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Maintenance Scheduling Improvements In Flexible Manufacturing System Supply Chains

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Abstract: - Globalization and competitive markets have created new challenges for modern manufacturers. In the current marketplace, manufacturers must be agile, efficient, and capable of quickly responding to customer demands and changes in the modern manufacturing environment. Manufacturing systems do not exist in isolated environments. Manufacturing systems are always a part of an overall supply chain. The performance of each part of the supply chain has an effect on the performance of every other part of that supply chain. One of the most vital priorities for facilitating good supply chain performance is efficient maintenance scheduling and utilization throughout the supply chain. This article presents a brief discussion on flexibility, as it relates to manufacturing supply chains and general manufacturing environments. Two maintenance scheduling formulations are introduced. These formulations can be applied at any point in a supply chain.

I. INTRODUCTION

This article presents a brief discussion of supply chains for flexible manufacturing systems with a particular focus on an often overlooked aspect for efficient supply chain performance, maintenance scheduling. It is a common belief that Henry Ford created the blueprint for how manufacturing processes should be structured. Two of the most notable characteristics of Ford's process were: item mass production and the vertical integration of all manufacture-related processes. In terms of mass production Ford assumed that the manufacturing marketplace was company centered as opposed to customer centered. A company centered manufacturing marketplace is one in which associated variations and trends are dictated by the desires of the decision makers and designers of a corporate entity. For this kind of manufacturing marketplace, consumer demands are not the driving force behind change. In contrast, change occurs within a customer centered marketplace based on the desires (which are often quite fickle) of consumers. In this kind of marketplace an organization's success is dependent on its ability to quickly respond to customer demands.

The use of vertical integration allowed Ford to control all aspects of the production process. Figure 1 is a flow chart of general activities associated with a manufacturing environment. Suppliers for raw materials used to make Ford products were owned by Ford. Manufacturing and assembly processes associated with Ford products were owned by Ford. Distribution of final Ford products was also controlled by Ford. Some of the potential advantages of vertical integration are: greater overall protection for a company against changes in the marketplace, an increased control over determining the location of the supply chain activities (illustrated in Figure 1), and lower transportation costs. Some of the potential drawbacks of vertical integration are a decreased ability to respond to changes in marketplace demands, less item variety, and greater costs (outsourcing may be cheaper overall in comparison to using resources to produce an item internally).

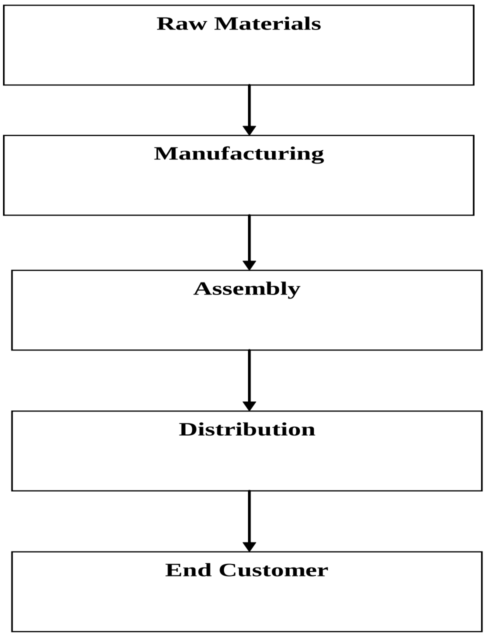

Figure 1 This blueprint was utilized by many for much of the twentieth century (between the decades of 1920 and 1970).

In contrast, one of the defining characteristics of the twenty first century manufacturing environment is that an organization's competitiveness is strongly determined by that organization's ability to respond to changes. The existence of trade blocs and the continuing development of new technology have lead to the globalization/internationalization of modern day manufacturing marketplaces. Organizations must consider that their potential customers are no longer limited to people who live in a certain community, reside in a limited region, or communicate in a particular language. Modern manufacturers must be able to adjust to variations in customer demands (quantity and quality), new technology, and other changes. Flexible manufacturing systems can allow organizations to meet these challenges. The next section of this article will briefly discuss the topic of flexibility from the perspective of the overall manufacturing supply chain.

II. SUPPLY CHAIN FLEXIBILITY

In terms of flexibility within manufacturing environments, much focus is put on the flexibility of the actual manufacturing processes. This section briefly discusses flexibility from the perspective of the overall manufacturing supply chain. (Leslie, Robert, and Rhonda 2003) identify six components for supply chain flexibility. These components are:

1. Operations Flexibility
2. Market Flexibility
3. Logistics Flexibility
4. Supply Flexibility
5. Organizational Flexibility
6. Information Systems Flexibility

Operations flexibility is defined as a manufacturer or service organization's ability to organize assets and operations to be able to respond to changing customer trends at every point in a supply chain. Market flexibility is defined as the ability to build close relationships with customers. This includes the designing, modifying and mass customization of products. Logistics flexibility is having the capabilities to deliver and receive products cost effectively regardless of customer and supplier changes. The ability to alter the organization or structure of the supply chain to respond to demand changes is called, Supply flexibility. Organizational flexibility deals with an organization's ability to match worker skills with the skills required by marketplace demands. Information systems flexibility is defined as an organization's information system being capable of allowing the organization to receive and respond to changes in the marketplace.

(Babu and More 2008) present a fairly thorough review of existing literature covering the topic of Supply Chain Flexibility. Research/evidence in (Fatemi 2010) discusses supply chain flexibility and provides a review of manufacturing flexibility and supply chain flexibility literature. (Sanchez and Perez 2005) and (Grigore 2007) divide supply chain flexibility into two categories: process flexibility and logistics flexibility. Process flexibility is described as the number of product types that can be manufactured by each producer.

Logistics flexibility is described as the ability to get a product to market or the ability to attain material from a supplier. Sanchez and Perez separate these flexibility categories into ten separate dimensions:

a. Product flexibility
b. Volume flexibility
c. Routing flexibility
d. Delivery flexibility
e. Trans-shipment flexibility
f. Postponement flexibility
g. Sourcing flexibility
h. Target market flexibility
i. Launch flexibility
j. Access flexibility

A summary of the definitions of these dimensions as stated by these writers is now given. Product flexibility is ability to meet customer specification and to make products of varying physical characteristics. Volume flexibility is the ability of an organization to increase or decrease its overall production in response to market changes. Routing flexibility is the ability to process an item in different ways. Delivery flexibility is the ability to adapt lead times according to customer requirements. Trans-shipment flexibility describes the ability to physically relocate stock between supply and demand locations of relatively small distances. Postponement flexibility is defined as the ability to incorporate a customer's product requirements within the later stages of production. Sourcing flexibility refers to an organization not being dependent on any single supplier for any component or raw material. Target market flexibility measures the ability to meet the needs of high priority markets. Launch flexibility is the ability to quickly introduce new products into a market. Access flexibility measures the ability to distribute in a widespread or intensive manner. The following figure gives a visual illustration of these ten flexibility dimensions. It was originally presented in (Sanchez and Perez 2005).

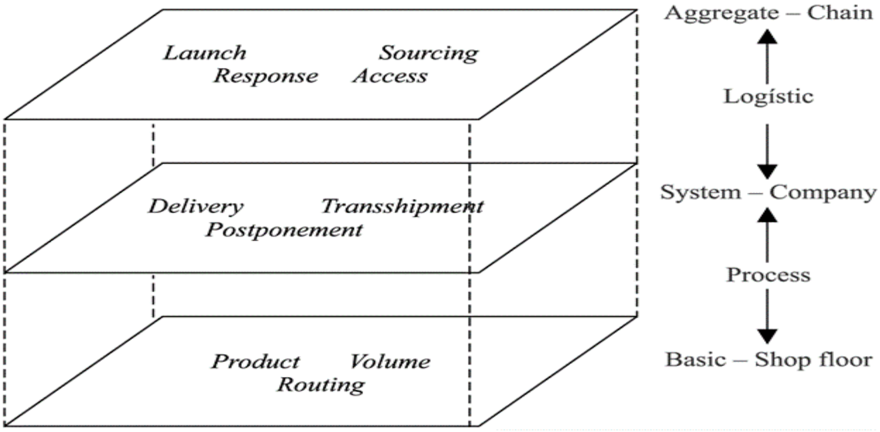

Figure 2: Source (Sanchez and Perez 2005)

Each of these dimensions requires the implementation of well designed maintenance processes for maximum efficiency. This section has briefly discussed some important aspects of manufacturing supply chain flexibility. The next section of this article will discuss the topic of flexible manufacturing systems.

III. FLEXIBILITY AND MANUFACTURING SYSTEMS

Flexible manufacturing systems are similar to automated production lines. An important difference between the two is that flexible manufacturing systems have capabilities for processing different parts simultaneously. (Inman 2010) says that the origin of the concept of flexible manufacturing systems is in the 1960s. During the 1960s and 1970s (and continuing into the following decades), the priorities of manufacturers began to center around three critical points: product cost, product quality, and product delivery speed. At this time robots, programmable controllers, and other computerized controls were beginning to be used in manufacturing environments for the control of machines. The desire to create both a customizable manufacturing environment that is also agile was essential to the development of flexible manufacturing systems. Currently there is a fourth manufacturing priority, flexibility.

Three classical categories of manufacturing environments are: batch manufacturing, continuous manufacturing, and job manufacturing. Batch manufacturing environments can increase their efficiency and ability to respond to changes in the marketplace by implementation of flexible manufacturing systems. Batch manufacturing environments produce a designated quantity of a certain item in a series of processes. From a process perspective, the reason for using batch processes is often directly related to machine capacity and process limitations. From an external (marketplace) standpoint, batch manufacturing tends to be more flexible in relation to other manufacturing environments. Batch manufacturing allows for the production of multiple items in a single production line. It is common for companies that produce seasonal products to use batch manufacturing. Also, the costs of discontinuing an unpopular product is much less in batch environments than it is in other manufacturing environments. While batch manufacturing processes can be very useful and productive, they tend to be inefficient. This inefficiency primarily stems from time wasted (i.e. downtime) because of the necessity to reset machines, and change raw materials before each new batch is started. Before the beginning of a new batch, a test output must be completed. This increases the amount of cycle time (time between the completion of one batch and the commencement of the next batch). Maintenance scheduling is very important in these environments, because it can help to decrease the amount of downtime and cycle time that could occur because of equipment or machine breakdown (unscheduled downtime) or scheduled (routine) downtime. In batch manufacturing, work is divided into sections or "breaks" often called workstations. However, continuous manufacturing environments are designed without breaks in the production line. Whereas batch manufacturing is constrained to a specific or finite amount of outputs (number of end products), in theory the number of outputs for a continuous manufacturing environment is infinite. Continuous manufacturing environments are more costly (in large part due to higher required initial capital). They are useful for producing similar items. An example of this is the continuous production of various models of similar automobiles. Because of their design, continuous manufacturing environments require maintenance to be performed while production continues. The design of continuous manufacturing environments may make them more suitable to automation and therefore more easily compatible to flexible manufacturing systems than are batch manufacturing environments. Job manufacturing is production that focuses on the need of a specific customer. The quality requirements for this type of environment are higher than it is in other manufacturing environments. It is more similar to batch manufacturing than it is to continuous manufacturing. The items produced within job manufacturing environments tend to be single and unique. The skills required in these types of manufacturing environments tend to be more specialized in relation to the required skills in other types of manufacturing environments. There is an intrinsic nature of flexibility in job manufacturing. Out of the three manufacturing environments discussed in this section, job manufacturing environments would benefit the least from the application of flexible manufacturing system technology. Job manufacturers can alter products in order to precisely respond to market demands. The next section of this article briefly discusses another type of manufacturing that is becoming more useful in the current marketplace, additive manufacturing.

IV. ADDITIVE MANUFACTURING

Additive manufacturing (or additive fabrication) is the process of combining (adding) materials in a layer by layer process in order to make objects from three dimensional data such as CAD drawings. It utilizes batch manufacturing in that multiple products, either similar or dissimilar, can be produced simultaneously. It allows for the construction of objects (both simple and complex) without the need for tools or castings, forgings, or other equipment. This can lead to an overall reduction of expenses to an organization. The use of additive manufacturing can reduce waste and enhance design and engineering processes. Proper utilization of additive technology can allow for the realization of more agile and flexible manufacturing systems. Significant advances have been made to the various additive manufacturing technologies such as stereolithography, laser sintering, and fused deposition. The newest of these technologies is three dimensional printing. Stereolithography was the first additive manufacturing technology. It is used to create a solid object from a three dimensional computer image. The object is constructed one layer at a time. Layers of material are deposited in a bottom to top manner by means of a computer-controlled laser which draws the shape of the object onto the surface of liquid resin (usually). The process in which prototypes and finished items are created from three dimensional drawings through the use of thermoplastics and metals is called laser sintering. In laser sintering the thermoplastics and metals are cured by a high temperature laser. The three dimensional drawings are cross-sectioned into thousands of layers and built up in a layer by layer fashion by the machine being used. Fused deposition modeling (FDM) is a type of additive manufacturing that can be used to create plastic prototyping models and production parts. The FDM process works by extruding layers of plastic from materials such as: polycarbonate, polyphenysulfone, or other material. The models produced by FDM can be assembled or used as normal objects. The term three dimensional printing is often used to include both rapid prototyping and rapid manufacturing. Rapid prototyping products are used for concept modeling primarily for the purpose of measuring if a design meets customer specifications. These products are also sometimes used to determine the fit or compatibly of the modeled product with other parts within its intended system. In contrast, rapid manufacturing products are created for specific application purposes.

The potential advantages of additive manufacturing over other manufacturing categories are:

- Cost reduction
- Lead time reduction
- Minimization of waste
- Greater flexibility for varying designs
- Increased energy efficiency
- Environmentally friendly
- Reduced maintenance costs

Although maintenance costs are reduced in additive manufacturing environments, as with all categories of manufacturing, maintenance is still a vital part of additive manufacturing supply chains. Maintenance must remain a high priority in order to actualize the potential advantages in the above list. The next section of this article will discuss the importance of maintenance in manufacturing supply chains.

V. MAINTENANCE IN SUPPLY CHAINS

In general, maintenance systems are created for the purpose of ensuring the serviceability and safety of equipment or systems so that maximum possible performance levels can be achieved. Scheduling and planning are two (of several) primary functions of the maintenance modeling paradigm. Scheduling is the arrangement of resources to be used and planning is the act of ensuring that resources and tools are in order before the required tasks are to take place. Within the construct of maintenance planning and scheduling, there are two categories. The first category consists of preventive maintenance, routine maintenance, and scheduled overhauls. The second category consists of unscheduled maintenance due to emergencies. Any maintenance schedule should consider both known and unknown circumstances. For regular manufacturing systems, it is vital to maximize the availability of resources at all points of the manufacturing supply chain. Increased availability of resources is even more vital within flexible manufacturing systems than it is in general manufacturing systems. This is because of the necessity of flexible manufacturing systems to be able to quickly respond to various changes. Efficient maintenance systems can be essential in facilitating the creation of manufacturing environments that have high resource availability. The rest of this section presents a brief discussion of an important tool for increasing resource availability at all points in a supply chain, total completion time maintenance scheduling. The consideration now is the minimizing the total completion time scheduling problem for a set of maintenance jobs. Minimization of the total completion time for a set of jobs leads to the overall availability of a set of resources (i.e. machines, vehicles, tools, etc.) being maximized. The United States military refers to this as maximizing the overall fleet availability. This objective is accomplished through intelligent scheduling of maintenance personnel (or maintainers). In this type of environment, a maintenance department with M number of maintenance workers is responsible for performing all maintenance jobs. However, both the number of maintenance workers and the number of operations that can be performed by the maintenance workforce are not varied in a given scenario.

Consider a process in which a set of Q pieces of equipment produces items at a constant rate R per unit time. These pieces of equipment are subject to periodic failure and a crew of maintenance workers is available to maintain the equipment. The approach is to have a schedule for maintenance workers devised so as to maximize the overall availability of these machines during a finite time interval. Availability can be quantified by the total production/work performed by all equipment/resources at the end of the time period. Each maintenance worker has a skill that may or may not be required on a certain resource. This means that each maintenance work order associated with any given equipment does not necessarily require each skill. Each worker has a set speed at which he or she can perform his or her required task.

Examples of these types of problems are presented next. The first example is simplified such that all of the assumptions associated with a general open shop scheduling problem hold. These assumptions are:

1. A job i is *not* allowed to be worked on simultaneously by more than one worker at a time.
2. There are *not* multiple workers for each operation.
3. In situations where multiple workers for each worker type are allowed, identical workers for each worker type have the same processing speed.

Maintenance Scheduling Example Number One

Consider a scenario in which there are 10 systems that each produce r = 100 units per hour. Three of the systems are down (i.e., N = 3 jobs) at the beginning of the time horizon (t = 0) and the Maintenance Department contains two skilled workers (i.e., M = 2). The Maintenance Department is composed only of machines each of which has one unique operation. The problem is to determine the sequence of processing jobs and/or machine schedules that maximizes the number of available systems of total time horizon T = 8 hours (the total length of one scheduling shift) which will be quantified by the total production at the end of the period. Every hour that a system is available during the time horizon is equivalent to 100 units of production by that system. However, every hour that a system is not available is equivalent to 0 units of production by that system. Three maintenance work orders (or jobs) have been sent to the maintenance department. Let x_{ij} be the assignment of job *i* to Machine *j*. Then consider the following information in Table 2 (note that 0 indicates that job *i* does not need to be processed by worker *j*).

Table 1: Processing Times

job i	machine j	
	1	2
1	2	0
2	5	3
3	0	1

The above problem will now be solved for this open shop environment using two different rules: shortest processing time and longest processing time. In an open shop environment, the scheduling heuristic is applied to each individual worker.

Shortest Processing Time (SPT) Results

Shortest processing time scheduling occurs when items are processed in increasing order of their required processing times. When shortest processing time is applied to the above problem, Machine 1 performs maintenance first on Job 1 and then on Job 2. Machine 1 does not have any scheduled maintenance for Job 3. Meanwhile, Machine 2 performs maintenance first on Job 3 and then on Job 2. Machine 2 is not scheduled to perform any maintenance on Job 1. Both workers can work on separate jobs simultaneously. However, for this example a delay scheduling assumption is made. According to the traditional scheduling theory with a delay scheduling implementation, only one worker can work on the same job at a time. Both workers are scheduled to perform work on Job 2. In this example, Machine 2 finishes maintenance on Job 3 before Machine 1 finishes maintenance on Job 1. Therefore, Machine 2 can begin to work on Job 2 first. Machine 1 must wait until Machine 2 completely finishes work on Job 2 before Machine 1 can perform work on Job 2. Figure 3 shows the schedule for each worker and the total completion time for the jobs. The sequencing of jobs on each machine can be seen in Figure 2. The completion times of each job can also be seen in this figure.

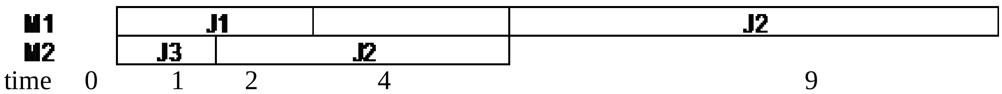

Figure 3: Shortest Processing Time Schedule for Example 1

System uptime (or availability) is assumed to be equal to the total time horizon minus total completion time for each job. The availabilities of each system are as follows: System 1 was made available for six hours, System 2 was made available for zero hours, and System 3 was made available for seven hours. Since every hour of system uptime is equivalent to 100 units of production, then the total production at the end of the time horizon is as follows:

(6 + 7) hours * 100 units/ time horizon in hours = 1300 units.

Longest Processing Time (LPT) Results

Longest processing time scheduling occurs when items are processed in decreasing order of their required processing times. Both Machine 1 and Machine 2 are scheduled to work on Job 2 at the same time. Since for this example delayed scheduling methods are being used and both workers are not allowed to work simultaneously on the same job, Machine 1 is scheduled to work on Job 2 first because it has the longer scheduled processing time. The processing time of Job 3 for Machine 2 is one hour and the processing time for Machine 1 on Job 2 is five hours. Therefore, Machine 2 can complete Job 3 before Machine 1 has completed Job 2. Because the overall processing time of the jobs is being minimized, Machine 2 is allowed to work on Job 3 first. In other words, idle time is not forced. Job 2 cannot be worked on by Machine 2 until Machine 1 finishes. The scheduling sequences and total completion times based on a delay scheduling assumption are shown in Figure 3.

Figure 4: Longest Processing Time Schedule for Example 1

The completion times for the jobs are as follows: Job 1 is 7, Job 2 is 8, and Job 3 is 1. The corresponding availabilities for the three resources are 1, 0, and 7 respectively. Since every hour of resource uptime is equivalent to 100 units of production, then the total production at the end of the time horizon is as follows:
8 hours * 100 units/hour = 800 units.
The above results show that scheduling using shortest processing time (SPT) is preferred over longest processing time scheduling. SPT both minimizes the total completion time of the machine/worker labor, while simultaneously maximizing the total production at the end of the time horizon. This gives a visual illustration that minimizing total completion time is equivalent to maximizing total production.

Maintenance Scheduling Example Number Two

An example of a personnel scheduling problem for maintenance personnel within a manufacturing supply chain is now considered. In order to make an open shop scheduling problem into a personnel scheduling problem, the assumption that states that there cannot be more than one machine/worker at a time at a job (scheduled maintenance task) is relaxed. The previous problem is considered and the new constraint (multiple machines/workers can work on the same job simultaneously) is applied, using the SPT and LPT once again. Figure 4 and Figure 5 give the results for this example.

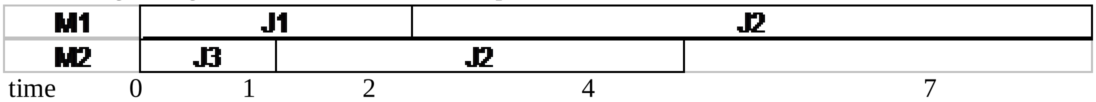

Figure 5. Shortest Processing Time Schedule for Example 2

The availabilities for the three resources are: 6, 1, and 7 for resources 1, 2, and 3, respectively. Since every hour of resource uptime is equivalent to 100 units of production, then the total production at the end of the time horizon is as follows:
(6 + 1+ 7) hours * 100 units/ time horizon in hours = 1400 units

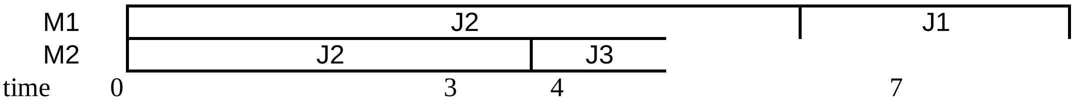

Figure 6. Longest Processing Time Schedule for Example Number Two

The availabilities for the three resources are one, three, and four for systems 1, 2, and 3, respectively. Since every hour of resource uptime is equivalent to 100 units of production, then the total production at the end of the time horizon is as follows:
(1 + 3 + 4) hours * 100 units/hour = 800 units.
The results for the example problems show that SPT sequencing produces better schedules than did the LPT. These results also show that the introduction of the new constraint where multiple workers can work on one job simultaneously actually increases machine availability for both rules. This is representative of maintenance environments which allow for differing maintenance tasks to be performed concurrently. Two such environments are discussed briefly later in this article.

Availability and Total Completion Time

The equivalence of the objectives of maximizing the availability of a collection of systems and minimizing the total completion time associated with repairing resources that are unavailable is now proved mathematically. As in the examples above, resource availability is observed at the beginning of a time period and the availability of a particular system is quantified by the total number of items produced by that system after a time period of length *T*. In this context, availability is measured by the total number of items produced collectively by the systems (resources) during the time interval [0, *T*].
In this situation A_i represents the availability of job *i*, C_i symbolizes the completion time of job *i*, p_j is the maintenance processing time for the j^{th} job, and *N* is the total number of jobs. Thus we have: $A_i = T - C_i$.

The maximum availability is $max(\sum_{i=1}^{N}(T - C_i))$. This is equal to both of the following: $max \sum_{i=1}^{N} T - \sum_{i=1}^{N} C_i$ and $NT - \sum_{i=1}^{N} C_i$. It can also be written as, $max(-\sum_{i=1}^{N} C_i)$ since NT is constant. Therefore, by duality, $mn \sum_{i=1}^{N} C_i$.

Maintenance Scheduling Environments

(Littlejohn and Stanfield (2005)) discuss two types of maintenance scheduling approaches that are found in manufacturing supply chain environments. In both approaches, the objective is to minimize the total completion time of scheduled jobs. The first approach is identified as, "Total Operation Completion Time Scheduling". This approach is observed when offline maintenance tasks are performed. For these environments, a part that needs work performed on it is removed and replaced by a part that is performing properly. The removed part is worked on at a separate location and only returned to service after maintenance work is completed. The formula presented by Littlejohn and Stanfield for this approach to maintenance is as follows:

$$min \sum_{i=1}^{N} \sum_{j=1}^{T} \sum_{k=1}^{M} \sum_{l=1}^{Z} (N-j+1) * p_{ijk} * x_{ijkl} \quad (1)$$

$$\sum_{k=1}^{M} \sum_{l=1}^{Z} x_{ijkl} = 1, \forall\ i = 1 \ldots N; j = 1 \ldots T \quad (2)$$

$$\sum_{i=1}^{N} \sum_{j=1}^{T} x_{ijkl} \le 1, \forall\ k = 1 \ldots M; l = 1 \ldots Z \quad (3)$$

$$x_{ijkl} = 0\ or\ 1 \quad (4)$$

Equation (2) ensures that each job and worker has exactly one position at a time. Equation (3) ensures that all positions have at most one job on a worker at a time. Equation (4) is a constraint that explicitly denotes x_{ijkl} as a binary decision variable.

For the second approach, multiple maintenance tasks must be performed in order for a system (ex.: assembly process, transportation truck, etc.) to be classified as ready to be used. The tasks are independent from each other. For example, consider a materials supply truck that is used to transport component machine parts from a supplier to a manufacturing plant. The truck has preventive maintenance scheduled several times a year in the following categories: engine maintenance, tire maintenance, and paint job. Each task can be completed separately from the other tasks. It is also possible for the simultaneous completion of these tasks. Since the truck is not considered ready to be used until all of these tasks are completed, the last task to finish determines the completion time for the system (where in this case the system is the supply truck). This approach is identified as, "Maximum Operation Completion Time Scheduling". The formula they presented for this approach is as follows:

$$\min \sum_{i}^{N} IJF_i \quad (5)$$

$$IJF_i = \max(woc_{jkl} * d_{ijkl}),\ \forall\ i=1\ldots N \quad (6)$$

$$woc_{jkl=1} = \sum_{i=1}^{N} t_{ijk} * d_{ijkl}\ \forall\ j=1\ldots T;\ k=1\ldots\omega; l=1 \quad (7)$$

$$woc_{jkl=1} = \sum_{i=1}^{N} t_{ijk} * d_{ijkl} + woc_{jkl-1}\ \forall\ j = 1 \ldots T; k = 1 \ldots \omega; l = 2 \ldots O \quad (8)$$

$$\sum_{k=1}^{\omega} \sum_{l=1}^{O} d_{ijkl} = 1\ \forall\ i = 1 \ldots N; j = 1 \ldots T \quad (9)$$

$$\sum_{i=1}^{N} d_{ijkl} \le 1\ \forall\ j = 1 \ldots T; k = 1 \ldots \omega; l = 1 \ldots O \quad (10)$$

$$d_{ijkl} = 0\ or\ 1 \quad (11)$$

Equation (6) defines the completion time of a job as the maximum of the operation completion times within that job. Equation (7) is used to figure out the time that an operation by worker type *j* is completed by individual worker *k* at position *l* when *l* is greater than 1. Equation (8) calculates the time that operation *j* is completed by worker *k* at position *l* when *l=1.* Equation (9) ensures that every job is assigned to only one position for a

worker. The next formulation ensures that for every worker type, at most one parallel worker is assigned to any job *i*. Equation (11) ensures that the decision variable, x_{ijkl} is binary.
This section has discussed maintenance and its importance in manufacturing environments. Two scheduling formulation were presented. These formulations can be used to increase the availability of resources at any point in a supply chain.

VI. CONCLUSION

This article has presented a discussion on flexibility in manufacturing systems. Important issues for consideration in flexible supply chains have been highlighted. The application of flexible manufacturing system technologies can improve the ability of some general manufacturing environments to meet the needs of customers. Maintenance requirements are ubiquitous within the supply chain for any manufacturing environment. Flexible manufacturing environments cannot exist in environments that have view maintenance as a low priority. Efficient maintenance scheduling is an important tool for any manufacturing environment. If properly understood and applied, good maintenance practices can greatly enhance the performance of any manufacturing supply chain and facilitate the creation of genuine flexible manufacturing systems.

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