DOCTORAL PROGRAM IN MECHANICAL ENGINEERING

Chair:
Prof. Bianca M. Colosimo

Within the current global economic scenario, striving to recover from general slowdown and uncertainty, Mechanical Engineering still stands out as one of the leading and driving sectors of industrial manufacturing in Italy. In terms of per-capita manufacturing production, our country ranks 2^{nd} in Europe and 5^{th} on a worldwide scale (Confindustria, Scenari Industriali n.3, June 2012); among major machine tools manufacturing countries, Italy holds a strong 4^{th} position (UCIMU, Annual Report 2011).

In this competitive panorama, and in order to respond to the requests of a challenging sector, the PhD Programme in Mechanical Engineering, organized within the Department of Mechanical Engineering, provides doctoral candidates with a strong scientific training, fostering and refining research and problem-solving abilities with respect to academic and non-academic *milieu*.

Our Doctoral Programme relies on the development of an interdisciplinary and integrated high-level educational offer, by focusing on a comprehensive scientific proposal, from conception to realization. PhD Candidates in Mechanical Engineering at Politecnico di Milano follow a three-year path which includes specific courses and lectures, held by faculty members and foreign professors and experts, in-depth research, laboratories, and active cooperation with international industries, institutions and research groups. With this background, our Doctorates are able to blend the exactness of scientific knowledge with the ability to deal with management and industrial issues. In this view, their scientific profiles are suitable for prestigious positions at national and international level within universities and research institutions, large industrial and consulting companies, SMEs.

RESEARCH AREAS

The PhD Programme in Mechanical Engineering covers a number of different disciplines, being devoted, in particular, to innovation and experimental activities in six major research areas; all doctoral thesis displayed in the following pages belong to one of these areas:
Dynamics and vibration of mechanical systems and vehicles: this research line is organized into five research areas, namely Mechatronics and Robotics, Rotordynamics, Wind Engineering, Road Vehicle Dynamics, Railway Dynamics. It features modelling of linear and non-linear dynamic systems, stability and self-excited vibrations, active control of mechanical systems, condition monitoring and diagnostics.
Measurements and experimental Techniques: the Mechanical and Thermal Measurements (MTM) group has its common background in the development and qualification of new measurements techniques, as well as in the customisation and application of well-known measurement principles in innovative fields. MTM major research focus is oriented towards the design, development and metrological characterisation of measurement systems and procedures, the implementation of innovative techniques in sound/vibrations, structural health monitoring, vision, space and rehabilitation measurements.
Machine and vehicle design: this research area is involved in advanced design methods and fitness for purpose of mechanical components. Advanced design methods refer to the definition of multiaxial low and high cycle fatigue life prediction criteria, and the assessment of structural integrity of cracked elements, the prediction of fatigue life criteria of advanced materials as polymer matrix composite materials (short and long fibres), the definition of approaches to predict the influence of shot peening on fatigue strength of mechanical components. Gears, pressure vessels and helicopter components are dealt with. Optimal design and testing of vehicle systems create a synergism between the theoretical and the experimental researches on ground vehicles.
Manufacturing and production systems: this research field gives relevance to the problem of optimal transformation of raw materials into final products, addressing all issues related with the introduction, usage, and evolution of technologies and production systems during the entire product life-cycle. PhD activities, in particular, are developed within the following research fields: Manufacturing Processes (MPR), Manufacturing Systems and Quality (MSQ).
Materials: this area is focused on the study of production process and characterization of materials, for structural and functional applications. Excellent research products were obtained both on fundamental research topics (e.g. nanostructured materials, foamed alloys, chemical phenomena in liquid melts, microstructural design ecc.) and on applied research (e.g. failure and damage analysis, texture analysis, high temperature behaviour, coatings for advanced applications, etc.). The research projects carried out in recent years addressed specifically the following research topics: Steelmaking and Metallurgical Processes, Advanced Materials and Applied Metallurgy.

Methods and tools for product design: two main research topics are addressed in this field: PLM-Product Lifecycle Management, which includes process modelling, engineering knowledge management, product innovation methods, systematic innovation principles and methods, topology optimization systems, and data/process interoperability, and Virtual Prototyping, which includes virtual prototyping for functional and ergonomics product validation, haptic interfaces and interaction, reverse engineering and physics-based modelling and simulation, emotional engineering.

LABORATORIES

One of the key elements of our Doctoral Programme is represented by our laboratories; we feature some of the most unique, active and innovative set-ups in Europe: Cable Dynamics, Characterization of Materials, DBA (Dynamic Bench for Railway Axles), Dynamic Testing, Dynamic Vehicle, Gear and Power Transmission, Geometrical Metrology, High-Temperature Behaviour of Materials, La.S.T., Manufacturing System, Material Testing, Mechatronics, MI_crolab Micro Machining, Microstructural Investigations and Failure Analysis, Outdoor Testing, Physico-Chemical Bulk and Surface Analyses, Power Electronics and Electrical Drives, Process Metallurgy, Reverse Engineering, Robotics, SIP (Structural Integrity and Prognostics), SITEC Laser, Test rig for the Evaluation of Contact Strip Performances, VAL (Vibroacoustics Lab), VB (Vision Bricks Lab), Virtual Prototyping, Water Jet, Wind Tunnel.

INTERNATIONALIZATION

We foster internationalization by strongly recommending and supporting PhD candidates' mobility abroad, for short-term study and research periods up to 18 months. We promote, draft and activate European and extra-European Joint Degrees, Double PhD Programmes and Joint Doctoral Thesis; our Department is actively involved in EU-based and governmental third-level education agreements such as Erasmus Mundus, Cina Scholarship Council and Brazilian Science Without Borders.
38% of PhD Candidates enrolled in 2012 are foreigners; female presence (Italian and non-Italian) accounts for 23%.
Our international network includes some of the highest-level and best-known universities all over the world, such as MIT, University of California at Berkeley, Imperial College, Delft University of Technology, Technical University of Denmark, Pennsylvania State University, University of Bristol, Technische Universität Darmstadt, University of Bristol, University of Sheffield, Fraunhofer Institut LBF Darmstadt, Universidad Politécnica de Madrid, Tokyo Polytechnic University, Universidad de Concepcion, University of Miami, the University of Western Ontario.

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TIME BUFFER: A CONTINUOUS APPROXIMATION FOR SIMULATION OPTIMIZATION OF DISCRETE EVENT SYSTEMS

Giulia Pedrielli - Supervisor: **Andrea Matta**

This work focuses on the optimization of stochastic Discrete Event Systems (DES's). The state of a DES changes only when events happen, whereas no modifications happen between consecutive events. As a result, the system dynamics is fully characterized by the sequence of events, which defines the system sample path. Stochastic DES's are such that given and sequence of known input the system sample path is a stochastic process instead of a deterministic sequence of events.
The optimization of stochastic Discrete Event Systems (DES's) is a critical and difficult task to be addressed. Indeed, besides the search for the optimal system configuration, it requires the assessment of the system performance. In other words, both an optimization problem and a simulation problem need to be solved. In the literature, this framework is referred to as Simulation-Optimization.
Traditionally, the simulation-optimization architecture is made of two decoupled modules: an optimization module (generative module), solving the optimization problem and a simulation module (evaluative module), solving the simulation problem. These two modules work iteratively until the optimal solution is found or a predefined stopping condition is met. The optimization module does not contain the description of the system dynamics. The simulation module, instead, can evaluate the system performance since it embeds the description (explicit or implicit) of the system behavior; however, as no optimization procedure is contained within this module, it cannot optimize the system configuration. Hence, in the scope of simulation optimization, both modules are required.
Mathematical Programming Representation (MPR) can be applied to avoid this decoupled architecture. Indeed, if the dynamics of the system can be represented by means of a set of constraints, they can be embedded in the optimization model. As a result, the DES is optimized and simulated at the same time.
This thesis proposes an integrated simulation-optimization framework based on the use of mathematical programming for both configuration generation (i.e., to solve the optimization problem) and system performance assessment (i.e., to solve the simulation problem). Specifically, LP models for simulation-optimization, developed based on the Time Buffer (TB) concept, are proposed. The TB is a continuous approximation to replace the integer decision variables defined in the original optimization problem. In general, to approximate a discrete variable with a TB, it must be possible to formally describe its effects on the events characterizing the system dynamics.
Herein, the time buffer framework is formalized, describing the tractable classes of Discrete Event Systems and optimization problems. The approach steams from the description of the simulation-optimization problem, i.e., (1) the objective of the optimization, (2) the constraints on the decision variables, (3) the description of the system behavioral rules. Afterwards, the IP mathematical model for simulation optimization can be developed and the TB-based LP counterpart can be derived. The solution of the TB models provides a good approximate integer solution to the optimization problem and robust bounds on the exact solution, i.e., upper and lower limit defining the interval where the optimal solution lays. The time buffer concept has been applied for approximating the buffer capacity in an open flow line to solve the Buffer Allocation Problem and for approximating the number of pallets in a loop line to solve the Pallet Allocation Problem. In particular, this thesis represents the first contribution in the modeling of closed queuing networks adopting the TB approach.
Three main results can summarize the brought research activity:

- **R1.** Development of the Time Buffer Framework for the simulation-optimization of DES's. This work has presented the main properties of the class of DES's and optimization problems in order to generate TB models. Moreover, the proposed approach has been characterized providing the main guidelines to derive and solve approximate models for simulation-optimization starting from the description of the dynamics of the system and the optimization problem (simulation-optimization problem setting).
- **R2.** Application of the Time Buffer Framework for the solution of (1) the Buffer Allocation Problem (BAP) for multiple stage open queuing networks and (2) the Pallet Allocation Problem for closed queuing networks with finite buffer capacities, laying the prerequisites for the simulation-optimization of multiple loop systems. This application led to the development of two optimization algorithms to solve the respective problems.
- **R3.** Solution of the developed models and proof of structural results exploiting the set of tools coming from the Mathematical Programming Representation framework and the theory of convergence.

This work was partially funded by the European research project Virtual Factory Framework (grant agreement No.: NMP2-LA-2010-228595). In the scope of the project, the developed simulation- optimization application has been integrated within the Virtual Factory (VF) platform forming, with other connected tools, a first proposal of a comprehensive suite for the factory design. As a result, besides the presented scientific results this thesis represents a contribution towards the answer to a relevant industrial issue: the presence of a collaborative platform supporting the design of virtual factories.
The design platform was tested on a real industrial case provided by the System Engineering Department of COMAU SpA Power Train division, one of the most important technology providers for FIAT automotive. The positive feedbacks received from COMAU fostered further extensions to the platform on which we are working at the present moment.
Three main future research directions were outlined:

- **F1.** Time Buffer framework extension. The general approach has to be further detailed and the whole framework extended both in terms of the class of optimization problems that can be managed and the class of discrete event systems that can be represented. The idea is to provide a definition of the time buffer as a mean to connect events affecting a DES. In this way a large class of discrete decision variables can be modeled based on their effects on the event sequence. This approach seems promising as it acts on the sequence of events that is among the most general ways to model a DES.
- **F2.** Definition of convergence requirements. The convergence study has to be extended to the closed queuing networks case with the purpose of understanding the convergence property of the time buffer models in general. As ultimate end, this activity should lead to the definition of the properties that the class of systems and optimization problems need to satisfy in order to guarantee the convergence of the time buffer models.
- **F3.** Computational efficiency. Increase the efficiency to solve the LP approximate models exploiting the derived properties. The proximity of the approximate integer solution and the one obtained running OptQuest (i.e., the optimization tool provided together with the commercial simulation software for Discrete Event Systems Arena), suggests that a branch and bound based search method, starting from the generated solution and the computed bounds, could reach the optimum requiring less time than other commercial applications do. However, to make this two-stage optimization appealing the computational time required to solve time buffer models needs to be decreased.

The results obtained in this thesis, despite the specific systems and optimization problems, considered, lay the foundations of a general framework for DES's optimization, hence oriented to a broader class of both discrete event systems and optimization problems.

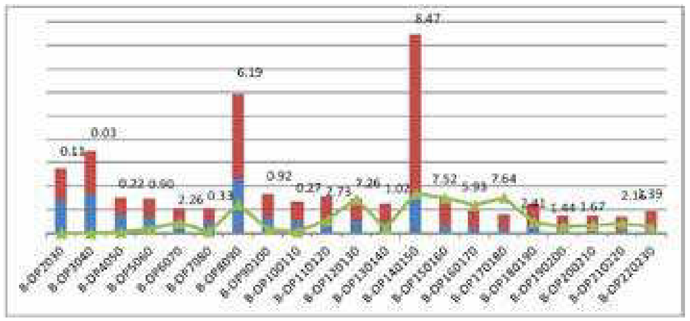
PERFORMANCE EVALUATION OF COMPLEX MANUFACTURING SYSTEMS: AN APPROACH BASED ON FORMAL METHODS AND APPROXIMATE ANALYTICAL MODELS

Andrea Ratti - Supervisor: **Tullio Tolio**

A production system is the set of technological resources that is capable to transform raw parts into a finished products in terms of time, location and shape. In such a system, the interactions between the resources make the behavior of the system quite complex to evaluate and to understand by the designers. For these reasons, the managers of the companies need proper tools and methods to quantitatively support the planning, control and performance improvement of the systems, throughout all the factory life-cycle phases, from early design, up to reconfigurations.
One of the most critical task along the process of design of production systems, is the evaluation of the performance. The goal is to provide the designer a measure of the productivity of a system like production volumes, utilization of the resources, average flow times and work in progress. Usually this task is carried out with the creation of a proper model, i.e. a meaningful simplification of the reality that can be used for a specific design purpose, that is usually a simulation or an analytical model.
Analytical methods are developed with the goal of describing the dynamic behavior of the system in terms of the solution of a set of equation, used to express the relations existing among the different variables. Concerning manufacturing systems, the variables are related with the stochastic processes that afflict the resources, like the failure and the repair of the machines, the processing times, the flow of parts, the blocking of the system, etc. Thanks to this formulation, analytical methods are usually very fast in terms of computational effort. This aspect is useful and desired during the early stages of manufacturing systems design because facilitate the reduction of the number of possible alternative system configurations.
However, the mathematical formulation of such a problem is a cognitive-intensive activity. This means that an extension of the model capabilities requires a big effort. Moreover, the designers need to understand what is happening inside the system, that means recognize the structure of the plant, the behavior of the resources, the relevant features and the numerical parameters, i.e. processing times and reliability. The information of this potential system configuration can be either about the structure or numerical. The structure include all the information about how the resources of the system are connected and how they operate, i.e. layout of the plant, type of machines, kind of operations performed, etc. The numerical include all the quantitative information about the system, i.e. reliability of the machines, processing times, bill of material, etc. At a first glance, such a system appears to be a chaotic composition of technological devices. This means that it takes a lot of time to an expert to figure out what is happening inside the system, i.e. determine the flow of parts, which operations are done by the machines, which are the resources of the system, how the reliability of the machines works, etc. Once the designers have figured out how the system works, they need to determine what is relevant and what is irrelevant from modeling purpose, that is, again, an hard activity.
Here, in this thesis, a new framework is presented, that is composed by an analytical methodology for manufacturing systems performance evaluation based on automatic model generation, obtained from a structured description of the manufacturing system, for aiding the designer both in the configuration and reconfiguration phases. This thesis makes contributions to performance evaluation

of manufacturing systems and automatic performance evaluation model generation fields.
The proposed methodology consists of two main elements The first element is the definition and analysis of manufacturing system structures by means of a new formal method. This new formal method, written using the specification language Alloy, provides a new general way to describe production system, through a series of native primitives of the domain of manufacturing systems. All the possible machines, buffers and structure configurations that can be found in a complex production system, i.e. assembly/disassembly, split/merge, parallel, loop, rework, etc. When a production system is described by means of this new formal language, it is possible to execute an automatic analysis and recognize automatically its relevant structures. Within this framework all the elements and the requirements that are needed to perform the automatic model generation, both in terms of methodologies and practical implementations, are defined.
The second element is the creation of general analytical model for the performance evaluation of manufacturing system, composed by a new analytical model of a two-machine continuous flow system with finite buffer capacity, multiple up and down states. The model provides a way to analyze a wide range of two-machine systems, including for example systems with phase-type failure and repair time distributions and series/parallel machines. The two elements are then used together to build the model of the system. The exact solution of the two-machine line is used as a building block for the analysis of larger systems, using decomposition techniques. The two-machine lines are automatically configured according to the automatically recognized structures from the formal method, and to the numerical parameters from the plant, fitting phase-type distributions. In the thesis, the decomposition techniques used, are already available in the literature.

The framework is validated on a real case production line, dedicated to the machining of components for the automotive sector, integrating all the elements of the framework. The model of the system is created automatically using the empirical distributions available from the plant. The new formal method is validated on a real case production system, dedicated to the assembly of electrical components and on a set of some didactic examples. Moreover, the two-machine line model is used for the investigation of the effect of phase-type distribution approximation on the performance of the system, both in terms of productivity and of average buffer inventory.

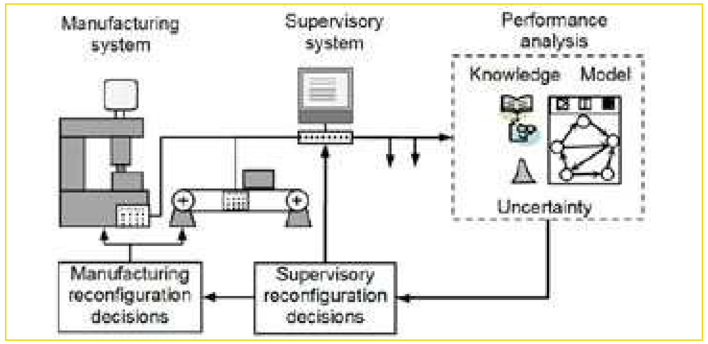


1. Plot of average inventory level obtained from the analytical model on a real production example

INTEGRATED ANALYSIS OF MANUFACTURING AND SUPERVISORY SYSTEMS

Anteneh Yemane - Supervisor: **Marcello Colledani**

The design, development and operation of manufacturing systems that highly guarantee desired target performances is a crucial goal in manufacturing as enterprises are facing an increasingly competitive global market. In response, the last decades of manufacturing systems engineering research has generated powerful tools to support the modeling and analysis of manufacturing system performances. Besides, companies are increasingly interested in assisting the design and operation of advanced manufacturing systems by implementing modern digital manufacturing tools. Technological advances in sensor and information technology enable the acquisition and storage of huge amount of information about the behavior of the systems. Thus, decision making in the design and operation of advanced multi-stage manufacturing systems is more and more supported by digital manufacturing tools. In order to be effective in their scope, such tools have to be based on high-fidelity virtual representations of the real system.
At various stages of the manufacturing system life cycle there is a need to consider the link between digital technologies which gather information and the manufacturing systems analysis tools that must be fed with this information. During the design phase, the technical efficiencies of the resources/ machines that shall compose the manufacturing system are considered as nominal values, provided by the equipment producers. In operational phase the reliability of machines is modeled through the characterization of the Mean Time to Failure (MTTF) and the Mean Time to Repair (MTTR) of each failure mode affecting the machine productivity. Although these are assumed to be the mean of statistical distributions, their value is considered as known deterministically. Depending on the level of confidence and knowledge on the estimation of the input parameters they are subjected to uncertainty. Performance analysis with an explicit consideration of the associated uncertainty is of paramount importance for generating system configurations/ reconfigurations that are robust to input parameter estimation uncertainty.
The relationship between the amount of data used for parameter estimation and the subsequent performance evaluation is strong. Results from this research have also shown that uncertainty modifies the performance evaluation results and can significantly affect the related system design decisions. This perspective paves the way for the development of a new manufacturing system engineering theory for the robust design of manufacturing systems under uncertainty. However, in spite of the strong relationship between the two fields they are normally treated independently by researchers and practitioners.
To this goal the impact of performance analysis using real data in contrast with precisely known parameters assumptions is investigated. Performance deviations as high as 15% estimation errors are observed by carrying out the analysis ignoring uncertainty in estimations. Moreover, analyses with the traditional approach that assume precisely known parameter estimates from actual data are observed to provide performance guarantee level as low as 43%, which compromises system robustness in achieving desired target performance.
In order to clearly present the relevance of the problem and the differences between traditional approaches and the proposed approach primarily the analysis of simpler manufacturing systems is introduced. Performance analysis of smaller manufacturing systems using exact analytical methods with uncertain parameters estimates is demonstrated. The impact of performance analysis using real data in contrast with precisely known parameters assumptions is investigated. Important findings from this analysis are highlighted and the relationships that explain the observed differences are analytically presented.
Emphasizing the proven advantages of performance analysis on smaller systems with real data the study extends a similar approach on the development of tools that support performance analysis in complex systems. Alternative approximate techniques that are accurate and efficient in measuring the performance of multi-stage manufacturing systems are proposed. Numerical accuracy and applicability of the proposed methods are presented under different conditions. Additionally a new method based on the decomposition of multi-stage manufacturing lines for estimating the distribution of the average throughput *TH* is proposed. The method is proved to be accurate and computationally efficient to study long lines. Moreover, the method is used to study and understand important system behaviors under uncertainty, providing important insights in system design under practical scenarios.
A gradient based algorithm for the optimal supervisory systems reconfiguration and manufacturing systems reconfiguration is proposed. The method attempts to improve the estimation of the output performance uncertainty by optimally allocating supervisory resources to reduce performance uncertainty. Exploiting the developed techniques in this work it targets to minimize input uncertainty on the parameters which highly contribute to the output uncertainty. On the other hand it addresses the impact of configurations on performance uncertainty by choosing alternative buffer configurations so that target performances can be guaranteed. This allows system designers to evaluate alternative solutions that satisfy a required level of robustness for the available resources and knowledge on design parameters.
Based on existing buffer optimization techniques, a new approach for the optimization of manufacturing systems under uncertain parameters is proposed. The approach aims at providing the optimal buffer configuration that guarantees the satisfaction of target performances with a given confidence level. By using this method the level of additional information or the necessary buffer configuration required to satisfy the desired level of robustness can be analytically determined.
Finally, based on the result of this study general design and managerial insights are provided in the design and operation of manufacturing systems under uncertainty. The proposed approach is also used for the analysis of an industrial case in automotive industry featuring a buffered multi-stage manufacturing system. Future research works extending the benefits of this research and introducing additional problems in the integrated analysis of supervisory and manufacturing systems are proposed.



1. Integrated data acquisition and performance analysis