Lecture Notes in Production Engineering

Katja Windt *Editor*

Robust Manufacturing Control

Proceedings of the CIRP Sponsored Conference RoMaC 2012, Bremen, Germany, 18th–20th June 2012

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Preface

The international conference on “Robust Manufacturing Control—Innovative and Interdisciplinary Approaches for Global Networks” (RoMaC 2012) was held on the campus of Jacobs University in Bremen, Germany. As expressed by the title, one major intention of the conference is to focus on transdisciplinary approaches toward robustness in manufacturing. The conference was sponsored by the International Production Engineering Academy (CIRP) and the Alfried Krupp von Bohlen und Halbach-Foundation, to both of which I am very thankful.

Today, Global Production Networks (i.e., the nexus of interconnected material and information flows through which products and services are manufactured, assembled, and distributed) are confronted with and expected to adapt to:

- sudden and unexpectable large-scale changes of important parameters which occur more frequently.
- event propagation in networks with high degree of interconnectivity which leads to unforeseen fluctuations.
- non-equilibrium states which increasingly characterize daily business.

These multi-scale changes deeply influence logistic target achievement and call for robust planning and control strategies. Therefore, understanding the cause and effects of multi-scale changes in production networks is of major interest in order to achieve robustness in respect of stabilizing and sustaining systems performance. New methodological approaches from different science disciplines are promising to contribute to a new level of comprehension of network processes. Unconventional methods from biology, perturbation ecology, or auditory display are gaining increasing importance as they are confronted with similar challenges. Advancements from the classical disciplines such as mathematics, physics, and engineering are of continuing importance.

This Lecture Notes Volume starts out with Part I “Interdisciplinary Approaches for Robustness in Manufacturing”. The contributions presented in Part I cover interdisciplinary work between manufacturing research and a wide range of disciplines, such as systems biology, auditory display, network sciences, or nonlinear dynamics. Especially for today’s global manufacturing systems, interdisciplinary research offers a possibility to tackle research questions that arise due to the interplay between a need for robustness and a growing system complexity in manufacturing. As for instance shown in the first paper of Part I by Beber et al., strong parallels exist between manufacturing and metabolic systems. This justifies the application of methods from systems biology, which are designed to cope with the complexity of natural systems (i.e., cells) and offer possibilities to analyze and describe system robustness. Further, it is shown in Part I by Iber et al. that the analysis of manufacturing feedback data with methods from auditory display can identify causes and impacts of certain parameters in complex manufacturing networks which graphical analysis is not able to. This can support and contribute to an increasing robustness of manufacturing processes.

Part II “Robust Manufacturing Control Methods” addresses the issue of how important it is to have novel tools and approaches, which enable manufacturers to keep their high performance in today’s unpredictable market conditions. Techniques from three different areas are presented. First, several scheduling methods are described. Scheduling is a well-known problem, which has been extensively studied in the literature. However, manufacturing systems nowadays are highly complex and also often highly automated and therefore further advancements are necessary. Moreover, as production systems have to face sudden changes and fluctuations, innovative robust scheduling procedures are needed. Second, this part also presents methods related to the concept of autonomous control. Granting various logistic objects decision-making abilities could lead to increased robustness of the systems. Third, the part finishes with data mining techniques, which can be used in order to discover knowledge from databases. Such tools are commonly applied in many fields and their use is also growing in manufacturing and logistics. Data mining algorithms can be very beneficial in a complex manufacturing environment, where numerous parameters are involved. For example, they can be utilized to form different product families or to generate production planning rules.

The central topic of the contributions summarized in Part III is “Robustness in Manufacturing Networks and Adaptable Logistics Chains”. All contributions focus on the fact that the majority of nowadays manufacturing companies organize their production in a production network: suppliers, manufacturing sites, distribution hubs, and customers are spread around the whole world. Challenges that companies are faced with and solutions to problems that they encounter if they want to keep their production network robust and adaptable are presented here. Within this overarching range, contributions in Part III address several different problems: first, methods to design, configure, or plan robust production networks are presented. This is followed by contributions that deal with the issue of quality management as a means to achieve robustness in global production networks. Part III further includes contributions on collaboration, coordination, and adaptability within global production networks. It concludes with contributions that address questions of decentralized manufacturing, putting also a focus on environmental impacts and issues.

Part IV "Process Optimization and Strategic Approaches toward Robustness" presents a selection of papers, which elaborate on diverse aspects of robust manufacturing control. First, companies should establish adaptable production processes, which are able to operate under changing market conditions. Manufacturers need to ensure that their logistics performance matches the requirements of the customers in terms of delivery reliability, for example. Therefore, concepts such as productivity of the production processes, the level of decentralization of production control, and optimization of the decision-making procedures in production planning and control are of high importance and are addressed in some of the papers in this part. In addition to looking into their processes, manufacturers should also carefully select their strategies. They need to develop manufacturing and strategic flexibilities, which enable them to have strategies of higher robustness. Finally, it is argued that enterprises should also consider the trade-off between robustness and efficiency when making their strategic decisions.

I would like to express my gratitude to all authors contributing to the conference as well as to all participants of the conference making this event successful. Moreover, I would like to thank the members of the program committee for their valuable comments in the respective reviews. In particular, I cordially thank Professor Neil A. Duffie and Professor Hans-Peter Wiendahl acting as editorial committee members for their highly appreciated recommendations and advice on how to prepare and run an international conference as RoMaC 2012 was the first conference ever organized by the Global Production Logistics workgroup at Jacobs University. I am explicitly grateful to Stanislav Chankov and Mirja Meyer who are research associates in my workgroup for their valued assistance in organizing and double checking all paper-relevant processes including the conference preparation. And finally, I thank Silke Tilgner for her high engagement in the conference planning and organization.

I very much hope that with this conference Robust Manufacturing Control was started as a topic on its own and will get further consideration in the future.

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Hans-Peter Wiendahl Prof. Dr.-Ing. E.h. mult. Dr. sc. h.c. Dr.-Ing. Hans-Peter Wiendahl studied mechanical engineering in Dortmund and Aachen. After one-year research visit at the Massachusetts Institute of Technology (MIT), he started as a research associate and Ph.D.-student at the “Laboratory for Machine Tools and Production Engineering” at RWTH Aachen, from which he graduated as a Ph.D. in 1970. After Post-Doc work in Aachen, Prof. Wiendahl gained extensive industry experience, before he was appointed professor and chair of the Institute of Production Systems and Logistics (IFA) at the Leibniz University of Hannover in 1979. Prof. Wiendahl has been a member of the International Academy for Production Engineering (CIRP) since 1989. He is an honorary doctor of several universities and in 2003 he became an emeritus professor at the Leibniz University of Hannover. In 2010 he received the Society of Manufacturing Engineers (SME) Gold Medal.

Neil Duffie Prof. Neil A. Duffie earned his Bachelor (1972), Master (1974) and Ph.D. (1980) degrees from the University of Wisconsin-Madison, where he now works as a professor at the department of mechanical engineering within the college of engineering. His research and teaching focus on the design and control of manufacturing systems. He is mainly interested in the integration of sensors, actuators, and data sources in highly automated, non-hierarchically controlled production systems. Prof. Duffie became a member of the International Academy for Production Engineering (CIRP) in 1999. He has been a fellow of the American Society of Mechanical Engineers (ASME) since 2006 and has received several awards.

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Part I

Interdisciplinary Approaches for Robustness in Manufacturing

How Do Production Systems in Biological Cells Maintain Their Function in Changing Environments?

Moritz Emanuel Beber and Marc-Thorsten Hütt

Abstract Metabolism is a fascinating natural production and distribution process. Metabolic systems can be represented as a layered network, where the input layer consists of all the nutrients in the environment (raw materials entering the production process in the cell), subsequently to be processed by a complex network of biochemical reactions (middle layer) and leading to a well-defined output pattern, optimizing, e.g., cell growth. Mathematical frameworks exploiting this layered-network representation of metabolism allow the prediction of metabolic fluxes (the cell's 'material flow') under diverse conditions. In combination with suitable minimal models it is possible to identify fundamental design principles and understand the efficiency and robustness of metabolic systems. Here, we summarize some design principles of metabolic systems from the perspective of production logistics and explore, how these principles can serve as templates for the design of robust manufacturing systems.

Keywords Systems biology · Metabolic networks · Enzymes · Design principles · Simulated evolution

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1 Introduction

There is a deep intrinsic parallel between the metabolism of biological cells and industrial production. Cells function efficiently under typical environmental conditions. At the same time, they are viable (thus maintaining a certain level of function) across a vast range of atypical environments. It is precisely this robustness with respect to large changes (and significant fluctuations) in the composition of the environment (the 'input pattern') that makes metabolic networks a potentially very interesting role model for technical production and distribution systems (see, e.g., [1]).

The network of metabolic reactions in a cell is responsible for providing a wide range of substances at the right time in the right proportions for a specific purpose of consumption. At the same time, metabolic systems construct complicated chemical substances out of nutrients taken up from the environment. With several thousands of interacting machines (enzymes, catalyzing biochemical reactions) the underlying production network is about as complex as the most involved processes of industrial production. The key challenges are comparable: How do systems in both domains ensure robustness with respect to perturbations? How can these systems react rapidly to important changes in their environment by ensuring the achievement of the logistics targets? For metabolism, the young scientific discipline addressing these questions in a strong interplay between mathematical approaches and experimental efforts is called Systems Biology. It is a 'melting pot' of many scientific fields, contributing to the understanding of the larger-scale organization of living cells and their dynamic behavior in response to external and internal stimuli, including disease development (see, e.g., [2–4]). Systems Biology is situated at the intersection between the Biological Sciences, Mathematics, Statistical Physics, Biophysics, and Computer Science. For the part of Systems Biology discussed here, the principal aim is not the representation of a cell in a computer, but rather it is about understanding function beyond the level of a few elements: How is robustness achieved? How can a system react rapidly to changes in the environment?

The parallel between metabolism and manufacturing has been emphasized by others before (e.g., [5, 6]; see also [7]). Systems Biology has over the last 6–8 years provided a remarkable basis for a more refined, detailed and quantitative comparison of these two realms. In the present paper we repeat some of the arguments from [8] and briefly review two articles exploring abstract model representations of metabolic systems [1, 9].

Our focus here is on metabolism as a potential 'template' for manufacturing systems. Other biological principles, like adaptation, self-organization and aspects of biological evolution have been explored to allow manufacturing systems to deal with environmental variability and internal fluctuations. Two important examples are the framework of Biological Manufacturing Systems (see, e.g., [10, 11]) and the idea of Emergent Synthesis [12], which suggests that regulation on all scales requires integration in a self-organized fashion.

The aim of this paper is to review some material from Systems Biology on the functioning of metabolism and then show, how abstract model representations of metabolic systems can serve as a starting point for transferring metabolic design principles to industrial production. We first describe the general features of metabolic systems that form the basis of a comparison with industrial production (Sect. 2). Next, we discuss a broad range of recently identified metabolic design principles of interest to manufacturing (Sect. 3). In Sect. 4 we then explore the possibility of constructing abstract mode l representations of metabolic systems that are suitable interfaces between Systems Biology and industrial production, helping us to transfer such knowledge into manufacturing contexts. Lastly, in Sect. 5 we discuss, how such biological understanding, in particular of design principles of metabolic systems, can serve as templates for robust technical and industrial systems.

2 Metabolism From a Production Logistics Perspective

Metabolism is at the same time a transportation network, an assembly line, and a storage depot. Substances are taken up from the environment (by exchange reactions) and distributed in the cellular compartments (by transport reactions). Large parts of metabolism are responsible for degrading complex substances into more elementary building blocks (catabolism). These chemical building blocks are used in the formation of more complex compounds (anabolism) that are needed for cellular maintanance, growth or storage. The elementary organizational unit of metabolism is the individual biochemical reaction, often represented by the enzyme (or enzyme complex) serving as catalyst for a reaction. Qualitatively speaking, the exchange reactions can be regarded as an input layer, followed by a complex intracellular processing layer. In many modeling approaches the overall goal of metabolic function is abstracted as a (fictitious) biomass reaction, where each component entering this reaction is known to contribute to cell growth. Figure 1 (left) summarizes this situation.

The flow of substances through the metabolic network is the cell's equivalent of the complex material flows encountered in industrial production. The enzymes represent machines responsible of constructing well-defined products out of a specific set of incoming materials.

The appropriate mathematical tools for analyzing successful configurations of metabolic systems on the scale of a whole cell (rather than an individual metabolic pathway) are constraint-based modeling and, more specifically, flux-balance analysis (FBA), reviewed, e.g., in [14, 15]. FBA can be used to predict metabolic flux distributions (the biological equivalent of material flow) under various nutrient input patterns and for diverse cellular objective functions (serving as the output pattern of the system maximized during flux-balance analysis).

Within the elegant framework of flux-balance analysis, the optimal steady-state distribution of metabolic fluxes can be predicted, given the structure of the