import of orders. These orders are either customer orders or ERP work orders and contain order number, due data, part number, and demand quantity. The FMS control maintains this list of orders and retains status as un-scheduled, scheduled, or complete.

The FMS control uses this list of orders as input to an allocation algorithm. This algorithm (may be customized for each FMS) will establish a priority for each order and optimize the sequence to balance load machines, pallets, and fixtures. The output of the allocation algorithm is the daily schedule and defined in terms of routing instructions. These routing instructions are then automatically downloaded (transferred electronically) to the cell control. These routing instructions include all data the cell needs to control to execute the schedule.

As the parts are tracked, serial numbered, and completed in the FMS, they are assigned to fill specific orders. This order tracking maintains the list of specific parts with each part serial numbered used to fill each order. Orders are tracked with number of completed parts and include both standard machine hours and actual machine hours. The reporting of actual machine hours is one of the benefits of FMS. This data is exported to the ERP system as frequent as desired.

Work instructions. With daily scheduling, the production mix within the FMS will change frequently. When routing instructions are downloaded automatically, the operator needs some means of notice. The notice is accomplished using work instructions. Work instructions are displayed at each load station and contain the list of part numbers, the quantity that is being unloaded, and a list of part numbers and quantity to load. Links can be provided to display drawings and instructions specific to the load and unload tasks. The work instruction display will include the serial numbers for the parts unloaded, inspection signals, and order assignment.

Performance monitor. The flexibility plan includes how the FMS performance will be monitored and measured. The FMS was justified on meeting specific performance criteria and it is essential to monitor the performance to ensure the economic benefit performance measures include: production counts, standard machine hours, OEE, actual machine hours, order status, machine cycle times, load station cycle times, and inspection signals. A log of every pallet movement in the FMS operation provides the basic data where performance measures can be obtained.

Weekly review is needed to compare actual FMS performance to plan. As deviations occur, corrective action is needed to determine root cause and implement solutions. This begins the “hand off” from implementation to operation.

35.6 Operation

In many FMS installations, it is difficult to determine when implementation ends and operation begins. Operation assumes many of the tasks and procedures that start during implementation. Adding new parts, proving new paths, and qualifying parts are normal on-going procedures in the daily operation of an FMS. Proving new paths and maintaining quality on existing paths is an essential component of daily operation. In many FMS installations, implementation has provided alternative paths and operation chooses not to utilize them. The primary reason operation does not use alternative paths is the lack of an effective part marking system.

Material Tracking

Marking serial numbers on parts is one of the most important tasks in the operation of an FMS. Without part marking and path tracking, alternative paths will not be implemented and the benefits of flexible manufacturing will not be fully realized. Several techniques are available for marking parts in an FMS.

The simplest technique is to print a label while the part is being unloaded and its pallet is present at the load station. The label will contain a unique serial number supplied by the control system and attached to the part by adhesive or tag. The serial number on the label will link to the data containing the specific details of the path used by this specific part. This data will contain pallet, fixture, machine assignments, cycle times, load durations, inspection signals and order assignment.

Another method to label parts is to use a pin printer. A pin printer will stamp a dot matrix pattern on the surface of the part. This pattern can be readable characters to a variety of bar codes. However, positioning the part properly for the pin printer to make a clear mark is difficult. This positioning is best accomplished using a robot arm or fixture.

Scribing characters on the part surface while the part is being processed in a machine is another method of marking the part. The accurate positioning of the part is not a problem but the marking adds process time and a data sharing method is needed to link the tracking data to what is marked on the part. Scribing in the machine is usually used when no alternative paths are implemented in the FMS. Some scribing techniques have the control system deposit, a serial number into a text file, and then consume the serial number within the part processing. The control system monitors this activity and then records the deposited serial number in the data tracking of the part.

Any method that results with a physical mark on the part that matches the contents of a data field in the tracking data is acceptable. This link must be done while the part is under system control. Once the part is unloaded and its pallet leaves the load station, the linking opportunity has passed. Having operators scan tags and then attach them to a part is acceptable, provided the operator follows a strict routine. Even if only one part is missing a tag, the use of alternative paths will be limited.

Quality Plan

The quality plan is a set of inspection types, each with specific instructions, frequencies, and defined for a set of part numbers. The control system tracks each path a part takes through all of its operations. For the example shown in Table 2, a part has two operations on the same pallet and the pallet can be processed at two alternative machines.

Table 2: Path Definition

Machine	Pallet #	Operation 1	Operation 2
Path #1	1	Machine 1	Machine 1
Path #2	1	Machine 1	Machine 2
Path #3	1	Machine 2	Machine 1
Path #4	1	Machine 2	Machine 2

This configuration has four possible paths and each of these must be recorded, signaled for inspection according to the signal frequency, and audited. Suppose the quality plan has three inspection types. Each of these must be signaled for all four paths and the audits must be done for all twelve inspections.

The audit is a review of inspections performed over a specified period of time. The audit reports the total number of times each path and the number of instances each path has been signaled for each inspection type. This audit reviews the plan versus the actual inspection frequency settings. Included in the audit is the list of serial numbers that have been signaled for inspection during the audit period. This provides a chronological review of inspection results that contributes to root-cause analysis of quality issues.

Performance Monitoring

The most common measurement of production systems is production counts. Counting the number of parts produced in an FMS over a period of time is not an effective indicator of performance. The reason is the FMS is intended to produce a different mix of parts from one time period to the next. One part mix can have a large count but yield low use of capacity and another mix can have low counts but high use of capacity. Monitoring the percent used of the capacity is more effective when measuring performance than production counts.

Capacity of an FMS is defined as the available machine hours over a period of time. For example, a three machine FMS that is operated 24 hours per day has capacity of 72 machine hours. As parts are completed, the standard machine hours are earned and the use of capacity is the ratio of these earned hours divided by the available hours (defined as OEE). The problem with earning machine hours is that some of these hours are not processed during the reporting period. All of the standard hours are counted only when the part completes its entire process. Changes to work-in-process levels from one reporting period to the next contributes to accuracy of this performance monitor. Reporting periods must be expanded to reduce the impact of variation in work-in-process levels.

Any performance measure of an FMS is difficult to interpret due to the variable nature of its operation. Simply counting parts or recording OEE cannot determine whether it has been a good or bad day. Determining the performance of an FMS requires the comparison of these performance measures to a plan. Having a daily plan provides base values that actual measurements can be compared. Comparing the plan to the actual performance is an effective measure of FMS performance. The plan comes from daily scheduling described in the following section.

When an FMS has a planned OEE level and this level is not observed over a period of time, an investigation is needed to determine the cause of this under performance. The first place to review is process cycle times. Each process cycle time has a planned time that is the standard hours. The actual or observed time of each cycle can be compared to this planned time. When cycles are taking longer than planned due to faults, the machines are occupied but not earning hours. Repeating cycle times, both at machines and load stations, are essential for high FMS performance.

Another important performance measure to help diagnose FMS performance is pallet flow time. Pallet flow time is the elapsed time from when a pallet has completed its load, signaled by pressing the "Ready" button, to be successive completed load. The pallet can be considered as the primary consumer of capacity. With a fixed number of active pallets, the faster these can cycle, the more capacity that they will consume. The plan will include targets for the pallet flow time and actual observations can be compared to root cause performance issues.

Scheduling

Scheduling provides the plan for which performance monitoring can be effective. Without a plan, FMS performance is usually low and undermanaged. Scheduling is the process of using orders to determine a specific production mix for the scheduling period (usually daily). Orders are imported into the control system and updated frequently. These orders provide two roles: one to define demand and the other to assign completed parts and report actual hours. The actual tracking of the orders is best performed by the ERP system. It is not effective to have both the ERP and the control system tracking orders.

Demand defined in terms of quantity and due date is input into the allocation algorithm. This algorithm uses computer simulation to optimize the flexible capacity to best fit the demand. This allocation approach is opposite to traditional scheduling methods that prioritize demand to fit capacity. Allocation algorithms include objectives to balance load capacity, consider capacity of each path, add or subtract paths to best fit demand, and resolve due date-capacity conflicts. The outcome of the allocation process is a specific production mix and OEE targets for each machine and operator during the schedule period.

Once the schedule is defined, it must be transferred into the control system for operation. Most operations under-estimate the amount of data needed to schedule an FMS. It is not possible to involve a supervisor or operator in the transfer of the schedule data. The accuracy and timing of the data requires the need for electronic data transfer. Generating a schedule once each day, downloading this schedule automatically, and adding hot jobs as needed are the most effective solutions for FMS scheduling.

Capacity Planning

Capacity planning is not usually included in operation. Capacity planning is performed during the acquisition of capacity and once the capacity is implemented, capacity planning stops. However, FMS operation depends on the continued review of its capacity. By the very nature, FMS possess a variety of part mixes, and all of these mixes define different capacities of the FMS. As the production demand mix evolves, the FMS requires capacity planning to evaluate and configure its flexible capacity.

Capacity review is needed when the production mix changes. This can be weekly in some FMS to annually on others. Whatever the period is, a capacity review is needed to configure the flexible capacity to best fit the future production mix. This capacity review begins with a forecast of part demand. This demand defines the period of time, or the production period, when the production mix must be processed.

The first step in the capacity review is to use the current path configuration and forecast demand to determine if this will fit in the box of FMS capacity. Demand fitting means that no FMS component (pallet, fixture, machine, operator, and tools) are burdened more than 90% of its available time. If the demand fits and the FMS has at least 25% of its forecast standard hours with an alternative path, no adjustments are needed to the FMS configuration. As this forecast demand transitions to actual orders, allocation scheduling in the FMS will sustain performance objectives.

If the forecast demand does not fit in the box (i.e., one component is burdened higher than 90%), then the FMS must be reconfigured. Reconfiguring an FMS is the process of defining new paths that best serve the forecast demand. This involves removing unneeded paths, moving paths to other machines, and adding entirely new paths.

An FMS configuration is acceptable when no component is burdened more that 90% and at least 25% of total machine hours have an alternative path. At this point the capacity has been configured to fit the demand and is then transferred to the allocation algorithm for scheduling. Any new or un-proven paths must be qualified through the prove-out procedure before they can be scheduled.

35.7 Summary

No two FMS installations are identical. Even with the same hardware configuration, each FMS will have unique parts and processing. The production mix can change daily and/or evolve over months so one configuration can become something completely different.

This dynamic nature of FMS makes it important that each FMS has some essential features in order to sustain the benefits. The following critical features are needed in all FMS projects.

1. **Utilization of paths**. The most important feature of FMS is the availability of alternative paths. These paths must be on-line or made available with a short changeover event. The control system must be aware of these paths and utilize them

on an as-needed basis. Using the control system to select a path at the latest possible minute provides the optimal use of available capacity. Without the use of this feature, the benefits of flexible manufacturing are greatly diminished.

2. **Material tracking using serial number part marking**. Material tracking is essential to support alternative paths. The FMS control system must track all material and retain a data record of all processing events. The part is marked with a unique serial number that is recorded with the data to link the physical part with its data record. Without a material-tracking feature in FMS, it is impossible to obtain the full benefits of alternative paths and just-in-time control decisions.

3. **Inspection signal based on paths**. An effective quality plan for FMS must be based on signaling paths and not based on counting parts. Signaling every tenth part for inspection will not ensure that every pallet-fixture-machine combination is routinely inspected. Quality issues will persist and root-cause investigation will not be available. Chronic quality issues will exit and the FMS benefit of lower scrap will not be realized.

4. **Reporting of actual hours**. Reporting of actual hours needed to process each part provides the foundation to know the actual cost to produce each part. FMS provides the benefit of comparing standard cost to actual cost of each part. Gaining confidence in knowing the actual cost provides for more effective management decisions that result with a competitive advantage.

5. **Transition from acquisition to operation**. The decision to purchase FMS capacity is usually well investigated and supported. This decision is based on future performance characteristics that lower processing cost. However, the transition from purchase to operation is where most FMS benefits are lost and become unavailable. The operation takes on a personality that limits the FMS benefits to that of stand-alone machines.

6. **Use of flexibility plan during implementation**. Development of a flexibility plan that guides decisions during the implementation provides consistency to achieve the benefits of FMS. Many decisions are required during the implementation phase and without a plan, these decisions are resolving short-term issues that prevent long-term benefits. Having the FMS implementation and operational team develop the plan allows for inputs and resolution of conflicts before the decision process begins. Consistent decisions during implementation delivers an FMS for operation can meet its performance benefits.

7. **Documented prove-out process and use of offsets**. The prove-out process is the step-by-step procedure to add a part to the FMS operation. These steps involve several individuals and extensive data sharing for consistency. The documentation

becomes the communication among the prove-out personnel to maintain every part added to the FMS is properly qualified. Pallet offsets, fixture offsets, machine offsets, and tool offsets are variables that can be used in any number of ways. Many times these are utilized based on the prerogative of the individual. Inconsistent use of these offsets cut off the use of alternative paths that limit many FMS benefits.

8. **Daily scheduling**. Daily scheduling provides a daily plan of part numbers and quantities that the FMS is to process. The development of the daily schedule includes the balance loading of machines and pallets, use of alternative paths and targets an OEE. Having a daily plan that targets OEE is the first step in achieving the benefits of flexible manufacturing.

9. **Plan versus actual performance measurement**. The planned operation comes from having a daily schedule. Measuring performance of an FMS includes the assessment of actual operation to planned operation. Root cause investigation of under performance uses the planned versus actual performance of FMS components. Taking corrective action on the root cause leads to continuous improvement that then delivers the benefits of FMS.

10. **Capacity Planning**. Capacity planning is the process of comparing the current FMS configuration to future demand mix. Daily scheduling and flexibility is limited to 25% of a current part mix and will not maintain an FMS benefit for all part mixes. A periodic review of the current FMS configuration for future demand is needed to reset the FMS configuration with the addition of new paths and elimination of others. With an adjusted FMS configuration, daily scheduling can support the new mix and maintain FMS benefits.