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MILIND W. DAWANDE
School of Management, University of Texas at Dallas

H. NEIL GEISMAR
College of Business, Prairie View A&M University

SURESH P. SETHI
School of Management, University of Texas at Dallas

CHELLIAH SRISKANDARAJAH
School of Management, University of Texas at Dallas

Springer

Milind W. Dawande
University of Texas at Dallas, USA

H. Neil Geismar
Prairie View A&M University, USA

Suresh P. Sethi
University of Texas at Dallas, USA

Chelliah Sriskandarajah
University of Texas at Dallas, USA

Library of Congress Control Number: 2007920608

ISBN-10: 0-387-70987-8 (HB) ISBN-10: 0-387-70988-6 (e-book)
ISBN-13: 978-0387-70987-1 (HB) ISBN-13: 978-0387-70988-8 (e-book)

Printed on acid-free paper.

9 8 7 6 5 4 3 2 1

springer.com

To my parents Wasudeo and Arundhati. *Milind Dawande*

To Karen. *Neil Geismar*

To the memories of my mother Manak and aunt Manori.
To my sisters Mena, Kamalsri, and Sulochana.
To my sisters-in-law Sohani, Tara, Amrao, and Mena.
To my wife Andrea and my daughters Chantal and Anjuli. *Suresh Sethi*

To my wife Kohila.
To my children Vani and Madan. *Chelliah Sriskandarajah*

Foreword

This book presents research on sequencing and scheduling problems in robotic cells. The authors have been at the forefront of research activity in this area. Suresh Sethi and Chelliah Sriskandarajah coauthored (together with Gerhard Sorger, Jacek Błażewicz, and Wieslaw Kubiak) an influential paper titled "Sequencing of Parts and Robot Moves in a Robotic Cell," (*International Journal of Flexible Manufacturing Systems*, 1992) that helped establish the framework for the algorithmic investigation of throughput optimization problems in the robotic cell literature. Along with their colleague Milind Dawande and former student Neil Geismar, they have put together this treatise that incorporates their own research and that of others.

The authors have done a commendable job in bringing together the important analytical results on throughput optimization in a variety of robotic cells. The book starts by providing the reader with a snapshot of the different applications of robotic cells in the industry. In particular, such cells are used extensively in the production of semiconductors. The authors then devise a classification scheme (Chapter 2) for the scheduling problems that arise in the different types of robotic cells. Cyclic production, the most commonly used mode of production, is analyzed next (Chapter 3). Using a basic model of a robotic cell, the authors explain the notion of cycles and cycle times, and proceed to derive a variety of results, exact and approximation algorithms, concerning cyclic production. Scheduling problems in cells with more advanced hardware are discussed next. In Chapter 4, algorithms are presented for cells in which the robot has a gripper that can hold two parts simultaneously.

Chapter 5 discusses cells that have more than one machine at one or more processing stages. In Chapters 6 and 7, the authors then widen the scope of inquiry by addressing cells which are able to produce two or more different types of parts simultaneously. Cells with more than one robot are discussed in Chapter 8. Most of the descriptions in Chapters 3-8 are for cells in which a part that has completed processing on a given machine can stay on that machine indefinitely (until a robot picks it up). Chapter 9 briefly discusses two other types of cells that have noteworthy practical applications. The final chapter (Chapter 10) presents a number of open problems.

Throughput optimization problems for robotic cells are not at all like the classical machine scheduling problems with which I am familiar with and have published papers on. The notation required to state and analyze these problems is significantly different than that used in the previous scheduling literature, and it may take a reader some effort to gain familiarity with the notation used in this book. However, the reader will find the effort worthwhile and will appreciate that this new area has a number of well-defined and non-trivial combinatorial problems stemming from practical applications. Efficient solution techniques for solving such problems may lead to significant cost savings for factories using robotic cells in their production processes.

Two of the authors of this book, Suresh Sethi and Milind Dawande, received their Ph.D. degrees from the Graduate School of Industrial Administration (now the Tepper School of Business) at Carnegie Mellon University. Suresh was the first student to complete his Ph.D. degree in five semesters under my direction during the 43 years that I was a faculty member of Carnegie Mellon University.

Pittsburgh, Pennsylvania
August 2006

Gerald L. Thompson
Professor of Operations Research, Emeritus
Carnegie Mellon University

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Preface

The love of learning, the sequestered nooks,
And all the sweet serenity of books.
– Henry Wadsworth Longfellow, 'Morituri Salutamus,' 1875

Intense global competition in manufacturing has compelled manufacturers to incorporate automation and repetitive processing for improving productivity. As manufacturers strive to reduce cost and improve productivity, the benefits offered by computer-controlled material handling systems – efficiency and speed of processing, reduced labor costs, a largely contaminant-free environment, to name a few – are compelling reasons for their use. In their typical use, such systems are responsible for all inter-machine handling of work-in-process as raw materials progress through the multiple processing stages required to produce a finished part.

Many modern manufacturing systems use robot-served manufacturing cells, or *robotic cells* – a particular type of computer-controlled manufacturing system in cellular manufacturing. The exact time of the first use of such systems is difficult to pinpoint; however, several industrial implementations were in use in the 1970s. Most of these were classical machining applications such as automated tool loading and unloading for metal-cutting, grinding, turning, etc., and automated classification of parts before palletizing. Over the years, the scope has broadened to a wide variety of industries including the manufacture of semiconductors, textiles, pharmaceutical compounds, magnetic resonance imaging systems, glass products, cosmetics, fiber-optics, and building products.

As they become prevalent, using robotic cells efficiently becomes a competitive necessity. In this regard, research efforts have focused on three major issues: cell design, sequencing of robot moves, and optimal scheduling of the parts to be produced. The latter two issues are the subject of most of our discussion in this book. In particular, our emphasis is on cyclic production in which a sequence of robot actions is repeated until the production target is met.

This book is devoted to consolidating the available structural results about cyclic production in the various models used to represent real-world cells. As cells become larger and more complex, the need for increasingly versatile models and easy-to-implement algorithms to optimize cell operations has increased. We have made an attempt to bring together the results developed over the past 25 years. The material is organized into 10 chapters. We start by taking a look at industrial applications and formulating a classification scheme for robotic cell problems. After presenting some fundamental results about cyclic production, we proceed to analyze cells with dual-gripper robots, parallel machines, multiple-part-type production, and multiple robots. Finally, we discuss some important open problems in the area.

We envision this book as a reference resource for practitioners, researchers, and students. The book can also be used in a graduate course or a research seminar on robotic cells.

We extend our grateful thanks to our numerous colleagues whose contributions have been directly or indirectly included in this book. In particular, we are indebted to our co-authors, Jacek Błażewicz, Inna Drobouchevitch, Nicholas Hall, Hichem Kamoun, Wieslaw Kubiak, Subodha Kumar, Rasaratnam Logendran, Chris Potts, Natarajan Ramanan, Jeffrey Sidney, and Gerhard Sorger, whose collaboration has been critical for the development of a significant portion of the material covered in the book. We thank Alessandro Agnetis, Nadia Brauner, Chengbin Chu, and Eugene Levner for their encouragement and for suggesting several improvements to the manuscript. We also thank our student Mili Mehrotra for her help in proofreading parts of the manuscript. It was a pleasure working with Gary Folven and Carolyn Ford of Springer; we are grateful for their support. Finally, we thank Barbara Gordon for her help with LaTeX.

M.W. Dawande
S.P. Sethi
C. Sriskandarajah
Richardson, TX

H.N. Geismar
Prairie View, TX