PREFACE

Whether it is a manufacturing based company or a service based company, the key to stay at the apex of global competition is to meet the dynamically changing needs of customers. Flexible Manufacturing Systems (FMS) combine both the sophisticated manufacturing equipment and the advanced computer and information technology to impart flexibility to the manufacturing operations, thereby effectively meeting the changing needs of customers.

FMS consist of several types of machines, computers, robots, and automated guided vehicles and are designed to produce a great variety of products. While FMS give a cutting-edge advantage to a manufacturing company through their flexibility, they pose complex problems for their planning, designing, scheduling, controlling, and monitoring. This is primarily due to the inherent nature of FMS that are asynchronous concurrent systems. Modeling tools often help to address the above stated problems in FMS. There is a great demand for integrated tools that address the multifaceted problems in FMS. Unlike the several available tools such as mathematical programming, queuing networks, ladder logic diagrams, commercial simulation packages, Petri nets offer such an integrated solution to address effectively many issues in design and operation of FMS.

In order to address these problems, this book focuses on both the theory and several applications of Petri nets in modeling, analysis, simulation, scheduling, and control of FMS. It not only contributes to the theory of Petri nets by introducing new types of Petri nets such as Augmented Timed Petri Nets and Real-Time Petri Nets but also applies them to address issues related to breakdown handling and real-time discrete event control. It illustrates the use of Petri nets to compare the performance of push and pull systems and to develop object-oriented control software. Basic comparative studies that compare Real-Time Petri Nets and ladder logic diagrams for discrete event control are also presented. Roughly speaking, this book draws a half of material from the second author's doctoral dissertation, and another half from the lecture materials of a graduate level course entitled "Discrete Event Dynamic Systems" at New Jersey Institute of Technology (NJIT) by the first author and some recent research results obtained by his research group at NJIT.

Organization

This book is organized as follows. Chapter 1 discusses the background, motivation, and purpose of this book. Chapter 2 presents an overview of FMS and concludes by emphasizing the importance of integrated modeling tools. It is based on the paper entitled "Flexible Manufacturing Systems: An Overview" in *International. Journal of Operations and Production Management*, Vol. 13, No. 4, pp. 26-49, 1994 by Kaighobadi and Venkatesh. Chapter 3 presents Petri nets as an integrated tool and methodology in FMS design. A significant portion of this chapter is based on the article entitled "Petri nets: tool and technology" by Zhou and Zurawski in the March 1994 issue of *IEEE IES Newsletter*, the Newsletter of IEEE Industrial Electronic Society. Some representative papers and reports are surveyed with the focus on the applications of Petri nets in modeling, analysis, performance evaluation, simulation, control, planning, and scheduling of FMS.

The fundamentals of Petri nets are introduced in Chapter 4. Several simple yet interesting manufacturing and assembly examples are used to illustrate the concepts. Chapter 5 presents several important classes of Petri nets in modeling automated manufacturing systems and their application scope. The modeling and synthesis procedures are discussed and many FMS examples are given. Chapter 6 focuses on the analytical performance modeling and evaluation of FMS. The materials presented in Chapters 4-6 are based on several papers including

- "Modeling, Analysis, Simulation, Scheduling, and Control of Semiconductor Manufacturing Systems: A Petri Net Approach" by Zhou and Jeng, to appear in *IEEE Transactions on Semiconductor Manufacturing*, August 1998.
- "Petri Nets and Industrial Application: A Tutorial" by Zurawski and Zhou in *IEEE Transactions on Industrial Electronics*, 41(6), pp. 567-583, December 1994; and
- "Petri Net Synthesis and Analysis of A Flexible Manufacturing Cell" by Zhou, McDermott and Patel in *IEEE Transactions on Systems, Man and Cybernetics*, 23(2), pp. 523-531, March/April 1993.

As the model complexity increases, the use of analytical techniques for performance analysis becomes harder and impossible for many cases. Discrete event simulation becomes an indispensable alternative for the performance analysis. Chapter 7 presents the basic principles of Petri net simulation and explores the use of Petri net simulation tools. It is based on the paper by Venkatesh, Chetty, and Raju, "Simulating Flexible Automated Forming and Assembly Systems," *Journal of Material Processing and Technology*, Vol. 24, pp. 453-462, December 1990.

Chapter 8 demonstrates Petri nets as a powerful tool to investigate the problem often encountered in manufacturing systems management, namely comparing

the performance of push and pull systems. It is based on the paper by Venkatesh, Zhou, Kaighobadi, and Caudill, "A Petri Net Approach to Investigating the Performance of Push and Pull Paradigms in Flexible Factory Automated Systems using Petri Nets," *International Journal of Production Research*, Vol. 34, No. 3, pp. 595-620, 1996. Chapter 9 introduces a new type of Petri nets called Augmented Timed Petri Nets for breakdown handling and presents a case study on their use in modeling and analysis of a multi-robot assembly system. It is based on the paper "Augmented Timed Petri Nets for Modeling of Robotic Systems with Breakdowns," *Journal of Manufacturing Systems,* Vol. 13, No. 4, pp. 289-301, 1994 by Venkatesh, Kaighobadi, Zhou, and Caudill.

Another class of Petri nets called Real-Time Petri Nets is introduced in Chapter 10 along with their unique features and how they are different from the various existing classes of Petri nets for real-time control. Chapter 11 presents a case study comparing Real-Time Petri Nets and ladder logic diagrams. It also develops some comparison criteria and analytical formulas to quantify the complexity of models designed by Real-Time Petri Nets and ladder logic diagrams. These two chapters are based on the papers by Venkatesh, Zhou, and Caudill, "Comparing Ladder Logic Diagrams and Petri Nets for the Design of Sequence Controllers Through a Discrete Manufacturing System," *IEEE Transactions on Industrial Electronics,* Vol. 41, No. 6, pp. 611-619, 1994, and "Evaluating the complexity of Petri nets and ladder logic diagrams for sequence controllers design in flexible automation," in *Proc. of Seiken/IEEE Workshop on Emerging Technologies and Factory Automation*, pp. 428-435, Tokyo, Japan, November 1994.

Chapter 12 introduces Petri Nets in the design of object-oriented control software. By combining the existing modeling methods such as Object Modeling Technique Diagrams and Petri Nets, it presents a case study in which Petri Nets are formally applied for the dynamic modeling in the object-oriented software development. The material is based on the paper entitled "Object-oriented design of FMS Control Software based on Object Modeling Technique Diagrams and Petri nets" by Venkatesh and Zhou in *Journal of Manufacturing Systems*, Vol. 17, No. 2, pp. 118-136, 1998. Chapter 13 explores the application of Petri Nets in scheduling of FMS by combining them with heuristic-based search approaches. This chapter is based on several sources including

- The doctoral dissertation research performed by Huanxin H. Xiong under the first author's supervision,
- The paper entitled "Hybrid Heuristic Search for Petri Net Scheduling of an FMS" by Xiong, Zhou and Caudill, in *Proceedings of 1996 IEEE International Conference on Robotics and Automation*, Minneapolis, MN, pp. 2793-2797, April 1996, and

- The paper entitled "Scheduling of Semiconductor Test Facility via Petri Nets and Hybrid Heuristic Search" by Xiong and Zhou, to appear in *IEEE Transactions on Semiconductor Manufacturing*, August 1998.

Finally, Chapter 14 presents the future research and development of Petri Nets in flexible automation.

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MengChu Zhou
New Jersey Institute of Technology, Newark, New Jersey
E-mail address: *zhou@njit.edu*
Website: *http://megahertz.njit.edu/~zhou*

Kurapati Venkatesh
AT&T, Middletown, NJ
E-mail address: *amita@mtmail.att.com*