Formal Methods *in* Manufacturing

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
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CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

No claim to original U.S. Government works
Version Date: 20131227

International Standard Book Number-13: 978-1-4665-6156-4 (eBook - PDF)

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Preface

Design and operation of manufacturing systems and their supply chains is a domain of significant research worldwide. The complexity of this domain stems from the large dimension of such systems that are highly parallel and distributed, from significant sources of uncertainties and from the degrees of flexibility. Formal methods are mathematical techniques, often supported by tools, for developing man-made systems. Formal methods and mathematical rigor enable manufacturing engineers to handle fundamental design principles, such as abstraction or modular and hierarchical development, and to deal with typical engineering problems and quality goals, like reliability, flexibility, and maintainability. Formal methods can provide both a deep understanding of the system, thus helping to cover holes in the specification, and an improved system reliability, through verification and validation of the desired properties. Automata, statecharts, queueing networks, Petri nets, min-max algebras, process algebras, and temporal logic–based models are becoming more and more used for an integrated view of design specification, validation, performance evaluation, planning, scheduling and control of manufacturing systems and their supply chains.

This book presents some of the most significant works representing the state of the art in the area of formal methodologies for manufacturing systems, combining fundamentals and advanced issues. It is divided into four main parts, each devoted to a specific issue: modelling and simulation, supervisory control (including deadlock prevention), performance evaluation (including scheduling and optimization), and fault diagnosis and reconfiguration. Several formalisms are considered, including finite state automata, Petri nets (discrete, timed, continuous, and hybrid), process algebra and max-plus algebra, exemplifying the advantages of each of them in the solution of a specific problem. Within each part, more detailed problems are considered, and the most significant solutions are discussed and illustrated with a series of interesting and significant examples in the manufacturing area. Individual chapters are written by leading experts in the field. Each topic is illustrated in detail, its significance in manufacturing systems is underlined, and the most important contributions in that specific area are surveyed.

The book is intended for researchers, postgraduate students and engineers interested in problems occurring in manufacturing systems. In particular, it provides a comprehensive overview of the most important formal model-based solutions to a series of major problems in manufacturing systems and their supply chains, which are based on formal and rigorous modelling of the underlying system. Each chapter in the book aims at providing a balance mixture of (1) fundamental theory, giving the reader a clear introduction to the most important formalisms used for the modelling, analysis and control of manufacturing systems; (2) tutorial value, providing the state of the art on a series of problems that occur in manufacturing systems, such as deadlock prevention, supervisory control, performance evaluation and fault diagnosis; and (3) applicability, presenting a series of case studies and applications taken from the industrial world, that make it particularly appealing to practitioners.

A brief description of the book is as follows. Part I (Chapters 1 through 5) concerns modelling and simulation of manufacturing systems. Chapter 1 focuses on Petri nets (untimed and timed) and shows how these can be effectively used to represent manufacturing systems in a bottom-up and modular fashion. Chapter 2 deals with a particular class of manufacturing systems for which a linear representation in an algebraic structure called dioids can be given. Chapters 3 and 4 deal with hybrid models of manufacturing systems. In particular, Chapter 3 focuses on hybrid Petri nets (HPNs), a formalism that combines fluid and discrete event dynamics. Particular attention is devoted to first-order hybrid Petri nets (FOHPNs) whose continuous dynamics are piecewise constant. It is shown how FOHPNs can be effectively used to model both manufacturing systems and inventory control systems. Chapter 4 focuses on stochastic flow models (SFMs) that preserve the essential features needed to design effective controllers and potentially optimize performance without any need to estimate the corresponding optimal performance value with accuracy. An overview of recently developed general frameworks for infinitesimal perturbation analysis (IPA) is also presented, through which unbiased performance sensitivity estimates of typical manufacturing performance measures can be obtained in such SFMs with respect to various controllable parameters of interest. Finally, Chapter 5 deals with a problem occurring in many real manufacturing systems, namely, freight transportation. It reviews the established transportation system modelling, including theory and applications of transportation supply models, trip demand models and dynamic traffic assignment methods, both for passenger and freight transportation, and also points out the characteristics of freight transportation that influence the logistic chain performance.

Part II (Chapters 6 through 12) is devoted to the supervisory control of manufacturing systems. In particular, Chapters 6 through 8 introduce deadlock avoidance/prevention policies; Chapters 9 through 12 deal with supervisory control problems. Chapter 6 addresses the problem of deadlock avoidance in flexibly automated manufacturing systems through the modelling abstraction of the (sequential) resource allocation system (RAS). The pursued analysis uses concepts and results from the formal modelling framework of finite state automata (FSA). Chapter 7 investigates the problem of deadlock prevention in the Petri net framework. After an overview of the classical approaches based on the addition of monitors that prevent siphons to become empty, a novel methodology is presented. Chapter 8 also deals with Petri nets. Here the digraph theory is used to effectively derive control laws that avoid deadlocks in single unit RAS, that is, systems where each part requires a single unit of a single resource for each operation. In Chapter 9, Petri nets are used to solve supervisory control problems of manufacturing systems. Different problem statements, depending on the considered specifications, and different solutions are considered, in particular based on the theory of monitor places and on the theory of regions. Extended finite automata (EFA), that is, automata augmented with bounded discrete variables, and updates of these variables on the transitions, are introduced in Chapter 10 and effectively used to automatically synthesize a supervisor. Decentralized control and modular control problems are discussed in Chapter 11. Finally, Chapter 12 discusses how manufacturing systems can often be modeled as max-plus-linear (MPL) systems and controlled via model predictive control (MPC).

Part III (Chapters 13 through 20) addresses the issue of performance evaluation of manufacturing systems and supply chains. Chapter 13 discusses approaches based on coloured Petri nets and state space analysis. Performance evaluation and control of manufacturing systems using fluid (i.e., continuous) Petri nets are discussed in Chapter 14. Chapter 15, discusses how timed process algebra called bounded true concurrency (BTC) can be effectively used for performance evaluation of flexible manufacturing systems. The problem of designing the lean, that is, the smallest buffers necessary and sufficient to achieve the desired line performance, is addressed in Chapter 16. Chapter 17 deals with the issue of inventory allocation and cycle time improvement in manufacturing systems and supply chains. Chapter 18 covers timed weighted event graphs, a subclass of Petri nets whose transitions are associated with workshops or specific treatments and whose places represent storages between the transitions. It deals with the minimization of the overall capacities of places, under throughput constraints. Chapter 19 focuses on the application of Petri nets to the scheduling of semiconductor manufacturing systems. To this aim, a hierarchical coloured timed Petri net (HCTPN) is proposed and genetic algorithms are extended and then embedded into the constructed HCTPN to find optimal/suboptimal schedules. Finally, Chapter 20 focuses on organization problems of health-care systems, presenting a Petri net–based software for health-care service modelling and simulation called MedPRO. Resource planning and scheduling are also in the scope of the tool.

Finally, Part IV (Chapters 21 through 23) illustrates fault diagnosis approaches for discrete event systems that can be successfully applied to manufacturing systems. In particular, in Chapters 21 and 22 finite state automata and interpreted Petri nets, respectively, are used as reference formalisms. In both chapters, diagnosability analysis is also performed. Chapter 21 also discusses the problem of sensor selection for diagnosability and the problem of cooperative diagnosis for systems with decentralized information. Chapter 23 addresses a problem strictly related to fault diagnosis occurring in automated manufacturing systems, namely, that of online control reconfiguration.

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Editors

Javier Campos received his MSc in applied mathematics and his PhD in systems engineering and computer science (with extraordinary doctorate award) from the University of Zaragoza, Spain, in 1986 and 1990, respectively. In 1986, he joined the Department of Computer Science and Systems Engineering at the University of Zaragoza, where he served as director from 2001 to 2003. In 2005, he was named full professor in computer languages and systems in the same department after winning one of the first two national competitive habilitation positions announced.

Dr. Campos' research interests include modelling and performance evaluation of distributed and concurrent systems, Petri nets, software performance engineering, and discrete event systems in automation. He has supervised the completion of a hundred master's thesis students and two PhD students. Since 1989, he has coauthored about 80 papers published in refereed journals and conferences. He has been plenary session invited speaker and tutorial invited speaker in several important meetings such as the IEEE International Workshop on Petri Nets and Performance Models, the International Conference on Application of Concurrency to System Design, and the International Conference on Application and Theory of Petri Nets and Other Models of Concurrency. He has served in the program committee, sometimes as a chair, of several international conferences such as the International Conference on Quantitative Evaluation of Systems, the European Performance Engineering Workshop, the International Workshop on Software and Performance, the IEEE Conference on Automation Science and Engineering, and the IEEE International Conference on Emerging Technologies and Factory Automation.

Dr. Campos is a founding member of the Aragn Institute for Engineering Research, a member of the Aragonese Informatics Engineering Association, and president of the Spanish Concurrent and Distributed Computing Society. He has been a member of the IEEE IES Technical Committee on Factory Automation, cochair of the IEEE IES Technical Sub-Committee on Industrial Automated Systems and Controls, guest editor of the special section on formal methods in manufacturing of *IEEE Transactions on Industrial Informatics*, and associate editor of *IEEE Transactions on Industrial Informatics*.

Carla Seatzu received her laurea degree in electrical engineering and her PhD in electronic engineering and computer science from the University of Cagliari, Italy, in 1996 and 2000, respectively. In 2002, she joined the Department of Electrical and Electronic Engineering at the University of Cagliari as an assistant professor of automatic control. She currently serves as an associate professor of automatic control in the same department.

Prof. Seatzu's research interests include discrete-event systems, hybrid systems, Petri nets, manufacturing systems, networked control systems, and control of mechanical systems. She has published over 150 papers and 1 textbook on these topics.

Prof. Seatzu has served as general cochair of the 18th IEEE International Conference on Emerging Technology and Factory Automation (ETFA2013). She was chair of the National Organizing Committee of the 2nd IFAC Conference on the Analysis and Design of Hybrid Systems (ADHS'06) and member of the international program committees of around 50 international conferences. She is associate editor of the *IEEE Transactions on Automatic Control* and of *Nonlinear Analysis: Hybrid Systems*. She is chair of the IEEE IES Technical Committee on Factory Automation — Subcommittee on Industrial Automated Systems and Controls.

Xiaolan Xie received his PhD from the University of Nancy I, Nancy, France, in 1989, and the Habilitation à Diriger des Recherches degree from the University of Metz, France, in 1995.

He is a professor of industrial engineering and head of the Healthcare Engineering Department at the Ecole Nationale Supérieure des Mines de Saint-Etienne (ENSM.SE), France. He is leader of the ROGI team of the CNRS laboratory LIMOS UMR 6158 on operations research and industrial engineering, a team that received the top A+ ranking in the 2010 national AERES research evaluation. He is also a chair professor at Shanghai Jiao Tong University, China. Before joining ENSM.SE, he was a research director at the Institut National de Recherche en Informatique et en Automatique (INRIA) from 2002 to 2005, a full professor at Ecole Nationale d'Ingénieurs de Metz from 1999 to 2002, and a senior research scientist at INRIA from 1990 to 1999. His research interests include design, planning and scheduling, supply chain optimization, performance evaluation, and maintenance of manufacturing and health-care systems. He is the author or coauthor of over 200 publications, including over 80 journal articles and 5 books. He has rich industrial application experience with European industries. He was co-principal investigator (PI) for various national or EU-funded projects, including ANR-HOST on hospital tension avoidance strategies, Labex IMoBS3 on home health-care services, NSF-China project on health-care resource planning and optimization, FP6-IST6 IWARD on swarm robots for health services, FP6-NoE I*PROMS on intelligent machines and production systems, the FP5-GROWTH-ONE project for the strategic design of supply chain networks, and the FP5- GROWTH thematic network TNEE on extended enterprises.

He has been an associate editor on the conference editorial board of the *IEEE Robotics and Automation Society*, *IEEE Transactions on Automation Science and Engineering*, *IEEE Transactions on Automatic Control* and *IEEE Transactions on Robotics and Automation*. He has also been guest editor of various special issues on health-care engineering in *IEEE Transactions Systems, Man and Cybernetics*, *Annals of Operations Research* (*AOR*, 2010), *Healthcare Management Science* (*HCMS*, 2009), and four other special issues on discrete event systems and manufacturing systems for *IJCIM* (2005), *IJPR* (2004, 2001), and *IEEE Transactions Robotics and Automation* (2001). He served as general chair of ORAHS'2007 and IPC chair of the *IEEE Workshop on Health Care Management WHCM'2010* and was IPC member for many other conferences.

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