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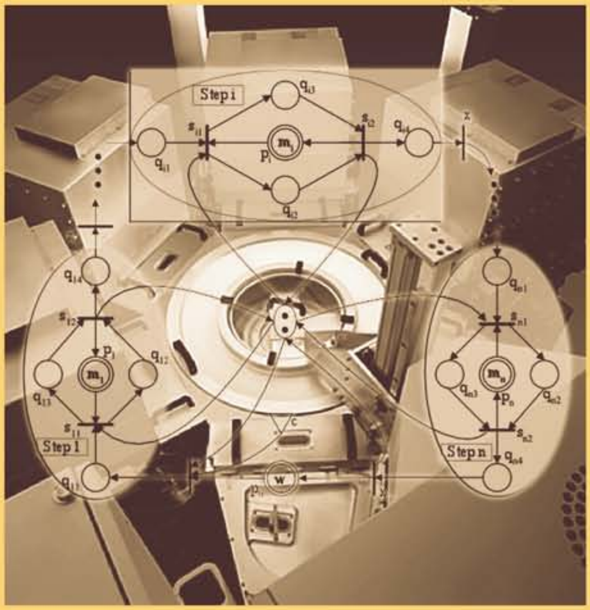
# System Modeling and Control with Resource-Oriented Petri Nets





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# System Modeling and Control with Resource-Oriented Petri Nets

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# System Modeling and Control with Resource-Oriented Petri Nets

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# Contents

# Preface

The hardest thing in life is to know which bridge to cross and which to burn.

**—David Russell**

In the early 1990s, Naiqi Wu was a visiting scholar at the School of Industrial Engineering, at Purdue University, West Lafayette, Indiana, and worked in the field of design, scheduling, and control of automated manufacturing systems (AMS). One day, the paper "Deadlock Prevention and Deadlock Avoidance in Flexible Manufacturing Systems Using Petri Net Models" (Viswanadham et al., *IEEE Transactions on Robotics and Automation*, volume 6, pp. 713–723, 1990) attracted his attention. It deals with a deadlock avoidance problem in flexible manufacturing systems, an important issue in automated manufacturing processes. Wu decided to study the subject. It is known that deadlocks in flexible manufacturing systems are caused by a circular wait for resource competition, caused by limited shared resources. At that time, he knew nothing about the Petri net theory. Then, Wu read Peterson's book *Petri Net Theory and the Modeling of Systems* (Englewood Cliffs, NJ: Prentice-Hall, 1981), Murata's paper "Petri Nets: Properties, Analysis and Applications" (*Proceedings of the IEEE*, volume 77, pp. 541–580, 1989), and some papers written by MengChu Zhou, Dr. Frank DiCesare, and their sizable RPI Petri net research group at Rensselaer Polytechnic Institute. Soon thereafter it was found that process-oriented Petri nets (POPNs) were almost exclusively used as a net model of flexible manufacturing systems in the literature at that time. Although the POPN methodology is powerful in system modeling, the resultant model easily tends to be unmanageably large. Furthermore, it cannot explicitly describe circular wait, the very nature of deadlock in any resource allocation system. Based on this observation, a new way to model a flexible manufacturing system is considered such that resource circuits behind circular wait can be explicitly described. To do so, one can treat a resource in the system as a server and a part to be processed in the system as a customer. The way in which customers (parts/jobs) visit servers (resources) can in fact describe the dynamic behavior of the system. In 1997, Wu and Zhou met at the IEEE International Conference on Robotics and Automation in Albuquerque, New Mexico, and talked with each other regarding the emerging field of Petri nets and their applications to automation. Wu presented his paper "Avoiding Deadlocks in Automated Manufacturing Systems with Shared Material Handling System." This was the first time that he presented the idea of resource-oriented Petri nets and their applications when a material handling system must be considered as a part of an AMS in deadlock resolution. Listening to the presentation, Zhou became deeply interested in the new modeling philosophy. He immediately realized the great significance a modeling paradigm could bring to the solution of difficult deadlock problems, as he had already worked in the process-oriented Petri net modeling field for 10 years and coauthored the first monograph* on the topic with his former advisor, Professor Frank DiCesare. Since that meeting, Wu and Zhou began to communicate with each other and worked together to obtain many new interesting results. Wu spent the summer of 2004 at the New Jersey Institute of Technology to conduct collaborative research with Zhou, upon his invitation. Zhou also paid several visits to Wu and to Wu's laboratory. Some important results gained from this collaboration and related to this monograph are explained as follows:

1. Our first joint paper, "Resource-Oriented Petri Nets for Deadlock Avoidance in Automated Manufacturing" (*Proceedings of 2000 IEEE International Conference on Robotics and Automation*, San Francisco, April 2000, pp. 3377–82), and its extended version, "Avoiding Deadlock and Reducing Starvation and Blocking in Automated Manufacturing Systems Based on a Petri Net Model" (*IEEE Transactions on Robotics and Automation* 17 (2001): 658–69) use resource-oriented Petri nets to address the benefit of applying a "liveness" margin to improve the system productivity. The idea is motivated by the stability margin in traditional feedback control systems. We can also find some real-life examples to explain why it is so important to leave an extra margin for the best performance. For example, consider a circular highway with entrances and exits allowing vehicles to enter and exit freely. When there are too many cars on it, all will be significantly slowed down, and thus the number of cars flowing through any segment in a unit of time will be decreased (called throughput). Yet we find no deadlock, only congestion, as all the cars will be able to exit from the highway. On the contrary, if too few cars are allowed to enter it, the throughput is very low, and each car reaches its highest allowed speed. Clearly this will significantly lower the utilization. Therefore, the best cases are those in which we have enough cars on the highway able to utilize their allowed high speed without yielding congestion. This way we enjoy the highest throughput and highway utilization. This applies to AMS as well. Our work has revealed this important fact: A maximally permissive deadlock control policy may admit some congestion cases that can lower productivity when rule-based or other heuristic scheduling policies apply. As a result, a policy with some margin should be used such that those congestion cases are completely excluded. The contents of these two papers are described in Chapters 7 and 8 of this book.
2. Our second important work is on the use of resource-oriented Petri nets to faithfully model automated guided vehicle (AGV) systems and derive the deadlock control policies suitable for real-time implementation. They can handle both bidirectional and unidirectional paths. The former offer additional flexibility, efficiency, and cost savings when compared with the latter. Yet, they exhibit more challenging AGV management problems. Unlike jobs that can enter and leave an AMS, AGVs always stay in the system. In AGV systems, a lane and a node may hold one—and only one—AGV.

* Zhou, M. C., and F. DiCesare, *Petri Net Synthesis for Discrete Event Control of Manufacturing Systems* (Boston: Kluwer, 1993).

This leads to a single-capacity resource allocation system, invalidating many elegant deadlock policies that require multiple-capacity resources. By modeling nodes with places and lanes with transitions, the proposed method can construct Petri net models for changing AGV routes. In addition to a deadlock control policy, our study also leads to a method that finds the shortest time routes while avoiding both deadlock and blocking. The method needs to perform rerouting whenever necessary. As a result, the proposed method can offer better solutions than the existing ones. For some cases, it can find a solution while the existing ones cannot. Our work was published as “Modeling and Deadlock Control of Automated Guided Vehicle Systems” (*IEEE/ASME Transactions on Mechatronics* 9 (2004): 50–57) and “Shortest Routing of Bidirectional Automated Guided Vehicles Avoiding Deadlock and Blocking” (*IEEE/ASME Transactions on Mechatronics* 12 (2007): 63–72). This part of the material is presented in Chapter 9 of this book.

3. The deadlock problems are separately treated for parts in production and transportation. Many techniques are developed for either problem. In general, it is intractable to obtain maximally permissive control policies for either one. Conventional thinking suggests that the combination of two problems would complicate the issue. When we investigated the combined problem for a flexible manufacturing system that adopted multiple AGVs for material handling, we found that they brought the flexibility and opportunity to help resolve deadlocks for parts in production. More surprisingly, we established a novel control policy for deadlock avoidance that was maximally permissive and had only polynomial computational complexity if the complexity for controlling the part transportation by AGVs was limited. Thus, the complexity of deadlock avoidance for the whole system is bounded by the complexity in controlling the AGV system. It is known that most AGV systems in practice seem to be easily controlled because of (1) limited number of AGVs in a system, (2) the prior known configuration, and (3) some special designs. Note that general AGV systems have nonpolynomial complexity for their optimal control. Our work appeared in “Modeling and Deadlock Avoidance of Automated Manufacturing Systems with Multiple Automated Guided Vehicles” (*IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics* 35 (2005): 1193–202). We have dedicated Chapter 10 to this topic.
4. Multiple AGVs can create opportunities to help resolve those otherwise deadlock situations, partially due to their mobility. Robots in most industrial settings are often fixed while serving one or multiple machines within their reach. The question is whether they can also create some opportunity to ease deadlock issues. Our joint work proves this by extending resource-oriented Petri net models to model both parts in production and their transfers from one machine to another. We are able to eliminate some deadlocks in the corresponding process-oriented models by simply using such models in fact. We have published the results in a paper entitled “Deadlock Resolution in Automated Manufacturing Systems with Robots” (*IEEE Transactions on*

*Automation Science and Engineering* 4 (2007): 474–80). Chapter 11 discusses the details of the extended models and their application results.

5. The massive need for various chips used in consumer electronics, automobiles, and other engineering systems has greatly promoted the area of semiconductor manufacturing automation. In particular, the development of cluster tools and track systems has helped the industry achieve high yield with high product quality. The modeling, control, and scheduling of these highly integrated flexible automated systems become a very challenging task. Our work has successfully associated time delays with the places and transitions in their resource-oriented Petri net models and derived deadlock-free optimal or near-optimal schedules. The work was published in the following articles: "Real-Time Deadlock-Free Scheduling for Semiconductor Track Systems Based on Colored Timed Petri Nets" (*OR Spectrum* 29 (2007): 421–43), "Deadlock Modeling and Control of Semiconductor Track Systems Using Resource-Oriented Petri Nets" (*International Journal of Production Research* 45 (2007): 3439–56), and "A Petri Net Method for Schedulability and Scheduling Problems in Single-Arm Cluster Tools with Wafer Residency Time Constraints" (*IEEE Transactions on Semiconductor Manufacturing* 21 (2008): 224–37). The majority of these published articles are combined and presented in Chapter 12.
6. Automated flexible assembly systems represent one of the hardest systems in terms of deadlock resolution. This extreme difficulty is due to their particular features that other automated manufacturing systems do not have. For example, deadlocks can take place in both the flows of base components and parts to be mounted onto the former. The assembly operations can also result in a deadlock due to inappropriate allocation of different types of parts or fixtures. The optimal solution to this deadlock avoidance problem is computationally infeasible. Our work uses heuristics to well address this challenge and greatly outperforms the existing method. A short version of this work was presented at the 16th IFAC World Congress, Prague, Czech Republic, and a full version, "Resource-Oriented Petri Net for Deadlock Avoidance in Flexible Assembly Systems," appeared in *IEEE Transactions on Systems, Man, and Cybernetics, Part A: Systems and Humans* (38 (2008): 56–69). Chapter 13 covers this topic with an industrial example.

We have continued our collaboration on the extension of resource-oriented Petri net models to deal with hybrid systems. For example, we have studied the short-term scheduling issues for oil refineries. We have obtained some significant results that we have published in *IEEE Transactions on Automation Science and Engineering*, *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, and *International Journal of Intelligent Control and Systems*. We cannot include the results in this book due to space limitations and the lack of a close relation with the topics of automated manufacturing systems—the focus of this book.

Chapter 1 of this book introduces a modeling process, contemporary automated manufacturing systems, and a historic perspective on Petri net studies as related to automation. Chapter 2 presents the fundamentals of Petri net theory with the definitions and examples known to the Petri net research community. Chapter 3 presents the classical colored Petri nets and their definitions. Chapter 4 presents process-oriented Petri net models and modeling methodologies. Some examples from manufacturing automation are given to illustrate them. We used "Resource-Oriented Petri Nets in Deadlock Prevention and Avoidance," our jointly published chapter in *Deadlock Resolution in Computer-Integrated Systems* (M. C. Zhou and M. P. Fanti, eds. (New York: Marcel Dekker, 2005), 349–406), in Chapter 5. It covers the basics of resource-oriented Petri net models, the colored version, and the related characteristics. In particular, it presents the necessary and sufficient deadlock-free conditions for the class of automated manufacturing systems represented with the proposed models. This significant result was obtained by Naiqi Wu in his 1999 paper "Necessary and Sufficient Conditions for Deadlock-Free Operation in Flexible Manufacturing Systems Using a Colored Petri Net Model" (*IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews* 29 (1999): 192–204). We compare resource- and process-oriented Petri net modeling methodologies and resulting models in Chapter 6. We discuss their advantages and disadvantages in the design of discrete event systems.

Finally, we hope that this monograph will stimulate more engineers and researchers to investigate and apply resource-oriented Petri nets for modeling, analysis, performance evaluation, simulation, control, and scheduling of their particular engineering systems. We hope that the work serves as a beginning step toward the better understanding and modeling of increasingly complex engineering systems and eventually toward the better design of such systems to benefit humankind.

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# Acknowledgments

The following are important books and papers that address the fundamentals of Petri nets and their applications to the field of automation science and engineering:

Murata, T. 1989. Petri nets: Properties, analysis and applications. *Proceedings of the IEEE* 77:541–80.

Viswanadham, N., and Y. Narahari. 1992. *Performance modeling of automated manufacturing systems*. Englewood Cliffs, NJ: Prentice Hall.

Zhou, M. C., and F. DiCesare. 1993. *Petri net synthesis for discrete event control of manufacturing systems*. Boston: Kluwer Academic.

Desrochers, A. A., and R. Y. AI-Jaar. 1995. *Applications of Petri nets in manufacturing systems: Modeling, control, and performance analysis*. Piscataway, NJ: IEEE Press.

Zhou, M. C., ed. 1995. *Petri nets in flexible and agile automation.* Boston: Kluwer Academic Publisher.

Proth, J.-M., and X. L. Xie. 1996. *Petri nets: A tool for design and management of manufacturing systems*. New York: John Wiley & Sons.

Zhou, M. C., and K. Venkatesh. 1998. *Modeling, simulation and control of flexible manufacturing systems: Petri net approach*. Singapore: World Scientific.

Cassandras, C. G., and S. Lafortune. 1999. *Introduction to discrete event systems*. Boston: Kluwer Academic Publishers.

Zhou, M. C., and M. P. Fanti, eds. 2005. *Deadlock resolution in computer-integrated systems*. New York: Marcel Dekker.

Bogdan, S., F. L. Lewis, Z. Kovacic, and J. Mireles. 2006. *Manufacturing systems control design: A matrix based approach*. London: Springer-Verlag.

Hruz, B., and M. C. Zhou. 2007. *Modeling and control of discrete-event dynamic systems*: *With petri nets and other tools*. (Series-Advanced Textbooks in Control and Signal Processing) London: Springer-Verlag.

These publications cover many topics related to this book. The significant difference, however, lies in the fact that they take a Petri net modeling approach from the viewpoint of the processes a job must take, while this book adopts the viewpoint of the resources. As a result, the routes a job takes are not as obviously seen as those in a process-oriented Petri net model. Instead, they are implicitly reflected by the routes through which a job visits resources. Consequently, the graphical modeling complexity is drastically reduced, while the tokens representing jobs have to carry job-related information. From the perspective of deadlock analysis and control, this resource-oriented approach can yield significant benefits.

During our research toward efficient analysis and control of deadlocks in various systems, including flexible manufacturing, material handling, flexible assembly, and semiconductor fabrication tools, we have received much help. The following researchers have contributed to this book through a variety of ways, including guidance, advice, discussion, and critique, and are deserving of our mention: Prof. Peter B. Luh, University of Connecticut; Prof. N. Viswanadham, Indian School of Business; MuDer Jeng, National Taiwan Ocean University; Prof. Y. Narahari, Indian Institute of

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# The Authors

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**MengChu Zhou** received his BS degree from Nanjing University of Science and Technology, MS degree from Beijing Institute of Technology, and PhD degree from Rensselaer Polytechnic Institute. He joined New Jersey Institute of Technology (NJIT) in 1990, and is currently a professor of electrical and computer engineering and director of the Discrete-Event Systems Laboratory. His interests are in computer-integrated systems, Petri nets, networks, and manufacturing. He has written more than 300 publications, including 9 books and over 130 journal papers. Professor Zhou was managing editor of *IEEE Transactions on Systems, Man, and Cybernetics* from 2005 to 2008, and associate editor of IEEE *Transactions on Automation Science and Engineering* from 2004 to 2007, *Transactions on Systems, Man, and Cybernetics, Part B* from 2002 to 2005, and *IEEE Transactions on Robotics and Automation* from 1997 to 2000. He is presently editor of *IEEE Transactions on Automation Science and Engineering*; associate editor of IEEE *Transactions on Systems, Man, and Cybernetics: Part A* and *IEEE Transactions on Industrial Informatics*; and editor-in-chief of *International Journal of Intelligent Control and Systems*. He has served as general and program chair of many international conferences.

Dr. Zhou has led or participated in thirty-six research and education projects with budgets totaling over $10M that were funded by the National Science Foundation, the Department of Defense, and industry. He was the recipient of the CIM University–LEAD Award by the Society of Manufacturing Engineers, Harlan J. Perlis Research Award by NJIT, the Humboldt Research Award for U.S. Senior Scientists, and a distinguished lecturer of the IEEE Systems, Man, and Cybernetics Society. Dr. Zhou has been invited to lecture in Australia, Canada, China, France, Germany, Hong Kong, Italy, Japan, Korea, Mexico, Taiwan, and the United States. He was the founding chair of the Discrete Event Systems Technical Committee of the IEEE Systems, Man, and Cybernetics Society, and founding chair of the Semiconductor Manufacturing Automation Technical Committee of IEEE Robotics and Automation Society. Dr. Zhou is currenlty co-chair (founding) of the Enterprise Information Systems Technical Committee of IEEE Systems, Man, and Cybernetics Society and the vice chair of the IFAC Technical Committee on Economic and Business Systems. He is a life member of the Chinese Association for Science and Technology–USA and served as its president in 1999. He is a fellow of the IEEE.

# List of Abbreviations

AGV = automated guided vehicle
AMS = automated manufacturing system
$C(p)$ = a set of colors for place $p$
$C(p_i(A_k))$ = color for a token representing an A part at its kth operation in place $p_i$
$C(t)$ = a set of colors for transition $t$
$c$, $c_i$ = a color for a transition, or a token
CPN = colored Petri net
CROPN = colored resource-oriented Petri net
DES = discrete event system
DPP = a direct place path in a Petri net
FAS = flexible assembly system
FMS = flexible manufacturing system
$I$: $P \times T \rightarrow N$ = an input function that defines the directed arcs from places to transitions in a Petri net
IBS = ill-behaved siphon in a Petri net
IIT = intercircuit input transition
IOT = intercircuit output transition
$K$: $P \rightarrow N$ = a capacity function where $K(p)$ represents the maximal number of tokens that place $p$ can hold at a time
$K(v_i)$ = the capacity of PPC $v_i$
$M$: $P \rightarrow N$ = the marking vector in a Petri net
$M_0$ = the initial marking in a Petri net
$M_i$ = the ith marking in a Petri net
$M(p_i)(c_i)$ = the number of tokens with color $c_i$ in $p_i$ at marking $M$
$M(p_i)(v^n)$ = the number of cycling tokens of subnet $v^n$ in place $p_i$ at marking $M$
$M(L(v_i))$ = the number of possible leaving tokens in PPC $v_i$
$M(v)$ = the number of cycling tokens of PPC $v$ in marking $M$
$M(v^n)$ = the number of cycling tokens in subnet $v^n$ at marking $M$
MG = marked graph
MHS = material handling system
$\eta(v^n, M)$ = the number of enabled PPCs in subnet $v^n$
$N = \{0, 1, 2, \ldots\}$, the set of nonnegative integers
$O$: $P \times T \rightarrow N$ = an output function that defines the directed arcs from transitions to places in a Petri net
$P$ = a set of places in a Petri net
$P(v)$ = a set of places on circuit $v$
$P(v^n)$ = a set of places in subnet $v^n$
PME = parallel mutual exclusion
PN = $(P, T, I, O, M_0)$ is a marked Petri net
POPN = process-oriented Petri net

PPC = production process circuit
$R$ = the set of non-negative real numbers
$R(M_0)$ = the set of reachable markings of a PN from initial marking $M_0$
$R_c(M_0)$ = the set of reachable markings of a CROPN under control from initial marking $M_0$
RC = resource circuit
RMS = reconfigurable manufacturing system
ROPN = resource-oriented Petri net
$S$ = siphon in a Petri net
$S(v_i)$ = the number of free spaces available in PPC $v_i$ in a CROPN in marking $M$
$S(v^n)$ = the number of spaces available in subnet $v^n$ in a CROPN in marking $M$
$S'(v_i)$ = the number of currently potential spaces available in PPC $v_i$ in a CROPN in marking $M$
SDPP = shared direct place path in ROPN
SM = state machine
SME = sequential mutual exclusion
$\tau$: $P, T \rightarrow R$ = time delay in place or transition
$T$ = a set of transitions in a Petri net
$T(v)$ = set of transitions on circuit $v$
$T(v^n)$ = set of transitions in subnet $v^n$
$T_I(v^n)$ = set of input transitions of subnet $v^n$
$T_O(v^n)$ = set of output transitions of subnet $v^n$
$t_{iik}$ = intercircuit input transition (IIT) external to $v_k$
$t_{iok}$ = intercircuit output transition (IOT) on $v_k$
$v$, $v_i$ = a PPC in an ROPN
$v^n$ = interactive subnet composed of $n$ PPC in an ROPN
$Y$, $Y_i$ = a cycle in CROPN for AGV system

# 1 Introduction to Petri Net Modeling

## 1.1 THE MODELING PROCESS

A modeling process is a method by which people understand a concerned object, system, or phenomenon. Various modeling methods, tools, and models have been developed since people started to design man-made and engineering systems to benefit human beings. It is well known that *mathematical modeling* helps one to understand, analyze, evaluate, simulate, and control the systems under consideration. Traditionally, a resulting mathematical model is a description of a system in terms of equations. These equations are derived based on physical laws, such as Newton's laws, using continuous variables driven by time. *Discrete time models* are driven by clocks such that values of a variable at discrete times are observed, studied, analyzed, and used. The last type of models are *discrete event driven*. In other words, they represent the evolution of system states as driven by events that are often asynchronous. This asynchrony distinguishes the last class of models from the other two types. As a result, differential or difference equations cannot be used to describe them. We have to seek new models in order to well describe asynchronous event-driven dynamics. Additional features include concurrency, choices, and mutually exclusive use of shared resources. In reality, hybrid models may be used to describe the components/subsystems, interactions among components/subsystems, and the entire system.

In ancient times, the Chinese observed the season, sun, and moon changes and developed the lunar calendar, which has greatly helped farmers for more than 1,000 years. A lunar calendar can be viewed as a rough model of the seasonal changes over time in a year. It defines proper times for people to perform all farming activities to ensure a higher likelihood of a successful crop harvest.

A typical electronic circuit consists of resistors, capacitors, inductors, and sources. Each element is characterized by a certain law. For example, a linear resistor satisfies Ohm's law that the voltage across its two ends is proportional to the current flowing through it. A linear capacitor can be described by a model in which the current through it is proportional to the first derivative of the voltage across its two ends. For an electronic circuit containing such elements, one needs to use interconnection laws to characterize the entire circuit, for example, Kirchhoff's voltage law and current law. Modeling such a system takes two steps: First, we build a model for each individual element. Next, we use interconnection laws to build the entire system model. This approach certainly works for discrete event system models as well, which will be discussed in this book.

Another widely used modeling idea is to start and then keep adding to it to make it more complex. Initially, one may ignore most details by just focusing on major aspects of the system. Then, step by step, we add more features to the model to describe more details of a system. This can help one identify some important problems at an early stage without wasting too much time in unnecessary details. Only after the design satisfies the desired properties can one continue with more fine details to make the design better. This modeling strategy will be used when we build Petri net models for the system considered in this book.

In most engineering design, an accurate mathematical model becomes indispensable for designers. It is indeed the first step toward the development of any efficient and sustainable man-made system. This book contributes to the field of discrete event systems by presenting their modeling and analysis using a novel Petri net model.

## 1.2 AUTOMATED MANUFACTURING SYSTEMS

Conventional manufacturing has such features as mass production, sales from stock, long pipeline, and cost of inventory. Modern manufacturing calls for mass customization or eventually one-of-a-kind production. For example, a computer company now allows customers to select from a range of possibilities to specify their own computer and collects the payment from the customers up front. This minimizes a company's risk in overproducing unwanted or obsolete computers. As a sports wear company, Adidas has a project called miAdidas. It uses laser scanning techniques to create a three-dimensional model of a customer's feet. The model is then used to produce shoes that fit the customer perfectly. It is expensive and used primarily by professionals, but it may become common for average consumers after such value-added service becomes less expensive. For example, if we could use a webcam, available in many personal computers, and related software to catch a precise three-dimensional model, we could then lower the cost to produce such highly individualized products.

As a result, automated manufacturing systems must be designed and developed with new characteristics, i.e., flexibility, agility, and reconfigurability, in mind. Gaining these characteristics requires reconfigurable fixtures, material handling devices and systems, storage space, tools and machines, and more importantly, the use of advanced computer, communication, and management technologies to design reconfigurable control systems. A typical automated manufacturing system (AMS) consists of the following hardware entities:

1. Programmable computer-numerically-controlled components such as machines.
2. Automated material handling system that allows parts to flow freely from one station to another. Programmable robots and automated guided vehicles are often required.
3. Automated storage and retrieval system and buffering spaces where raw, intermediate, and final pieces can be stored until required for further processing.
4. A supervisory control system to monitor, coordinate, and control all the involved entities and release jobs into such an AMS. It has to ensure that the system is deadlock-free and can achieve its highest productivity and best product quality.

Contemporary manufacturing systems have had different goals over the past several decades. These goals are reflected through programmability, flexibility, agility, and reconfigurability, as described below:

1. **Programmability:** The early automated machines were implemented by rigid electromechanical devices, which resulted in so-called wired solutions. Such solutions suffered from many limitations, e.g., bulky size, rigidity in terms of any changes, low scalability, difficulty to debug and maintain, and inability to handle complex functions. Around 1970 the automobile industry realized their limitations and hence developed and adopted programmable logic controllers (PLCs) for their production lines, to keep pace with technical evolution and a growing number of new car models demanded by customers. The invention and use of PLCs greatly moved forward the automation technology and made the control system of a manufacturing system programmable. A PLC can be viewed as a special computing system. Its functionality has been vastly expanded since its early models. Today's PLCs have much computing and communication power, allowing them to accomplish not only control tasks but also communicating tasks with others and the Internet. This further allows engineers to develop remote diagnosis and maintenance capability for automated manufacturing facilities.
2. **Flexibility:** With the advent and wide use of PLCs and computers in control systems, flexible manufacturing is a current reality; its origins can be traced back to the 1960s with the Ingersoll-Rand factory in Roanoke, Virginia. The concept of manufacturing flexibility refers to manufacturing system designs that can adapt when external (likely uncertain) changes occur. According to Browne et al. (1984) and Sethi and Sethi (1990), we have the following eleven types of flexibility:

   - **Machine flexibility:** The different operation types that a machine can perform. It can be partly measured by the number of tool types.
   - **Material handling flexibility:** The ability to move the raw material pieces, parts, and products within a manufacturing facility.
   - **Operation flexibility:** The ability to produce a product in different ways.
   - **Process flexibility:** The set of products that the system can produce.
   - **Product flexibility:** The ability to add new products in the system.
   - **Routing flexibility:** The different routes (through machines and workshops) that can be used to produce a product in the system.
   - **Volume flexibility:** The ease with which the output of an existing system can be profitably increased or decreased.
   - **Expansion flexibility:** The ability to build out the capacity of a system.
   - **Program flexibility:** The ability to run a system automatically.
   - **Production flexibility:** The number of products a system currently can produce.
   - **Market flexibility:** The ability of the system to adapt to market demands.

3. **Agility:** Agile manufacturing was initially proposed to deal with the production of military products, as different technologies often led to very different products. Consequently, the agility to manufacture products from one generation to the next is highly desired. It requires both flexible manufacturing capability and the capability to respond to the rapid changes of customer needs and market demands. For example, Motorola developed an automated factory with the ability to produce physically different pagers on the same production line. Panasonic can manufacture different bicycles from combinations of a group of core parts. Agile manufacturing has been seen as the next step after Lean manufacturing in the evolution of production paradigms. The former is like an athletic person, and the latter a thin one. Thus, agile manufacturing is beneficial if the customer order cycle (the time the customers are willing to wait) is short. Lean manufacturing becomes possible if the supplier has a short lead time. Goldman et al. (1995) suggest that agility has four underlying components:

   - Delivering value to the customer
   - Being ready for rapid change
   - Valuing human knowledge and skills
   - Forming virtual partnerships

4. **Reconfigurability:** Reconfigurable manufacturing has become famous due to the a vast amount of work performed by the Engineering Research Center for Reconfigurable Manufacturing Systems (RMSs) at the University of Michigan College of Engineering, which is sponsored by the National Science Foundation and many manufacturing companies, especially those in the automobile industry. Reconfigurable manufacturing systems (Koren et al., 1999; Mehrabi et al., 2000) have the following single goal statement: *exactly the capacity and functionality needed, exactly when needed.* They must be designed at the outset for rapid change in their structure, as well as in their hardware and software components, in order to quickly adjust their production capacity and functionality within a part family in response to sudden market changes or intrinsic system changes. Their characteristics include modularity, integrability, customized flexibility, scalability, convertibility, and diagnosability.

   - **Modularity** is the degree to which a system is modularized, e.g., machines, tools, control systems, and material handling systems. Modular components can be replaced or upgraded to better suit new applications.
   - **Integrability** is the ability to integrate modules by a set of mechanical, informational, and control interfaces that enable integration and communication. The machine modules are integrated via material handling systems (such as conveyors and gantry robots), and their controllers are integrated into a factory control system.
   - **Customized flexibility** is the ability of a system to produce a product or part family, fulfilling the mass customization or one-of-a-kind

production. This characteristic distinguishes reconfigurable manufacturing systems from flexible manufacturing systems (FMS) and allows a reduction in investment cost. Examples of product families are all types of Boeing 747 and all sizes of Adidas tennis shoes. A product family is defined as all products that have similar geometric features and shapes, have the same level of tolerances, require the same processes, and are within the same range of cost.

- **Scalability** is the ability to scale up the system size in terms of the number of machines, robots, and other resources or their processing capabilities in order to produce a larger quantity of products. Scalability is achieved by the additional resources or the improvement of the modules, e.g., conveyor's speed, motor speed, or better tools.
- **Convertibility** is the ability to transform the functionality of existing systems, machines, and controls to suit new production requirements. For example, RMS can switch the production between two members of a product family.
- **Diagnosability** is the ability to identify and use the current and past states of a system for detecting and diagnosing the root cause of output product defects and, subsequently, correcting operational defects quickly. Higher diagnosability means higher capability of detecting machine failure and unacceptable part quality. It requires reconfigurable product quality measurement systems.

It should be noted that flexibility, agility, and reconfigurability share some significant characteristics, such as programmability and modularity. They all emphasize the system's ability to respond to market and demand changes. Their differences, in fact, seem smaller than these terms imply. Consider RMS and FMS. FMS aims at increasing the variety of parts produced. RMS aims at increasing the speed of responsiveness to markets and customers. RMS requires only limited flexibility that is confined only to what is necessary to produce a product family. It is not the general flexibility that FMS offers. RMS tends to offer rapid scalability to the desired volume and convertibility, which are obtained within reasonable cost to manufacturers. Similar goals can be achieved by FMS with its high volume flexibility and expansion flexibility. The best application of an FMS is found in manufacturing small sets of products. With RMS, manufacturers can vary their production volume from small to large for a product family. RMS has introduced a new dimension, i.e., diagnosability, which becomes critically important.

RMS and FMS can only be implemented through a programmable control system, which has to rapidly configure itself when needed. Their design requires a powerful modeling tool that can rigorously reveal their intrinsic discrete event characteristics, such as sequential, concurrent, and mutually exclusive relations among activities, potential conflicts, and deadlock states. This monograph offers a resource-oriented Petri net framework to facilitate the modeling, deadlock analysis and control, and scheduling for them.

## 1.3 HISTORICAL PERSPECTIVE OF PETRI NETS IN AUTOMATION

A **Petri net** is a graphical tool invented by Carl Adam Petri. Its origins can be traced back to August 1939 when, at the age of 13, Petri created the graphics to describe chemical processes that produced a final compound from various elements through some intermediate compounds. The net-like representations were formalized in his doctoral thesis, "Communication with Automata," at the Technical University of Darmstadt, Germany, in 1962. The rules for transition enabling and firing, also called a token game, were defined. The algebraic aspect of distributed systems was described in detail. His thesis argued that the theory of automata had to be replaced by a new theory that respected the results of modern physics, e.g., the relativity theory and uncertainty principle. The new models were applicable to distributed systems. Thereafter, Petri and his collaborators published a number of papers applying their nets to such areas as economics, mechanics, computer science, logic, organization, biology, and telecommunication protocols, with a purpose to create a net tool for interdisciplinary transfer of structural knowledge. General net theory has been their primary research focus.

Petri net theory and applications were greatly advanced by the Computation Structure Group at MIT in the early 1970s. The first conference related to Petri nets was, in fact, held at MIT in 1975. A more sizable Petri net conference was held in Hamburg, Germany, in October 1979, and was attended by about 135 researchers, mostly from European countries. It included a 2-week advanced course on general net theory of processes and systems. The first Petri net conference proceeding was published by Springer-Verlag in 1980 and contained seventeen papers (Brauer, 1980). The first European Workshop on Applications and Theory of Petri Nets was held in Strasbourg, France, in 1980. Since then, every year there is such a Petri net conference, and selected papers are compiled and published normally in the following year, as edited volumes called *Advances in Petri Nets*. In 1981, Peterson published the first Petri net book, *Petri Net Theory and the Modeling of Systems*, by Prentice-Hall. It has greatly popularized Petri nets as a tool for the modeling of various systems. In particular, it has attracted many noncomputer scientists to consider Petri nets for their specific applications.

Dr. M. Silva of the University of Zaragoza, Spain, has led his group since the early 1980s and produced significant research results related to Petri nets and their applications to automation. His Spanish book *Petri Nets in Automation and Computer Engineering* was published by Editorial AC, Madrid, Spain, in 1985. In the same year, Dr. W. Reisig's 1982 book *Petrinetze*, in German, was translated and published as an English book by Springer-Verlag. *Petri Nets: An Introduction*, Dr. T. Murata's award-winning paper "Petri Nets: Properties, Analysis and Applications" was published in 1989. It is the most cited paper in the area of Petri nets according to SCOPUS—the most extensive database covering all engineering and science research papers in the world. The paper has well documented the key research results prior to 1989, including behavioral and structural properties, marked graphs, free-choice nets, analysis methods (reachability analysis, invariant analysis, and reduction), timed Petri nets, stochastic Petri nets, and high-level Petri nets (predicate/transition nets, colored Petri nets, and nets with individual tokens). Several influential Petri net tools were developed to help various researchers in the 1980s. The theories of generalized stochastic Petri nets (SPNs) and GreatSPN as a simulation and performance analysis tool were developed in the early 1980s by an Italian group (Ajmore Marsan et al., 1995). Stochastic Petri net package (SPNP), another stochastic timed Petri net tool for performance analysis, was generated by the group led by K. S. Trevidi with two key developers, G. Ciardo and J. Dugan, at Duke University. In the late 1980s, CPN was developed by a group led by K. Jensen, with some support from the U.S. government, and has been used to specify and simulate colored Petri nets for the design of complex systems.

The aforementioned publications and tools strongly affected academic researchers and industrial engineers when selecting a powerful model to deal with various issues in the design and implementation of more and more complex man-made systems, especially computer-integrated manufacturing systems. The traditional approaches based on finite state machine or automata were proved inadequate, since the state explosion problems would be met at the beginning of the system design. In addition, any design flaws or mistakes could invalidate the entire system design and the performance analysis results. Any system specification changes could require tremendous effort to modify the design. As result, it is extremely difficult, if not impossible, to use such traditional approaches to design modern manufacturing systems with high flexibility, agility, and reconfigurability.

In the mid-1980s, Prof. N. Viswanadham and Y. Narahari and their group in India made great contributions to the Petri net theory and applications to automated manufacturing systems. Their work dealt with performance modeling and analysis, bottom-up modeling methods, invariant analysis, and deadlock control. They detailed some of their Petri net work in their 1992 book, *Performance Modeling of Automated Manufacturing Systems*, published by Prentice Hall.

In the late 1980s, Dr. Frank DiCesare and Dr. Alan A. Desrochers established a sizable research group at Rensselaer Polytechnic Institute to tackle the design issues in computer-integrated manufacturing systems. They chose Petri nets as their major modeling tool and generated many interesting results in Petri net theory and applications to automated manufacturing. Their research was supported by such industrial firms as IBM, GM, Johnson & Johnson, Sun Microsystems, and Digital Equipment Corporation (now HP) via an 8-year-long Computer Integrated Manufacturing Research Program of the Center for Manufacturing Productivity and Technology Transfer at Rensselaer Polytechnic Institute. The following contributions by the Rensselaer group are summarized:

- Its first doctoral graduate was Dr. Robert Al-Jaar, whose 1989 dissertation was entitled "Performance Evaluation of Automated Manufacturing Systems Using Generalized Stochastic Petri Nets." He used the above-mentioned GreatSPN and SPNP tools to study the transfer lines with varying buffer sizes. He and his advisor, Dr. A. A. Desrochers, published a monograph, "Applications of Petri Nets in Manufacturing Systems: Modeling, Control and Performance," through IEEE Press in 1994.
- The second doctoral graduate was the second author of this book, MengChu Zhou, whose 1990 dissertation was called "A Theory for the Synthesis and Augmentation of Petri Nets in Automation." His dissertation work included

the development of new concepts, e.g., parallel and sequential mutual exclusions for shared resource modeling, formulation of top-down, bottom-up, and hybrid methodologies for net synthesis, Petri net augmentation and its applications in error recovery, Petri net modeling of buffers, and design of discrete event controllers for flexible manufacturing systems. With his advisor, Dr. DiCesare, he published the monograph *Petri Net Synthesis for Discrete Event Control of Manufacturing Systems* through Kluwer Academic Publisher in 1993. Two years later, he edited a volume, "Petri Nets in Flexible and Agile Automation," through the same publisher. In 1998, with his first doctoral graduate, Dr. K. Venkatesh, he published the book *Modeling, Simulation and Control of Flexible Manufacturing Systems: A Petri Net Approach* published by World Scientific.

- Dr. Fei-Yue Wang graduated with his doctoral dissertation, "A Coordination Theory of Intelligent Machines," supervised by Dr. G. N. Saridis, in 1990. He has applied Petri nets to design intelligent machines and has built an intelligent control foundation. He has also contributed to the Petri net modeling and analysis of a communication protocol for manufacturing message specification. He later made a great contribution to the development of modified reachability trees for liveness analysis of unbounded Petri nets.
- Dr. Desrochers' second doctoral graduate, Jagdish S. Joshi, completed his work in the Petri net area in 1991. Dr. Joshi's dissertation title was "Design and Performance Prediction of Computer Resources for Real-Time Computer Integrated Manufacturing Systems." His work dealt with the performance modeling and analysis of computer network and database transactions in a computer-integrated manufacturing environment.
- Dr. I. Koh, the next doctoral graduate of Dr. DiCesare, finished his dissertation, "A Transformation Theory for Petri Nets and Their Applications to Manufacturing Automation," in 1991. His work perfected the bottom-up approach to the synthesis of Petri nets with desired behavioral properties.
- Dr. MuDer Jeng was the third doctoral graduate of Dr. DiCesare in the area of Petri nets and completed his dissertation, "Theory and Applications of Resource Control Petri Nets for Automated Manufacturing Systems," in 1992. He was the primary inventor of a new class of Petri nets called extended resource control net (ERCN)-merged nets. They are still being cited and used by many researchers today. Dr. Jeng has continued his Petri net research. He has made many significant contributions in the areas of Petri net methods for deadlock analysis, discrete event control, scheduling of flexible manufacturing systems, analysis of unbounded Petri nets, and modeling, simulation, and scheduling of semiconductor manufacturing systems.
- In 1992, Dr. DiCesare graduated Alessandro Giua, whose doctoral thesis was entitled "Petri Nets as Discrete Event Models for Supervisory Control." This work fully opened the door to the supervisory control study in a framework of Petri nets when most of supervisory control theory was based on automata. Dr. Giua made many theoretical contributions in the area, from Petri net language to general mutual exclusion constraints. His work has