An Integrated Approach for the Analysis of Manufacturing System States

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Abstract: With advancement in the manufacturing technology and rise in the purchasing ability, demand for newer products is increasing continuously. This is forcing manufacturing companies to persistently look for new techniques to improve the productivity of a manufacturing system and ensure optimum utilization of all the elements of a manufacturing system, including facility layout. Traditional research had viewed facility layout, material handling and productivity improvement as separate activities. Researchers depending on their area of specialization focused on either the production aspects of a company, the material handling aspects or facility layout. However, to ensure productivity, this study proposes a new theory to analyze the current state of the system with an integrated approach of production system and material handling system. In this study, the current state of the system is classified into three different states and a methodology is proposed to identify the current state of the system. This new theory can be used by manufacturers to identify appropriate strategies for improving productivity. The identification of the state of the system is necessary for effective improvement of the system.

Keywords: Manufacturing systems, states, integrated production and material handling systems analysis

1. Introduction

Every manufacturing system, irrespective of the type, has two important elements: production system and material handling system. Production system is defined as, those elements of the system that are responsible for transforming the raw materials to create parts which are usually then further assembled to form subassemblies or final products. The production system is responsible for processing of materials with consistent quality, in required quantities as and when needed. Material handling system is defined as those elements of the manufacturing system which are responsible for picking up, transporting, and setting down the raw materials. According to Tompkins, White, Bozer, and Tachoco (2010), material handling system is responsible for transporting the right amount of the right material, in the right condition, at the right place, in the right position, in the right sequence, and for the right cost, by the right methods. Material handling activities do not typically add any value to the product, but may contribute about 30 to 75% of total manufacturing cost, 55% of factory space, and 87% of production time (2010). Thus, any improvement in material handling activities can result in significant cost savings. An efficient material handling system can help reduce material handling cost, improve production operations, improve space utilization, improve flexibility and improve safety and working conditions.

Traditionally researchers have focused on either the production system or the material handling system. Several researchers have explored both these elements in detail, but in isolation to each other. For example, research focusing on material handling system ignores the aspects of production system, while research focusing on production system ignores the role of material handling system in the performance of overall manufacturing system. For successful implementation of the manufacturing system, both components should be considered simultaneously.

The role of material handling systems in manufacturing systems and its various aspects has been investigated over the past three decades. The research in material handling systems can be broadly classified into: a) systems aspect issues that are focused on scheduling techniques and b) resource parameters issues that are focused on the number of material handling units, the speed of material handling units, etc. Blazewicz et al., (1991) presented a polynomial time algorithm to find a feasible vehicle schedule, given that the production schedule is provided and proposed a dynamic programming approach to generate optimal production and vehicle schedules. Akturk and Yilmaz (1996) proposed a hybrid model for incorporating an Automated Guided Vehicle (AGV) module into a decision making hierarchies and developed a micro-opportunistic heuristic for solving the AGV scheduling problem. Klei and Kim (1996) proposed multi-attribute AGV dispatching rules and compared them with single-attribute AGV dispatching rules using simulation and concluded that the single-attribute dispatching rules are inferior to the multi-attribute rules. Langevin, Lauzon and Riopel (1996) presented an algorithm based on dynamic programming for a detailed plan of routing, dispatching and scheduling of two AGVs in Flexible Manufacturing Systems (FMS). Koo and Jang
(2002) proposed stochastic vehicle travel time models for FMS served by AGVs and used simulation experiments to validate the proposed models. Qiu et al., (2002) reviewed extensive literature related to scheduling and routing algorithms for AGVs and presented a comprehensive survey paper. The paper classified existing algorithms and suggested potential areas for future research. De Koster et al., (2004) evaluated the performance of various vehicle dispatching rules using discrete-event simulation models of three real world companies. Ho and Liu (2009) evaluated the effects of different load-selection rules and pickup-dispatching rules on throughput and tardiness, also the effects that load-selection rules and pickup-dispatching rules have on each other’s performance. Ho et al., (2012) proposed a multiple-attribute method to solve pickup-dispatching and load-selection problems for multi-load AGVs. All these studies have focused on the scheduling of AGVs while ignoring the facets of the production system (machining centers) and assumed a configuration for the AGVs (number, capacity and speed) mostly without any justification.

In the area of determining resource parameters for the Material Handling Systems (MHS), Egbelu (1987) was one of the first to develop analytical procedures for determining the number of AGV’s required for a given facility layout. He proposed four different models. Simulation tests done using the results of these analytical models showed that these models could be used to make an initial estimate of the number of AGVs required. Tanchoco et al., (1987) compared the effectiveness of CAN-Q (Computerized Analysis of Network of Queues) in determining optimum AGV fleet size with a simulation based method and concluded that the results obtained by CAN-Q can serve as a good starting point for the simulation based method. Lee et al., (1990) evaluated the different factors affecting the performance of the AGV served manufacturing system using discrete event simulation and concluded that a system with uniform arrival process might significantly reduce the job throughput time compared to a system with exponential arrivals. Sinriech and Tanchoco (1992) proposed a multi-criteria optimization model to determine the required number of AGVs considering two objectives: cost and throughput performance. Also, management decision tables were provided to enhance the solution procedures. Egbelu (1993) proposed a hybrid algorithm comprising of numerical search, computer simulation, and statistical analysis. The simulation provided the optimal unit load size and fleet size for AGV systems. Mahadevan and Narendran (1993) developed an analytical model to determine the required number of AGVs in the manufacturing system and tested the abilities of this model under various conditions. Rajotia et al., (1998) proposed an analytical model to determine empty vehicle travel time, which is a difficult task due to randomness of the FMS. The estimated empty vehicle travel time is then used for determining the required number of AGVs. Arifin and Egbelu (2000) developed an analytical model based on a regression technique to determine the optimal number of AGVs and compared the results of this model with that of the simulation method. Um et al., (2009) proposed a methodology to design AGV based material handling system by combining Multi-Objective Non-Linear Programming (MONLP) and simulation based evolution strategy techniques. All these studies that focused on determining the optimum resource parameters for AGV based material handling system ignores the facets of the production system in the manufacturing system.

Most of the researchers in the field of manufacturing systems have focused on scheduling and control strategies of parts on machines. A good number of these studies in this regard were carried out in the late 1980s and early 1990s. Denzler and Boe (1987) investigated various heuristic rules for the scheduling of parts in dedicated FMS. This study revealed simple heuristic rules were more effective compared to elaborate and complex ones. Han and McGinnis (1989) presented a discrete time flow control method for the flexible manufacturing cell. In this study, the cell operation was constrained by machine failures, limited buffer capacities and varying input rates from upstream cells. The objective was to minimize stock-out costs while meeting time varying demands. Wu and Wysk (1989) described a scheduling algorithm and evaluated various dispatching rules using discrete-event simulation. They also developed an expert system which learns from past decisions and generates candidate dispatching rules for ongoing operations. Lee and Jung (1989) applied a goal programming method to solve production planning problem in FMS. In this study, multiple conflicting objectives were considered. Park et al., (1989) developed a Pattern Directed Scheduler, which has the ability to learn patterns in heuristics and select the best scheduling rule under different scenarios. Kumar et al., (1990) presented multistage and multi-objective optimization models for grouping and loading problems in FMS. The compromise solution for the presented model was obtained using a min-max approach. Co, Bierrmann and Chen (1990) formulated a mixed integer program to address batching, loading, and tool configuration problems concurrently in the FMS. Chen and Chung (1991) investigated the FMS performance under different manufacturing policies and operating conditions. It was concluded that the performance of FMS reduces considerably if the inherent flexibility of the FMS is not exploited. Chandra and Talavage (1991) proposed an approach by which, a part, after finishing an operation, enters a general queue. Whenever a machine becomes available, it picks up a part from this general queue using an intelligent part selection strategy. This approach performed well compared to the heuristics utilizing conventional dispatching rules. Aytug et al., (2003) investigated interaction between dead-lock avoidance policies and effectiveness of dispatching rules in obtaining optimum system performance and found that both dead-lock avoidance policies and dispatching rules affect production rate, due date related performance measures, and time in system. Leus and Herroelen (2005) investigated the complexity status of machine scheduling problems with stability objective. In this study, a schedule is considered to be stable if it is robust enough to change little when uncertain events occur. Petrovic and Duenas (2006) proposed fuzzy logic based decision support system for parallel machine scheduling/rescheduling considering uncertain disruptions. Zandieh and Adibi (2010) introduced
scheduling method based on variable neighborhood search for dynamic job shop considering random job arrivals and machine breakdowns. All these studies that focused on scheduling and control strategies of parts in the manufacturing system do not consider the impact of the material handling system and therefore may lead to infeasible results.

Some of the literatures that considered the material handling system for analyzing the manufacturing system are given below. Akella, Choong and Gershwin (1984) described a method to calculate times at which parts should be dispatched into a system so that the effects of disturbances such as machine failures are minimized. Slomp, Gaalman and Nawijn (1988) analyzed three quasi on-line heuristic procedures used for scheduling of a work-station, a transport device, and an operator in the FMS. O’Grady and Lee (1988) described the use of an artificial intelligence technique for controlling operations in an automated manufacturing cell. Davis and Jones (1989) defined an online simulation approach for scheduling production in the FMS. In this approach, multiple simulators of FMS are initialized and stopped after some time to analyze the results based on which best rules were selected. Ro and Kim (1990) presented three new process selection rules and an AGV dispatching rule, based on heuristics, for solving operational control problems in FMS. A partitioning scheme was also presented which reduced the number of active schedules generated. Ishii and Talavage (1991) proposed a real-time scheduling algorithm for selecting the best dispatching rules dynamically for the next period of a brief time frame in order to respond to the complexities and dynamic behavior of FMS. Mukhopadhyay, Maiti and Garg (1991) presented an integrated heuristic approach to determine an optimal schedule of the FMS considering tool allocation, parts scheduling, pallets scheduling, machines scheduling and material handling equipment scheduling. Sabuncuoglu and Hommertzheim (1992) investigated the performance of different scheduling rules for machines and AGVs in a FMS environment using discrete event simulation. All these studies consider a material handling system for analysis. However, all these studies either assume uninterrupted availability of the material handling system or consider a random number of material handling units. The assumption of uninterrupted availability is valid only for conveyor based material handling systems and not for other types of material handling systems. Considering random numbers of the material handling units without any rationale and ignoring other factors such as capacity and speed of material handling units fails to reflect the exact role of material handling system in overall performance of the manufacturing system.

Based on the above discussion, it is evident that there is a need for an integrated approach to analyze the performance of the manufacturing system. The type of resource additions/enhancements should be based on the current state of the system and a more holistic approach has to be adopted. This integrated approach should consider both material handling resources and production resources to determine optimal decision making for enhancing the productivity of the manufacturing system.

2. Problem Statement

For an efficient manufacturing system, the two most important elements are production system (Machining Centers) and material handling system (MHS). To achieve increased productivity, additional capacities/resources have to be added to the manufacturing system which in turn requires additional investment. This additional investment should be justified by the improved throughput. In order to increase the throughput, there is a need for an integrated approach. There is a strong correlation between the production system and the material handling system. The performance or lack of one has an immediate impact on the productivity of the other. Any improvements in the manufacturing system can be achieved only by considering the state of the material handling system and the production system. Therefore, in this research an integrated approach for analyzing the manufacturing system considering two elements - the material handling system and the production system - is proposed.

It can be theorized that when the production system and the material handling system interact, the state of each system defines the performance of the manufacturing system. It is possible that either the material handling system or the production system could act as a bottleneck to prevent further increase in the productivity of the manufacturing system. Thus, the manufacturing system can be influenced by either the material handling system or the production system, which in turn will lead to different states. The manufacturing system can be in a logistics constrained state, production constrained state, transition state or in a market constrained state.

2.1 Manufacturing System States

In a dynamic manufacturing system, the current state of the manufacturing system has to be identified before appropriate increases in capacity of material handling system or production system are performed. The manufacturing system could be in any one of the following states: logistics constrained, transition, production constrained, or market constrained state.

2.1.1 Logistics Constrained State (LCS)

In the logistics constrained state, the performance of the system is influenced by the characteristics of the material handling system. Any change in the resource parameters of the material handling system (e.g. increasing the number, speed, or load carrying capacity of material handling units) will result in a direct change in the output performance parameter. In this...
state, improving the production system resources will have no impact on system performance. This state is usually characterized by high work-in-process inventory often at the exit buffer of the production machines, low utilization of the production machines, and high utilization of the material handling units.

2.1.2 Production Constrained State (PCS)

In this production constrained state, one or more production centers from the production system act as dominant bottlenecks and therefore, the performance of the system is not influenced by the performance of the material handling system. The only way to improve the system performance parameter is to identify the bottleneck machining center/centers and improve their performance. Production constrained state is usually characterized by high utilization of the production machines, low utilization of the material handling units, and high work-in-process inventory at the input buffer of the production machines.

2.1.3 Transition State (TS)

In the transition state, both material handling system and production system may act as bottlenecks. Any increase in the resources of the material handling system or the appropriate production system may result in improving the system performance. However, the rate of improvement in the system performance parameter is less compared to that of in the Logistics Constrained State or the Production Constrained State. In the transition state, is a result of both systems being dominant with high utilization or the result of high variability. Hence, it is necessary to relieve both constraints simultaneously to improve the performance parameters.

2.1.4 Market Constrained State (MCS)

A market constrained state occurs when there are not enough products in the system. This is usually characterized by low utilization of the material handling units and large idle times for the production machines.

2.2 Objectives

The main objectives of this paper are to propose a theory and develop methodologies necessary for defining and classifying the states of a manufacturing system as: logistics constrained state, production constrained state, and transition state to assist in the analysis of manufacturing systems. The study of market constrained state is not conducted here as this can be easily identified. The classification of these states will play a critical role in facility layout as well.

3. Classifying the State of the Manufacturing System

There are several parameters that can be used for the study such as throughput, utilization of machines, WIP inventory etc. In this research, throughput has been used as the parameter for study. The resource parameters for the material handling system considered in this research are the number of material handling units, speed of the material handling units and capacity of the material handling units. The resource parameters for the production system is the number of machines at each machining center. The modification of the resource parameters should be based on the state of the manufacturing system. The manufacturing system can be in a) logistics constrained state, b) transition state, or c) production constrained state.

Based on extensive modeling and simulation studies, it is theorized that in a logistics constrained state, increasing the number of units of the material handling system, will provide a graph similar to the one in Figure 1. It can be observed that as any parameter of the material handling system is increased, the manufacturing system throughput increases monotonously. The rate of improvement in throughput is high initially (say from P1 to P2). However, the rate of improvement of performance parameters is a monotonously decreasing function. Therefore, the range within which there is a high rate of improved performance (from P1 to P2) is the Logistics Constrained State.

The throughput continues to improve with increases in parameters of the material handling system from point P2 to P3, but the rate of improvement in the performance parameter decreases. From P2 to P3, both the material handling system and the production system may act as bottlenecks simultaneously. Therefore, if the resource parameter of the material handling system is increased, between P2 and P3, there may or may not be an improvement in the system performance parameter. Thus, the range in which the system performance parameter may or may not improve with an increase in the resource parameter of the material handling system can be considered as a transition state. The transition state exists because of the variability present in the system. The size of the transition state region for any resource parameter variation is dependent on the variability in the system – the larger the variability, the larger the transition state region.
Beyond point P3, there is no improvement in the performance parameter for the manufacturing system with increase in manufacturing resource parameters. This indicates the change of the system state from the transition state to production constrained state. In fact, in simulation studies, it has been seen that blocking and other factors may lead to a reduction in performance parameter even before the production constrained state is reached. Thus, the region in which there is no improvement in the system throughput with increases in the parameters of the material handling system is the production constrained state. Previous studies of bottleneck machines in manufacturing systems were limited to production machines. In a holistic analysis of the manufacturing system, when the material handling system acts as the bottleneck, the system performance can be significantly improved by mitigating the impact of the material handling system rather than increasing the capacity of production machines.

Similarly, for a manufacturing system in a non-market constrained state and in a production constrained state, the change of performance parameter with any resource parameter of the production system, may provide a graph similar to the one in Figure 2. In this case, the system is moving from a production constrained state to a logistics constrained state. In a production constrained state, as any resource parameter (such as additional capacity, speed of processing etc.) of the production system is improved the performance parameter improves. Figure 2 is obtained by using process time as a resource parameter and the simulation assuming no variability in the system. The performance parameter improves at a higher rate with increase in resource parameter (from point P1 to P2). The manufacturing system undergoes a transition from a production constrained state to a transition state and then to the logistics constrained state. The transition of the system state is similar to the one explained before, except in this instance, it is the production parameters that are being increased.

Based on the characteristics of this graph, the current state of any given system can be categorized into three states as a logistics constrained state, a transition state and a production constrained state. Several case studies to understand and test the hypotheses were developed. Some of these case studies are used to demonstrate the concepts of manufacturing system states.

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**Figure 1. Ideal Case Graph of Performance Parameter vs. any Resource Parameter of MHS**

**Figure 2. Ideal Case Graph of Performance Parameter vs. any Resource Parameter of Production System**
3.1 Case Study for Studying Behavior of the Performance Parameter

In this case study, a system in a logistics constrained state is considered. The performance parameter of the manufacturing system considered for this case study is throughput and the resource parameter of the material handling system with respect to which the system states are observed is speed of the material handling unit.

3.1.1 Manufacturing System and Material Handling System Considered for Case study

The layout of the manufacturing system considered for this study is shown in Figure 3. There are a total of five machining centers (M) with one machine each. These machines are capable of performing multiple operations on parts. Each machining center has a drop-off station (D) and a pick-up (P) station for storing unfinished and finished parts respectively. The queue sizes at the pick-up and drop-off stations are maintained independently with infinite capacities. In addition to machining centers, one input center as well as an output center is present through which raw materials enter and final products exit the manufacturing system respectively. The inter-arrival time at the input center is assumed to be deterministic with a time of two minutes.

In this case study, all material handling paths are unidirectional and the arrows in Figure 3 indicate the direction in which material handling units (MHU) can travel. It is assumed that the MHU speed is constant, irrespective of the load. Requests to transport part/parts from one location to another are initiated by machining centers. When a task is assigned to an MHU, it moves along the minimum distance path. If there are multiple MHUs that are idle when a task is initiated, the closest idle vehicle rule is used to determine task assignment. If there are no idle MHUs when a task is initiated, the task is added to the waiting list and will be assigned to the next idle MHU. If multiple tasks have accumulated in the waiting list to be assigned and any single MHU becomes free, the closest task rule will be used to assign the vehicle to the task. This rule ensures that, the empty travel time for all the MHUs is minimized. The parts accumulated at pick-up and drop-off stations at each machining center are accessed on a First Come First Serve (FCFS) basis. All the part types processed in the manufacturing system are assumed to be of unit load. So, if the load carrying capacity of the MHU is specified to be four, the MHUs are able to carry four parts of any combination of part types. To make sure that the MHUs are utilized to their optimum capacity, the transportation request for a MHU is generated only when enough number of parts, which is equal to the capacity of the MHU, has accumulated at the pick-up station. Once the assigned task is completed by an MHU and if there is no any immediate task to be completed, the MHU returns to its home position.

The manufacturing system processes four types of parts concurrently and the product mix-ratio as well as processing sequence for each part type is provided in Table 1. The processing time is assumed to be deterministic for this case study and the processing time for each part type on respective machining centers is provided in Table 2. It is assumed that the setup time is negligible.

![Figure 3. The Layout of the Manufacturing System](image-url)
Table 1. The Mix-Ratio and Process Sequence for Each Part Type

<table>
<thead>
<tr>
<th>Part Type</th>
<th>Mix-Ratio</th>
<th>Sequence</th>
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<tbody>
<tr>
<td>1</td>
<td>0.25</td>
<td>M2-M3-M5</td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
<td>M1-M3-M4</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>M3-M4-M5</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>M1-M2-M4</td>
</tr>
</tbody>
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Table 1. The Processing Time on Each Machining Center

<table>
<thead>
<tr>
<th>Part Type</th>
<th>Processing Time</th>
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<tbody>
<tr>
<td></td>
<td>M1</td>
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<tr>
<td>1</td>
<td>4.5</td>
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<tr>
<td>2</td>
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<td>3</td>
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3.1.2 Experiments

The manufacturing system described in the previous section is simulated using the DELMIA QUEST simulation package. As the parts enter the system from a source they are transferred to the input buffer. As soon as a unit load is accumulated at the input buffer, a request for transportation is generated. The parts are then transported to the respective machining centers according to their routing sequences. Once the part is processed at the last machining center it is transported to the sink from where it exits the system. The resource parameters of the material handling system considered in this study are the number of MHUs, the speed of MHUs, and the load carrying capacity of MHUs. The different levels for each resource parameter considered in this study are listed in Table 3. In this study, the simulation experiments are run to investigate the behavior of the three proposed states with respect to the speed of MHUs and the effect of number and load carrying capacity of MHUs on the proposed states are investigated. The performance parameter used for the system is throughput. 350 experiments for all combinations were simulated (Table 3). For each combination, the simulation model is run for 10 days with one shift (8 hours) per day and warm-up period is 2 days.

Table 2. Different Levels of Resource Parameters of MHS

<table>
<thead>
<tr>
<th>Number of MHUs (N)</th>
<th>Speed of MHUs Feet/minute</th>
<th>Capacity of MHUs</th>
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<tr>
<td>1</td>
<td>10</td>
<td>1</td>
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<td>2</td>
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3.1.3 Results of the Case Study

Throughput is obtained for each combination of design parameters shown in Table 3. In this case study, at the initial speed of 10 feet/minute it is observed that irrespective of the number of MHUs and their load carrying capacity, the system is in a logistics constrained state. The utilization of the material handling system is almost 100%, whereas the production system is underutilized. For example, the utilization of each machine in the production system for single MHU and single load carrying capacity is 7.57%, 7.82%, 8.22%, 32.36% and 8.64% respectively. The graphs of throughput versus speed are plotted for different combinations of the number of MHUs and the load carrying capacity of MHUs as shown in Figures 4 through 8.

For example, Figure 4 shows the effect of increasing speed on throughput for different numbers of MHUs in the system. All MHUs are assumed to have a unit load capacity of one. In this case, with a single MHU, the system does not arrive at a production constrained state within the considered speed range of 0-300 feet/minute, whereas for 2, 3, 4 and 5 MHUs it arrives at the production constrained state around the speed of 100, 70, 50 and 30 feet/minute respectively. It can be seen that, as the number of MHUs increases the system approaches a production constrained state faster (slope of the curve increases) and consequently arrives at a production constrained state at relatively lower speeds. Figures 5 to 8 are similar in nature to Figure 4 except for the load carrying capacity of the MHU.

Comparing plots across the Figures 4 to 8, it can be seen that as the load carrying capacity of the MHU increases, the system approaches a production constrained state faster (slope of the curve increases) and consequently arrives at a production constrained state at comparatively lower speeds. For example, consider the case of a single MHU (N=1) across Figures 4 to 8. In this case, for a load carrying capacity of one, the system does not arrive at the production constrained state within the considered speed range of 0 to 300 feet/minute. Whereas, for load carrying capacities of 2, 3, 4 and 5; the system arrives at the production constrained state at around the speed of 200, 170, 110 and 90 feet/minute respectively. Comparing plots in Figures 6 to 10 for an increased number of MHUs (2, 3, 4 and 5) similar trends can be seen.

![Figure 4. Throughput vs. Speed, for N=1 to 5 and capacity=1](image)

![Figure 5. Throughput vs. Speed, for N=1 to 5 and capacity=2](image)

![Figure 6. Throughput vs. Speed, for N=1 to 5 and capacity=3](image)
4. Methodology to Identify the Current State of a Manufacturing System

Identifying the current state of a manufacturing system will help to focus on the right element (either production system or material handling system) of a manufacturing system which eventually, will lead to faster and effective decision making. The demands for products may change from period to period and manufacturing systems are expected to respond to the changing trends of the market. Hence, manufacturing systems have to undergo changes over time to maintain its productivity. These changes might include adding new product to the line, removal of existing product due to reduced demand, replacing existing machineries with advance ones, and changes in sequencing or control strategies. Every time a manufacturing system undergoes such changes, the current state might change and it becomes important to identify the changed current state. For all these reasons, it is essential to identify the current state of a manufacturing system. Therefore, in this section a generic method to identify the current state of any manufacturing system is proposed. A flowchart describing a generic method to identify the current state is provided in Figure 9.

This method is based on utilization threshold values for both the material handling system as well as the production system. In order to understand these terms, the ideal case graph of average utilization of MHUs and average utilization of bottleneck machine/machines versus any resource parameter of the material handling system, for the manufacturing system in a logistics constrained state and not in a market constrained state, is provided in Figure 10.

From Figure 10, it can be observed that at the lowest value of the resource parameter the average utilization of MHUs is almost 100% while average utilization of bottleneck machine/machines is relatively low. As the resource parameter increases, the average utilization of MHUs starts decreasing while that of bottleneck machine/machines starts increasing and at some value of the resource parameter they may cross each other. The utilization threshold for MHS and utilization threshold for production system can be defined as follows.

**Utilization Threshold for MHS**: Minimum average utilization of MHUs above which, the material handling system starts acting as a bottleneck which may or may not be dominant one.
**Utilization Threshold for Production System:** Minimum average utilization of bottleneck machine/machines above which, the production system starts acting as a bottleneck which may or may not be a dominant one.

**4.1 Principle of Selecting Utilization Threshold**

The selection of a threshold value depends on several factors such as type and size of manufacturing systems, scheduling and control policies of parts on machines, scheduling and routing policies for material handling units, price of the production system vs. price of the material handling system, and type of material handling system being used (manual vs. automatic or conveyor based vs. vehicle based). If the manufacturing facility is a job shop, the utilization threshold for the production system and material handling system may be set at 70 to 80% to ensure flexibility and taking into consideration the random nature of the process flow. On the other hand, for assembly shops the utilization threshold for both production system as well as material handling system may be set as high as 90 to 95%, as the flow sequences are more standardized and are relatively less variable. The price of production equipment can also influence the threshold value. In the case of expensive production machines, the company typically would be reluctant to add additional capacities unless it is required and would like to fully utilize the available resources. This can be achieved by setting higher utilization threshold values for the production system. If material handling equipment is relatively inexpensive, having a low utilization threshold for the material handling system ensures that more capacity is added to the material handling system and will ensure that the system is in a production constrained zone.
5. Conclusion and Future Work

In this paper, an integrated approach to analyze the current state of the manufacturing system is proposed. This approach integrates two important elements of the manufacturing system: the production system and the material handling system. According to this approach, at any given time, the manufacturing system under consideration can be in any state such as LCS, TS, or PCS. These three states of the manufacturing system have been defined and their characteristics are described in this paper. It is proposed that these three states of the manufacturing system can be identified by using simulation models.

With the help of a case study, the three proposed states of the manufacturing system are described with respect to the speed of the MHUs. A generic methodology to identify the current state of the manufacturing system is proposed. A methodology is explained to distinctly identify the speed of the MHU, at which the current state of the manufacturing system transforms from LCS to TS and from TS to PCS. In addition, the effect of other resource parameters of the material handling system such as the number of MHUs and the load carrying capacity of MHUs on the three proposed states is investigated. From results of the case study it is found that as the number of MHUs is increased, the speed at which the system enters the PCS decreases and the speed range within which the system appears to be in LCS and TS also decreases. The load carrying capacity of MHUs has similar effects as that of the number of MHUs on the three proposed states.

The proposed generic theory regarding the three states and the methodology explained with a case study helps manufacturing system designers to focus on the right element (production system or material handling system) of the manufacturing system and thereby assisting in making appropriate decisions. It is also useful in planning a transition from the current state of the manufacturing system to a desired one and can be used to verify if the manufacturing system is operating in desired state. Though this study provided the preliminary work necessary for an integrated approach for the analysis of the current state of the manufacturing system, the methodologies does not address the impact of variability on the manufacturing system states. In addition, the study assumes infinite buffer. The methodology can be extended to include the impact of finite buffer capacities in the design of the manufacturing system.

6. References


