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Some Control Strategies in a Flexible Manufacturing System-A Simulation Perspective

Amrik Singh[1], Dr. Jagtar Singh and Dr. Mohammed Ali[2],*

[1]Associate Professor, Department of Mechanical Engineering, Sant Longowal Institute of Engineering and Technology, Longowal (Deemed to be University) Longowal (Punjab), India.

[2]Professor, Department of Mechanical Engineering, Sant Longowal Institute of Engineering and Technology Longowal, (Deemed to be University) Longowal (Punjab), India.

[3]Professor, Department of Mechanical Engineering Department, Aligarh Muslim University, Aligarh-U.P, India.

**Corresponding Author*

Abstract

In the recent globally competitive manufacturing environment, the ardent need of the manufacturing system is performance in stipulated time. The manufacturing systems having inherent characteristics of flexibility, leads to the development of Flexible manufacturing systems (FMS) merging the ideology of flow shop and batch shop manufacturing system. Simulation is a most important and powerful analytical tools for process improvement and modeling of complex systems like flexible manufacturing systems (FMS). The planning , scheduling and control problems in (FMSs), are composed of a set of interrelated issues of part-type batching, machine grouping, part routing, tool loading, part input sequencing, resource assignment and utilization. The control decisions in an FMS must be capable of handling these diverse factors on a real-time basis simultaneously.

Because of the high investment costs of FMSs, choosing the worth control policy is of paramount importance. The control decisions in FMSs are dependent on an appropriate selection of the performance measures. In the Present work a review of simulation and the use of commercial packages have been explored and accordingly a conceptual model for the shop floor control system (SCFS) analyzing the control strategies have been developed and discussed.

Keywords: Flexible Manufacturing System; Real time control strategies; Dispatching; Shop Floor Control System (SCFS).

INTRODUCTION

Global manufacturing industries synthesized by shortened product life cycles and different product varieties are gradually changing from economies of scales to that of scope. Automation started at beginning of 20th century and increased productivity, quality thereby reduced the costs. Flexibility in manufacturing system responded for varying demand with different product variety and smaller production lots. Advent of flexible manufacturing systems (FMS) identifies this need for programmable automation thereby enabling higher productivity and quality.

FMS a system of semi-dependent workstations, controlled by an integrated computer system consists of number of processing stations interconnected by an automated material handling and automated storage/retrieval system. It efficiently manufactures different part types with low to medium volume. It is a set of independent machining centers .FMS provides the benefits of flexible job shops and the efficiency of large volume manufacturing (Siwamogsatham & Saygin, 2004). Asynchronous AGVs are widely used in large-scale FMSs for increasing the efficiency and reducing distribution costs. (Nishi et al, 2003; Barberaet al., 2003).

The complex work pieces with different operations on a variety of products are usually made due to versatile nature of FMS. The struggle for best quality, lower costs and shorter response time always pre dominates any competitive industry. Consequently products and production system become more complex with a large set of uncertainties. The decision making problems related to shop floor control in flexible manufacturing system are sensitive as compared to conventional manufacturing system. System integration, tight synchronization, and inter dependencies among components in FMS explore four stages i.e. design, planning, scheduling & control therefore requires immediate response to the changes in system state to be achieved by real time scheduling (RTS). Shop floor Control System (SFCS) or (PAC) production activity control in manufacturing system is well described by (Browne 1984), It essentially deals with priority control, allocation of shop orders, monitoring information on WIP for MRP ,shop order status, thereby providing output data for capacity control purpose. The shop floor control system should be designed to accomplish these functions. The major modules are order release concerning route sheets, material requirement job cards etc. order scheduling determines priority control and releases dispatch lists. Order progress accomplish data related to WIP, shop order status and capacity control.

The research paper is organized into four sections. Section two gives a review of the literature on the subject. Section three is on manufacturing flexibilities and section four covers the control modeling and discussions.

LITERATURE REVIEW

This research reviews the approaches which can be used for design and control of an FMS.A brief review on the design of FMS, scheduling, control system is hereunder.

The importance of flexibility has been explored extensively in the literature (Gerwin, 1983; Slack, 1987; Tombak, 1988). Among different types of flexibility referred in the literature, manufacturing flexibility is must, for coping with the internal and external disturbances in the organizations. Internal disturbance in the form of equipment breakdown, variable task times, queuing delays, rejects and rework (Buzacott and Handelbaum, 1985) and external disturbances attributes to uncertainty from changes or fluctuations in demand level, product prices, product mix etc.

The importance of simulation in studying the impact of system failures and delays on the output and cycle time of finished parts is presented by Williams (2002). Pate1 et a1 (2002) used discrete event simulation(DES) for estimating and analyzing first time success rate, repair and service routing logic, process layout, capacity of testing equipment and random equipment breakdown in manufacturing processes. Rogers (2002) has used Opt Quest module of ARENA for optimization to manufacturing system design and control problems. Altinkilic (2004) uses Arena simulation for improvement in performance of shop floor. Chen (2002) used simulation as critical decision support tool in a chemical plant for logistics operations, capital equipment requirements. A new concept based on the object oriented approach, of discrete event modeling is used to simulate continuous production flow. Applications of simulation in the fields of military problems have been studied by Hill (2001) and Standridge (1999) for health care applications respectively. Graves and Higgins (2002) presented a combined simulation study for logistics and military requirements in transportation and maintenance. The simulation have been used as a tool for developing, evaluating and analyzing different policies, business practices and procedures within set of operational and business constraints of cargo operations facilities at Toronto Pearson Airport.(Nsakanda and Turcotte ,2004).

MANUFACTURING FLEXIBILITY

Flexibility an inherent attribute and intangible asset of a manufacturing enterprise is a fuzzy word which is broadly used. A flexible system accommodates the ability to cope with customers' preference changes. Mandelbaum (1978) explores action and state flexibility. In Action flexibility outside intervention is required before the system can respond to change, where as in state flexibility system's capacity to respond to change is contained within the system. Carlsson (1989) discusses about Type-I and Type-II flexibility. Type-I flexibility accommodates known uncertainty and Type-II flexibility take care of unknown flexibility. Conversely, flexibility as multi-dimensional concepts within manufacturing functions which can be either reactive or proactive in nature as reported by Sethi and Sethi (1990); Hyun and Ahn (1992).

Table-1: Classifications of Flexibilities

Machine flexibility	ease of making changes among the machines required to produce a given set of parts
Process flexibility	An index of part types is the ability to manufacture a given set of parts, possibly using materials, in different ways without reconfigurations.
Product flexibility	Ease by which the part mix can be changed in order to manufacture or reassemble new products.
Routing flexibility	Ability to manufacture a part using different alternative routes, handle breakdowns, to continue producing a specific part. Determines number of potential routes & back-up machinery in case of breakdowns
Volume flexibility	Ability to operate profitably at the different throughput levels. Quantified by the range of volumes for profitable runs.
Expansion flexibility	Modular & expandable capability of a system measured by time or cost required for the system's expansion to given capacity
Operation flexibility	Ability to interchange the ordering of several operations for each part type. Measured by number of different operation sequences for producing a part.
Production flexibility	All the part types that the manufacturing system can produce

Flexibility is the ability to adapt to rapidly changing circumstances and processes as customer's requirements without wasting production recourses. Flexibility deals with environmental uncertainty, (internal and external), faced by an organization. Slack (1983), reported the proactive nature of flexibility allowing the organization to 'redefine market uncertainties'. Gerwin (1993). Cheng et al. (1997) reported three types of flexibilities, diversity flexibility to handle the variety of change, response flexibility to cope with the rate of change and volume flexibility for the magnitude of change whereas design flexibility is the incremental cost and the time of modifying a design. Three types of flexibility necessary flexibility, sufficient flexibility and competitive flexibility have been described. Sethi and Sethi (1990), proposes eleven types of flexibility adding three more that is material handling, program and market flexibility to this list of Brown et al. (1984). Koste and Malhotra (1999) describe ten types of flexibilities namely machine, material handling, routing, operation, expansion, labor, volume, mix, new product, and modification flexibility. Manufacturing flexibility as proposed by Brown et al. (1984) represents the most comprehensive classification and have been mentioned in the Table-1. The interdependency of these flexibilities is shown in Figure-1.

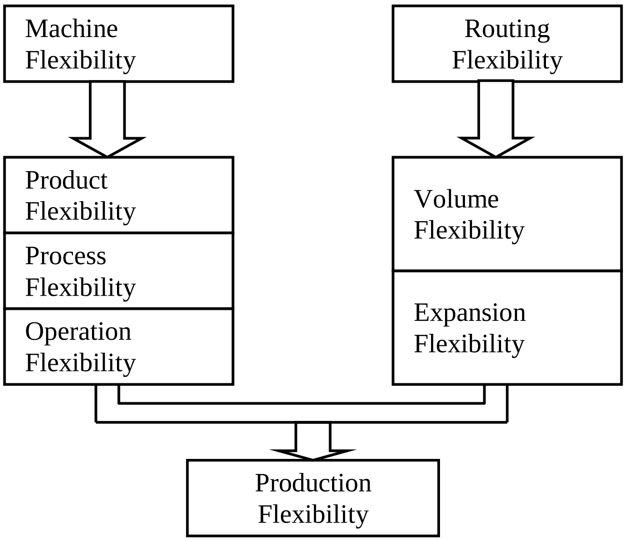

Figure 1: The interdependencies of Manufacturing Flexibilities

Flexibility is enabled in a manufacturing system by potential flexible and alternative production routes. Such potential routes uses different equipment types, capable & performing same operations or using different manufacturing processes. For achieving this, an efficient shop floor control system (SFCS) provides good scheduling decisions in dynamic manufacturing environment. The present work focuses on the effect of machine and routing flexibility on performance of flexible manufacturing system.

Machine Flexibility: The capability to adapt a given machine /workstation in the system to a wide range of production operations and part types. More the range of operations and part types, the greater is machine flexibility. The time required replacing worn-out or broken cutting tools, changing tools in a tool magazine, assembling or mounting the new fixtures required, preparing cutting tools, positioning the part, and changeover the numerical control program can be taken as the measure for machine flexibility. The easily accessible programs, numerical control, automatic tool changing ability, size of the tool magazine, standardized tools, number of axes, etc." can be taken as sources of machine flexibility (Sethi and Sethi ,1990). Barad et al. (2003) machine flexibility is the most fundamental flexibility type. It is easily grasped as a concept and measured on range and response dimension. Mohammed et al. (1995) presents a study where degree of machine flexibility and level of system performance is analyzed. Semra Tunali (1997) evaluated alternate routing policies in Scheduling a job-shop type FMS subjected to unexpected machine breakdowns. Singholi, Md Ali (2010) explored the effect of machine flexibility on the performance of FMS.Mohammed Ali (2014) explored the use of different manufacturing strategies decisions in a simultaneous manner, which improves the performance of the flexible manufacturing systems significantly.

Routing Flexibility: The capacity to produce parts through alternative workstations sequence in response to equipment breakdown, tool failures, and other interruptions. Routing flexibility, based on the concept of entropy includes the reliability of machines (Yao et al ,1985). Pankaj et al. (1991) incorporates the reliability of machines to study routing flexibility. Wadhwa et al. (1998), shows that the make span performance deteriorates with an increase in decision delays, and the deterioration is higher at higher levels of routing flexibility. Miltenburg (2001) considers routing and bill of materials for production planning. Zhao et al. (2001), considers genetic algorithm to the scheduling of FMSs with multiple routes. Barad et al. (2003), states that routing flexibility is the capability of processing a part through varying routes, using alternative machines. and increases with the individual versatility of the machines in the set. Garavelli (2001) analyzed the performance of several manufacturing systems using simulation characterized by a specific degree of routing flexibility. A system with limited flexibility performs better in terms of lead time and work in process. Chan (2003) reported the effects of dispatching and routing decision on the performance of FMS using simulation .ElMaraghy (2003) use flexible routing in order to avoid system deadlock caused by machine breakdowns and downtimes. Chang (2007) proposed a multi-attribute approach incorporating routing efficiency, versatility and variety for measuring routing flexibility. Mohammed Ali (2012), explores the Impact of Routing and Pallet Flexibility on make span in FMS.

SIMULATION METHODOLOGY

Simulation is the process of designing a model of a real or imaginary system and conducting experiments for the purpose of either of understanding the behavior of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system. Simulation, a numerical technique is an operating model of a real system for conducting the experiments & studying the behavior for performance evaluation. Three key elements decision, timing and information are essential for a successful simulation project. Simulation is used as a tool correct selection among the possible alternatives, time compression and expansion which allows exploring the possibilities of new policies, operating procedures, diagnose problems of complex systems impossible to deal within the real environment, identify the constraints for bottleneck operations and plan using the animation capabilities. Simulation analysis becomes more powerful, when used along with other techniques of industrial engineering such as sequencing and routing analysis, bottleneck, and facility layout analysis, for adopting appropriate control strategies for improving performance of the flexible manufacturing system. However simulation may not be the perfect tool for all types of system some of the limitations can be underlined as special training for modelers, correct interpretation of simulation results and inappropriate use of simulation models. Mohammed Ali, Subhash Wadhwa. (2005) explored the make-span performance of partial and total flexible systems considering different system variables using simulation modeling.

Simulation Software Packages

The various control strategies can be studied using Simulation analysis before one can suggest an optimum solution. Simulation can be used effectively for the design and operation of FMS as a decision support system for real time scheduling. A review of simulation work reveals that many real situations are modeled earlier using high level programming languages such as FORTRAN, PASCAL TURBO C etc. To name few more such SIMULA, SIMAN, GPSS, SIMSCRIPT have been reported by Kochhar (1989).

Table-2: Software Packages

Name of simulation tool	Web address
AUTOMOD	http://www.autosim.com
PROMODEL	http://www.promodel.com
ARENA	http://www.arenasimulation.com
AWESIM	http://www.pritsker.com
WITNESS	http://www.lanner.com
FLEXSIM	http://www.flexsim.com
EXTEND	http://www.imaginethatinc.com
GOLDSIM	http://www.goldsim.com
MAST	http://www.cmsres.com
SIMCAD	http://www.createasoft.com

In the recent times use of software packages have become more relevant to save the time, cost and efforts. Arena discrete event simulation software is used for simulation modeling of a complex manufacturing system. An experimental graphical model is built by placing modules in the graphic window, which represent processes or logic. Detail analysis of operations and flow is available.

Flexsim Software another powerful simulation analysis tool is used for making intelligent decisions in design and operations of manufacturing system. SIMPROCESS a hierarchical modeling tool combines processes mapping object oriented modeling, DES and process costing. A graphical drag and drop tool used for model development, process optimization, resources and product costing visualization of process dynamics and bottlenecks. Some of the user friendly softwares reported in the literature for manufacturing simulation are listed in Table II.

SIMULATION OF FLEXIBLE MANUFACTURING SYSTEM

Flexible manufacturing system (FMS) is a configuration of computer numerically controlled (CNC) machines with supporting workstations interconnected by conveyors/material handling systems and a centrally controlled by a computer. The four major subsystems of FMS are: automatic and reprogrammable machines, tool changing/delivery system, material handling system for loading and unloading parts in between machine and stations /finished parts and a computer control. The systems having few numbers of machines 2 to 3 are referred as flexible cells and with more numbers are referred as FMS. These systems are capital intensive and complex in nature from view point of routing the parts/machines and controlling the operations.

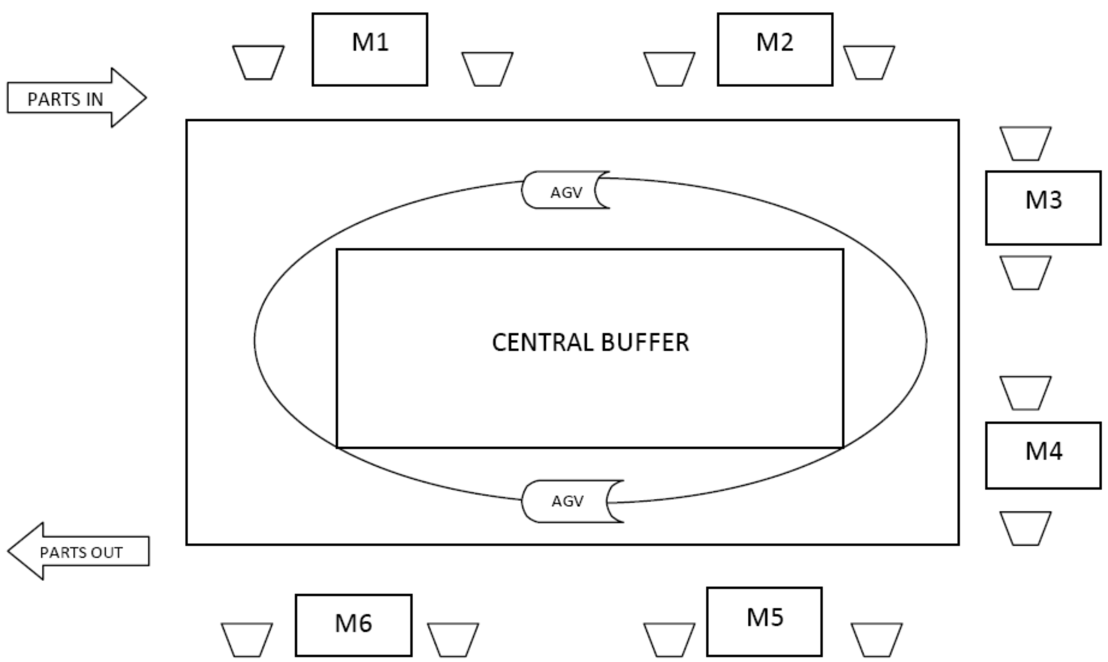

Figure 2: Sample Flexible Manufacturing System.

In the present study related to the dynamic environment of sample Flexible manufacturing system (FMS) has been configured as shown in Figure2. In this study FMS is comprised of six different workstations each with a local buffer at input and output. The system can manufacture ten different part types which arrives in the systems as work order. Each work order comprises of a set of different part types. To fabricate each part type three to six operations are required. Each machine is capable of performing different set of operations. The total numbers of different operations which could be performed on different machine are ten. Some of the operations can be performed by number of different machines. A central buffer and two AGVs are considered in the layout to meet the eventuality of bottleneck for satisfactory system performance.

CONTROL MODELING

According to Tang et al (1995) two kinds of decision are relevant in control modeling, firstly pre-release decision (sequencing decisions)and post release decisions (Dispatching).Pre-release decision deals with study of control framework at design stage, which ease management of resources and part types while post release decision deals with part routing while system is in operation. The decisions are real-time in nature and mostly deal with simulation studies. Mohammed Ali & Subhash Wadhwa (2010) found that there is the influence of control strategies on the performance of FSIM and observed that the impact on the system performance due to the system load condition is the largest, as that of the number of pallets.

Table-3: Sequencing Rules

FIFO First in first out	Part which arrives first on the machine is chosen for processing first.
SPT Shortest Processing time	This rule selects the part from the queue in the buffer with lowest processing time $SPT = min_{i \in SJ_q}(Pij)$ Pij = Process time of the operation of i_{th} job, i = Job index, SJ_q= Set of jobs in a queue
SRPT Shortest Remaining Processing Time	Selects of job for the next operation, having minimum remaining processing time. Mathematically SRPT $= min_{i \in SJ}\left(\sum_{j \in SR_i} P_{ij}\right)$ P_{ij} =Processing time of the operation of i_{th} job i = job index SJ_i = Set of jobs in queue SRi =set of remaining operation of job i.
MBPT Maximum balance processing time	Selects the part which has maximum balance processing time $MBPT = max_{i \in SJ_q}\left(\sum_{j \in SR_i} P_{ij}\right)$ P_{ij} =Processing time of the operation of i_{th} job i = job index SJ_q = Set of jobs in queue SR_i =set of remaining operation of i_{th} job in queue at input buffer

Sequencing rules

Sequencing rules are used for selecting a part for processing on a machine among the parts waiting in the buffer. Once the work order arrives in the system the decision for part launching is important.

The manufacturing lead time for different parts depends on the processes type, operation time resource /machine availability pallet fixture usage and level of parts congestion in the system. The following few sequencing rules considered prominently are shown in Table-3.

Dispatching decisions

Selecting the adequate resource according to the capability is a challenging decision for effective resource utilization and optimal system performance. Dispatching decisions considered are mention at Table-4.

Table-4: Dispatching Decisions

MQMWT Minimum queue with minimum waiting time	Part decides the machine with minimum queue length and waiting time in queue at buffer of all alternate machines.
MINQ Minimum queue at Buffer	Parts decides the machine having minimum queue length among all alternate machine

CONCEPTUAL MODEL

A conceptual model of the shop floor control system (SCFS) as shown in Figure 3 have been evolved *for* the sample FMS shown in Figure 2.This flexible manufacturing system under CIM domain having six numbers of workstations/machines have been considered along with two AGVs .The logical flow in this conceptual model is associated with physical flow of parts types. Each part type have been modeled as physical entities and for each physical entity a logical entity is associated. These entities are modeled based on input parameters (Design, Planning and Control) in order to evaluate the impact of manufacturing (machine, routing) flexibilities on the performance of flexible manufacturing system.

CONCLUSION

In the present paper an effort has been made to propose a methodology which allows integration between a simulation model, and physical model configuring to material flow, their physical characteristics and a logical model configuring to modeling of control system for the analysis of the performance of flexible manufacturing system using discrete event simulation modeling. The modeling of the control strategies has been outlined through a conceptual model which shall be useful to explore the development of CIM systems in phased manner with an emphasis on various Flexibilities. Further CIM systems and the SFCS model acts as a expedient platform to study such issues. In this work a SFCS framework was described from a simulation perspective. The SCFM model focused on judicious use of manufacturing system design parameters. SFCS model thus offers the possibility for further investigation in the present methodology and can be explored considering integration between sequencing and dispatching decision with respect to the stochastic operation times and machine breakdowns.

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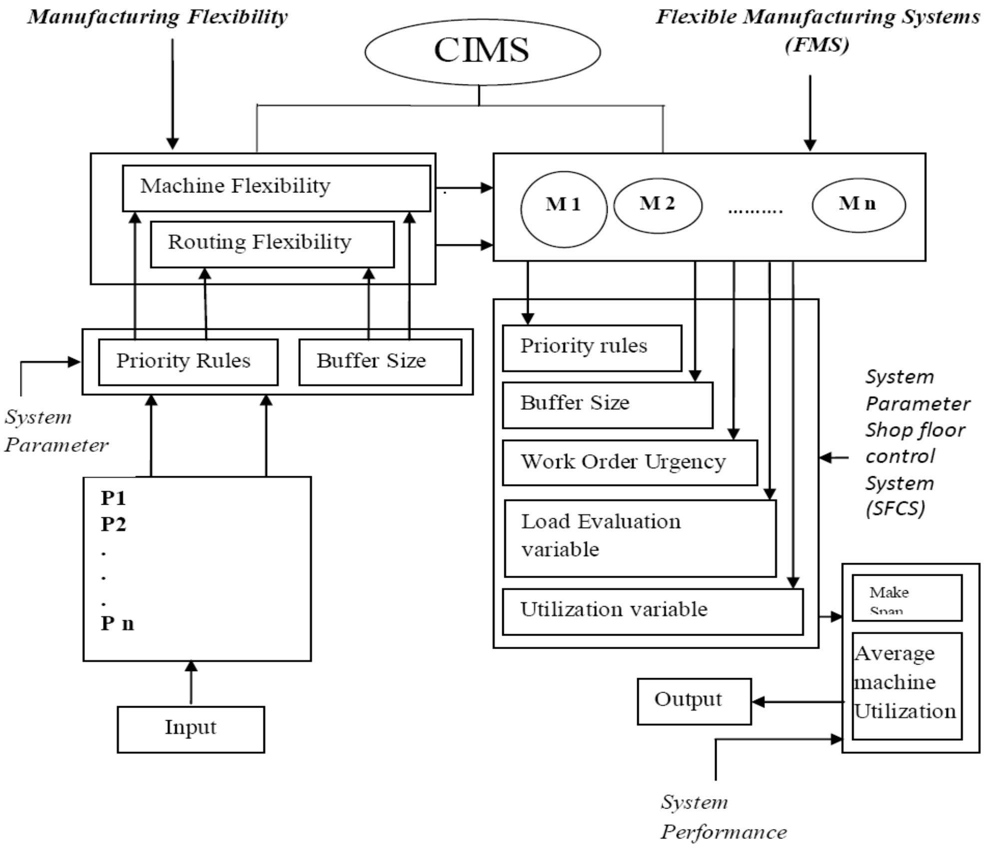

Figure 3: Developed Conceptual Models for SCFS.

REFERENCES

[1] Siwamogsatham, T. and Saygin , C. 2004 "Auction-based distributed scheduling scheme for flexible manufacturing system, International Journal of Production Research, Vol. 42,No 3, pp 547-572.

[2] Slack, N. 1983 "Flexibility as a manufacturing objective", International Journal of Operations and Production Management, Vol. 3, No. 3, pp. 4-13.

[3] Nishi, T., Ando, M., Konishi, M. and Imai, J. 2003 "A distributed route planning method for multiple mobile robots using Lagrangian decomposition technique", Proceedings of the 2003 IEEE International Conference on Robotics and Automation, Taipei, Taiwan, September, pp. 3855-61.

[4] Browne, J., Dubois, D., Rathmill, K., Seth, S.P., Stecke, K.E., 1984 "Classification of Flexible Manufacturing Systems." The FMS Magazine, 114.

[5] Gerwin, D., 1993 "Manufacturing Flexibility: A Strategic Perspective." Management Science, Vol. 39, No. 4, pp. 395-410.

[6] Slack, N. 1987 ``The flexibility of manufacturing systems", International Journal of Operations and Production Management, Vol. 7 No. 4, pp. 35-45.

[7] Tombak, M. and DeMeyer, A. 1988, "Flexibility and FMS: empirical analysis", IEEE Transactions on

Engineering Management, Vol. 35 No. 2, pp. 101-107.

[8] Williams, C.R., Chompuming., 2002 “A simulation study of Robotic welding system with parallels and series processes in metal fabrication industry “Proceedings of the 2002 Winter Simulation Conference, pp 1018-1025.

[9] Patel, V., Ashby, J., Ma, J., 2002 "Discrete event simulation in automotive final process system", Proceedings of the 2002 Winter Simulation Conference, pp 1030-1034.

[10] Rogers, P.,2002, "Optimum-seeking simulation in the design and control of manufacturing systems: experience with Opt Quest for ARENA", Proceedings of the 2002 Winter Simulation Conference, pp142-150.

[11] Altinkilic, M., 2004, "Simulation-based layout planning of a production plant", Proceedings of the 2004 Winter Simulation Conference, pp 1079-1084.

[12] Chen, J.E., Lee, Y.M., Selikson, P.L. 2002, "A simulation study of logistics activities in a chemical plant", Simulation Modeling Practice and Theory, Vol.10, No.3-4, pp 235-245.

[13] Hill, R. R., Miller, J. O., McIntyre, G. A., 2001, "Applications of discrete event simulation modeling to military problems", Proceedings of the 2001 Winter Simulation Conference, pp 780-788.

[14] Standridge, C. R., 1999, "A tutorial on simulation in health care: Applications and issues", Proceedings of the 1999 Winter Simulation Conference, pp 49-55.

[15] Graves, G. H., Higgins, J. L., 2002, “Applications of simulation in logistics combat developments", Proceedings of the 2002 Winter Simulation Conference, pp 911-916.

[16] Nsakanda, A. L., Turcotte, M., 2004, "Air cargo operations evaluation and analysis through simulation", Proceedings of the 2004 Winter Simulation Conference, pp 1790-1798.

[17] Carlsson, B., 1989, “Flexibility and the Theory of the Firm.” International Journal of Industrial Organization, Vol.7, pp 179-203.

[18] Mandelbaum, M., 1978, “Flexibility in decision-making: An exploration and unification. Ph.D. Thesis, Department of Industrial Engineering, University of Toronto, Canada.

[19] Sethi, A.K. and Sethi, S.P. 1990, ``Flexibility in manufacturing: a survey", International Journal of Flexible Manufacturing Systems, Vol. 2 No. 4, pp. 289-328.

[20] Hyun, J.H., Ahn, B.H., 1992, “A Unifying Framework for Manufacturing Flexibility.” Manufacturing Review, Vol. 5, No. 4, pp.251-260.

[21] Slack, N., 1983, “Flexibility as a Manufacturing Objective.” International Journal of Production Management, vol. 3, no. 3, pp. 4-13.

[22] Cheng, J.M.J., Simmons, J.E.L., Rithie, J.M., 1997, “Manufacturing System Flexibility: The Capability and Capacity Approach.” Integrated Manufacturing Systems, Vol.8, No.3, pp.147-158.

[23] Koste, L.L., Malhotra, M.K., 1999, “A theoretical framework for analyzing the dimensions of manufacturing flexibility.” Journal of Operations Management, vol.18, pp.75-93.

[24] Barad, M. and Sipper, D. 2003, ``Flexibility in manufacturing systems: definitions and Petri net modeling", International Journal of Production Research, Vol. 26 No. 2, pp. 237-48.

[25] Mohamed H. A., 1995, “A knowledge-based simulation model for job shop scheduling” International Journal of Operations& Production Management, Vol. 15 No. 10, pp. 89-102.

[26] Semra Tunali (1997), “Evaluation of alternate routing policies in Scheduling a job-shop type FMS” Computers and. Industrial Engineering, Vol. 32, No. 2, pp. 243-250.

[27] Singholi A; et al 2010, “Towards improving the performance of flexible manufacturing system: a case study”, Jounal of Industrial Engg & Management, Vol. 3(1): pp. 87-115.

[28] Mohammed Ali, Zameer Ahmad, 2014, “A Simulation Study of FMS Under Routing and Part Mix Flexibility”, Global Journal of Flexible Systems Management Vol, 15(4): pp 277–294.

[29] Mohammed Ali & Subhash Wadhwa ,2010, “The effect of routing flexibility on a flexible system of integrated manufacturing”, International Journal of Production Research, Vol. 48:19, pp5691-5709.

[30] F.T.S. Chan et al 2003, “Analysis of dynamic dispatching rules for a flexible manufacturing system” Journal of Materials Processing Technology, Vol.138 pp 325–331.

[31] Garavelli 2001, “Performance analysis of a batch production system with limited flexibility”, “International Journal of Production Economics” Vol-69, pp 39-48.

[32] ElMaraghy 2003, “Real-time scheduling with deadlock avoidance in flexible manufacturing systems”, International Journal of Advanced Manufacturing Technology, Vol.22 pp 259–270.

[33] Yao, D. D., 1985, “Material and Information Flows in Flexible Manufacturing Systems." Material Flows, Vol. 2 (Special Issue on Flexible Manufacturing System), pp.143-149.

[34] Pankaj C., Mihkel M. T., 1991, “Models for the evaluation of routing and machine flexibility.” http://www.decisioncraft.com.

[35] Wadhwa, S., Bhagwat, R., 1998, “Judicious Increase

in Flexibility and Decision Automation in Semi-Computerized Flexible Manufacturing (SCFM) Systems." International Journal, Studies in Informatics and Control, Vol. 7, pp. 320 - 342.

[36] Miltenburg, J., 2001, "Production Planning problem where products have alternative routings and bills-of-material." International Journal of Production Research, Vol.8, pp. 1755-1775.