## Springer Theses

Recognizing Outstanding Ph.D. Research

## Aims and Scope

The series "Springer Theses" brings together a selection of the very best Ph.D. theses from around the world and across the physical sciences. Nominated and endorsed by two recognized specialists, each published volume has been selected for its scientific excellence and the high impact of its contents for the pertinent field of research. For greater accessibility to non-specialists, the published versions include an extended introduction, as well as a foreword by the student's supervisor explaining the special relevance of the work for the field. As a whole, the series will provide a valuable resource both for newcomers to the research fields described, and for other scientists seeking detailed background information on special questions. Finally, it provides an accredited documentation of the valuable contributions made by today's younger generation of scientists.

## Theses are accepted into the series by invited nomination only and must fulfill all of the following criteria

- They must be written in good English.
- The topic should fall within the confines of Chemistry, Physics, Earth Sciences, Engineering and related interdisciplinary fields such as Materials, Nanoscience, Chemical Engineering, Complex Systems and Biophysics.
- The work reported in the thesis must represent a significant scientific advance.
- If the thesis includes previously published material, permission to reproduce this must be gained from the respective copyright holder.
- They must have been examined and passed during the 12 months prior to nomination.
- Each thesis should include a foreword by the supervisor outlining the significance of its content.
- The theses should have a clearly defined structure including an introduction accessible to scientists not expert in that particular field.

More information about this series at http://www.springer.com/series/8790

Thorsten Wuest

# Identifying Product and Process State Drivers in Manufacturing Systems Using Supervised Machine Learning

Doctoral Thesis accepted by
University of Bremen, Germany

Springer

*Author*
Dr.-Ing. Thorsten Wuest
Department of ICT Applications
for Production
BIBA—Bremer Institut für Produktion
und Logistik GmbH
Bremen
Germany

and

Department of Production Engineering
University of Bremen
Bremen
Germany

*Supervisor*
Prof. Dr.-Ing. habil. Klaus-Dieter Thoben
Department of ICT Applications
for Production
BIBA—Bremer Institut für Produktion
und Logistik GmbH
Bremen
Germany

and

Department of Production Engineering
Institute for Integrated Product
Development
University of Bremen
Bremen
Germany

ISSN 2190-5053 ISSN 2190-5061 (electronic)
Springer Theses
ISBN 978-3-319-17610-9 ISBN 978-3-319-17611-6 (eBook)
DOI 10.1007/978-3-319-17611-6

Library of Congress Control Number: 2015932070

Springer Cham Heidelberg New York Dordrecht London


Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

**Parts of this thesis have been published in the following documents**

**Journals**

Wuest, T., Tinscher, R., Porzel, R. & Thoben, K.-D. (2014). Experimental research data quality in materials science. *International Journal of Advanced Information Technology, 4*(6), 1–18. doi: 10.5121/ijait.2014.4601.

Wuest, T., Hribernik, K. & Thoben, K.-D. (2015). Accessing servitization potential of PLM data by applying the product avatar concept. *Production Planning and Control*. (accepted)

Wuest, T., Irgens, C. & Thoben, K.-D. (2014). An approach to quality monitoring in manufacturing using supervised machine learning on product state data. *Journal of Intelligent Manufacturing, 25*(5), 1167–1180. doi: 10.1007/s10845-013-0761-y.

Wuest, T., Dittmer, P., Veigt, M. & Thoben, K.-D. (2013). Ressourceneffiziente Fertigungssteuerung - Qualitätsbasierte Auftragszuordnung durch Produktzustandsbetrachtung. *wt-online, 2*(103), 100–103.

Wuest, T., Klein, D., Seifert, M. & Thoben, K.-D. (2012). Method to Describe Interdependencies of State Characteristics Related to Distortion. *Mat.-wiss. u. Werkstofftech., 1-2*(43), 186–191.

Wuest, T. & Thoben, K.-D. (2012). Exploitation of Material Property Potentials to Reduce Rare Raw Material Waste - A Product State Based Concept for Manufacturing Process Improvement. *Journal of Mining World Express (MWE), 1*(1), 13–20.

Wuest, T., Klein, D., Seifert, M. & Thoben, K.-D. (2011). Der Werkstückzustand im Informationsmanagement. *PRODUCTIVITY Management, 2*(2011), 26–28.

**International Conferences and Workshops**

Wuest, T., Knoke, B. & Thoben, K.-D. (2014). Applying graph theory and the product state concept in manufacturing. *Procedia Technology 15*(2014), 349–358. doi: 10.1016/j.protcy.2014.09.089.

Wuest, T., Liu, A., Lu, S. C.-Y. & Thoben, K.-D. (2014). Application of the stage gate model in production supporting quality management. *Procedia CIRP, 17*, 32–37. doi: 10.1016/j.procir.2014.01.071.

Wuest, T., Werthmann, D. & Thoben, K.-D. (2013). *Towards an approach to identify the optimal instant of time for information capturing in supply chains*. Prabhu, V., Taisch, M. & Kiritsis, D. (Eds.): APMS 2013, Part I, IFIP AICT 414, Heidelberg Berlin: Springer, 3–12. doi: 10.1007/978-3-642-41266-0_1.

Knoke, B., Wuest, T. & Thoben, K.-D. (2013). *Understanding Product State Relations within Manufacturing Processes*. In: Emmanouilidis, C., Taisch, M., & Kiritsis, D. (Eds.): APMS 2012, Part I, IFIP AICT 397, Heidelberg Berlin: Springer, 437–444. doi: 10.1007/978-3-642-40352-1_55.

Wuest, T., Irgens, C. & Thoben, K.-D. (2013). *Analysis of Manufacturing Process Sequences, using Machine Learning on Intermediate Product States (as Process Proxy Data)*. In: Emmanouilidis, C., Taisch, M., & Kiritsis, D. (Eds.): APMS 2012, Part II, IFIP AICT 398, Heidelberg Berlin: Springer, 1–8. doi: 10.1007/978-3-642-40361-3_1.

Wuest, T., Thoben, K.-D. (2012). *Information Management for Manufacturing SMEs*. In: Frick, J. & Laugen, B. (Eds.): APMS 2011, IFIP AICT 384, Heidelberg Berlin: Springer, 481–488. doi: 10.1007/978-3-642-33980-6_53.

Irgens, C., Wuest, T. & Thoben, K.-D. (2012). *Product state based view and machine learning: A suitable approach to increase quality?* In: Borangiu, T., Dolgui, A., Dumitrache, I., Pereira, C.E. & Vrba, P. (Eds.) (2012) Information control for smarter manufacturing. Proc. of the 14th IFAC Symposium on Information Control Problems in Manufacturing, 23–25. May, 2012, Bucharest, Romania, 190–195.

Wuest, T. (2011). *Tool to identify relevant product state characteristics for improved information management along distributed production process chains*. In: Frick, J. (Eds.) (2011). Value Networks: Innovation, Technologies and Management. Proceedings of the APMS 2011 International Conference of Advances in Production Management Systems – Doctoral Workshop, 24. September, 2011, Stavanger, Norway, 11–24 (ISBN 978-82-7644-461-2).

Wuest, T., Klein D., Seifert, M. & Thoben, K.-D. (2011). *Challenges for grown engineering SMEs with a diverse product portfolio on information management and product tracking and tracing*. In: Frick, J. (Eds.) (2011). Value Networks: Innovation, Technologies and Management. Proceedings of the APMS 2011 International Conference of Advances in Production Management Systems, 26–28. September 2011, Stavanger, Norway (ISBN 978-82-7644-461-2).

Wuest, T., Sitek, P., Seifert, M. & Thoben, K.-D. (2011). *Organisational and Technical Interdependencies in Collaborative Production*. Proceedings 17th International Conference on Concurrent Engineering, 20–22. June 2011, Aachen, Germany, 343–349.

Wuest, T., Klein, D. & Thoben, K.-D. (2011). State of steel products in industrial production processes. *Procedia Engineering, 10*(2011), 2220–2225.

*To my wife Irene and my parents Antonie and Peter.*

# Supervisor's Foreword

It is my great pleasure to introduce Dr.-Ing. Thorsten Wuest's Ph.D. research, accepted for publication within the prestigious *Springer Theses* series. Dr. Wuest joined my Department of ICT Applications in Production at BIBA—Bremer Institut für Produktion und Logistik GmbH, as a research scientist in 2009. Simultaneously, he pursued his Ph.D. research at the Faculty of Production Engineering at the University of Bremen under my guidance. Besides his Ph.D. work, Dr. Wuest worked on several collaborative research projects, among them the CRC 570 Distortion Engineering and the project InfoSys, both funded by the German Research Foundation (DFG), and was very involved in matters of teaching, service, as well as project and grant acquisitions. Additionally, he is an active member of several professional societies, e.g., being recently accepted as a Research Affiliate of CIRP, and acts as a reviewer for various journals and conferences. Furthermore, Dr. Wuest conducted parts of his research as a research scholar at the Viterbi School of Engineering, University of Southern California, USA, being awarded a full research scholarship of the German Academic Exchange Service (DAAD). He completed his Ph.D. research with an oral defense in November 2014. Dr. Wuest's thesis includes significant original contributions to the field and represents a considerable advancement in the way of handling steadily increasing data streams within multistage manufacturing systems. He successfully published selected parts of his research work in highly ranked, refereed archival journals and prominent, internationally recognized conferences.

The global manufacturing domain faces major challenges which may be summarized by increasing complexity and dynamics of products and processes as well as increasing requirements toward quality. The research problem of Dr. Wuest's thesis is set in multistage manufacturing programs and focuses on the holistic handling of data and information with the goal of improving the product and process quality. Existing solutions focus mostly on individual processes instead of the whole manufacturing system and do not incorporate product and process inter- and intrarelations. It was found that these process inter- and intrarelations have a significant and varying impact on the quality outcome of successive processes and thus on the whole manufacturing program.

In his dissertation, Dr. Wuest developed a concept to describe comprehensively a product by its states along a manufacturing process sequence. For this concept, it is of fundamental importance to identify a set of state characteristics allowing a comprehensive description of the product's state. A major aspect within the work was found to be process intra- and interrelations between states and state characteristics. Today, most manufacturing programs lack sufficient knowledge and transparency with regard to process intra- and interrelations rendering a complete modeling of the system unrealistic. In order to incorporate this crucial element in the analysis, supervised machine learning was employed in the form of SVM-based feature ranking to incorporate successfully implicit process intra- and interrelations of the manufacturing program.

Dr. Wuest evaluated the conducted research using three different scenarios from distinctive manufacturing domains (aviation, chemical, and semiconductor) based on "real world" datasets. The purpose of choosing three different scenarios was to highlight the general applicability of the developed concept. The evaluation confirmed that it is possible to incorporate implicit process intra- and interrelations on process as well as program level as required through applying SVM-based feature ranking.

Dr. Wuest's work addresses highly relevant and complex challenges which have been, and are emerging in modern manufacturing, taking current research streams like smart and advanced manufacturing, cyber-physical-production-systems, Industrial Internet, Industry 4.0 and Big Data approaches, and the resultant increase of data streams into consideration. A major asset of the concept is the possibility to identify currently unknown relations which may provide a basis for further in-depth research and experimentation.

The strength of Dr. Wuest's dissertation is its relevance and simplicity as well as its applicability in actual and realistic manufacturing situations. The selected approach and methodology is such that it is neither a constraint to specific products, manufacturing processes, or systems nor is it constraint to specific quality concepts. In this way it is a notable addition to knowledge. The work and its results are well projected into "real-life" applications and as such provide an important contribution to the application domain of analysis and management of product and process quality in the manufacturing domain.

Bremen, February 2015 Prof. Dr.-Ing. habil. Klaus-Dieter Thoben

# Acknowledgments

Many people have contributed to my success in completing this dissertation. I was fortunate to have been supported by my advisors, colleagues, friends, and family.

First of all, I want to thank Prof. Klaus-Dieter Thoben, my doctoral advisor, for his continuous support over the last years and his genuine interest in my work and development. Without the countless critical discussions and his outstanding mentorship, I would not be who I am today. I cannot thank Prof. Christopher Irgens, my second advisor, enough (even though he will insist that it is not necessary). He not only introduced me to a new research field, but more importantly, showed me that looking "beyond one's own nose" is exciting and stimulating. Together, these two mentors did spark my academic curiosity and encouraged me to develop my own research interest. Furthermore, I want to thank Prof. Dr.-Ing. Hans-Werner Zoch, Dr.-Ing. Jan Ohlendorf, Stefan Wellsandt, and Jakub Mak-Dadanski for their willingness to serve in my thesis committee and their constructive feedback.

I would like to thank Prof. Stephen Lu, my CIRP mentor, who invited me to his Lab at USC. He and his team, especially Dr. Ang Liu, made me feel at home from the beginning and opened my world to many fascinating new impressions. In this regard, I would like to thank the DAAD for the support of my research through the generous doctoral scholarship that allowed me to continue my research in the USA.

I want to thank the many inspiring researchers I met over the years and who always took the time to discuss ideas and provide critical feedback. There are too many to mention them all so instead I would like to highlight the great spirit of research communities and events like APMS, IFIP, and CIRP. Of course, I want to thank my colleagues at BIBA for their continuous support, professionally and privately. They were never too busy for a challenging discussion or a reassuring pep talk. Furthermore, I want to thank the many students, whose projects and Bachelor, Master, and Diploma theses, I had the opportunity to supervise. They all contributed with their work toward the completion of this research. My friends and fellow ruggers, thank you for always being there for me and distracting me from continuously thinking of my research. This allowed the most creative ideas to surface.

Most importantly, I would like to thank my beloved wife Irene. Her support, encouragement, quiet patience, and unwavering love despite the hardships of a long-distance relationship are the foundation this work was built upon. Many thanks also to her parents and brother, Tere, Gabriel, and Javier, who selflessly took me in during my research stay in LA and welcomed me as a son and brother.

Finally, I thank my loving parents, Antonie and Peter, who always encouraged me and taught me not to give up. Since I can remember, I felt safe knowing whatever happens they will always be there for me. Of course, I could always count on my brother Dennis, for needed distraction as well as professional input. Thank you all!

Bremen, February 2015 Thorsten Wuest

# Contents


**1 Introduction** . . . . . 1
1.1 Motivation . . . . . 2
1.2 Problem Statement . . . . . 5
1.3 Research Goal and Research Methodology . . . . . 7
1.4 Structure of the Dissertation . . . . . 8
References . . . . . 11

**2 Developments of Manufacturing Systems with a Focus on Product and Process Quality** . . . . . 15
2.1 Manufacturing Terms, Definitions and Developments . . . . . 15
2.1.1 Manufacturing Processes . . . . . 17
2.1.2 Process Monitoring . . . . . 21
2.1.3 Product in Manufacturing . . . . . 22
2.1.4 Quality in Manufacturing . . . . . 24
2.1.5 Example of a Manufacturing Programme . . . . . 26
2.2 Developments of Manufacturing System . . . . . 27
2.2.1 System View on Manufacturing . . . . . 28
2.2.2 Intelligent Manufacturing Systems . . . . . 29
2.2.3 Holonic Manufacturing Systems . . . . . 31
2.3 Developments in Information and Data Management in Manufacturing . . . . . 32
2.3.1 Information Management (Systems) in Manufacturing . . . . . 35
2.3.2 Data and Information Quality . . . . . 37
2.4 Challenges of MS from a Product and Process Information Perspective . . . . . 40
References . . . . . 42

**3 Current Approaches with a Focus on Holistic Information Management in Manufacturing** . . . . . 51
3.1 Product Lifecycle Management in Manufacturing . . . . . 51
3.1.1 Product Data Management . . . . . 52
3.1.2 Product Lifecycle Management . . . . . 54
3.1.3 Closed-Loop and Item-Level PLM . . . . . 56
3.2 Quality Monitoring in Manufacturing . . . . . 59
3.2.1 Quality Management in the Manufacturing Domain . . . . . 59
3.2.2 Quality Monitoring in Manufacturing Programmes . . . . . 61
3.3 Limitations of Current Approaches for Holistic Information Management in Manufacturing Systems . . . . . 62
References . . . . . 64

**4 Development of the Product State Concept** . . . . . 69
4.1 Rationale for the Product State Concept . . . . . 70
4.2 Product State . . . . . 74
4.3 Relevant State Characteristics . . . . . 79
4.3.1 Product State Characteristics . . . . . 79
4.3.2 Product State Transformation . . . . . 85
4.3.3 Categorization of Product State Transformation . . . . . 88
4.3.4 Relevant State Characteristics . . . . . 92
4.3.5 Identification of Relevant State Characteristics . . . . . 94
4.4 Process Intra- and Inter-relations Among State Characteristics . . . . . 97
4.4.1 Describing Process Intra- and Inter-relations of State Characteristics . . . . . 98
4.4.2 Visualization of Relations . . . . . 101
4.4.3 Limitations of Describing Process Intra- and Inter-relations . . . . . 109
4.5 Requirements of State Driver Identification . . . . . 112
4.5.1 NP Complete Nature of Product State Concept . . . . . 113
4.5.2 Suitability of Machine Learning Methods . . . . . 114
4.6 Derived Research Hypothesis of the Application of ML Within the Product State Concept . . . . . 117
References . . . . . 119

**5 Application of Machine Learning to Identify State Drivers** . . . . . 125
5.1 Machine Learning in Manufacturing . . . . . 125
5.1.1 Machine Learning . . . . . 126
5.1.2 Supervised Machine Learning . . . . . 127
5.2 Selection of Suitable Machine Learning Technique . . . . . 129
5.2.1 Support Vector Machines (SVM) . . . . . 131
5.2.2 Rationale of SVM Application for Identification of State Drivers in Manufacturing Systems . . . . . 138
5.3 Application of SVM for Identification of State Drivers . . . . . 142
References . . . . . 149

**6 Application of SVM to Identify Relevant State Drivers** . . . . . 153
6.1 Introducing Scenarios I, II and III . . . . . 153
6.2 Scenario I—Rolls-Royce . . . . . 155
6.2.1 SVM Kernel and Parameters for Hyperplane by X-Validation . . . . . 155
6.2.2 Feature Ranking Using SVM Classifier . . . . . 157
6.2.3 Classification on Previously Unknown Data . . . . . 161
6.3 Scenario II—Chemical Manufacturing Process . . . . . 162
6.3.1 SVM Kernel and Parameters for Hyperplane by X-Validation . . . . . 163
6.3.2 Classification on Previously Unknown Data . . . . . 167
6.3.3 Compilation of SVM Operation and Output Data . . . . . 169
6.3.4 Feature Ranking Using SVM Classifier . . . . . 171
6.4 Scenario III—SECOM . . . . . 177
6.4.1 SVM Kernel and Parameters for Hyperplane by X-Validation . . . . . 177
References . . . . . 187

**7 Evaluation of the Developed Approach** . . . . . 189
7.1 Evaluation Results . . . . . 189
7.1.1 Data Pre-processing . . . . . 189
7.1.2 Cross-validation Performance of SVM Classifier . . . . . 191
7.1.3 Unbalanced Data . . . . . 193
7.1.4 Feature Selection and Feature Ranking . . . . . 193
7.1.5 Classification Performance on Previously Unknown Data . . . . . 198
7.2 Discussion of Evaluation Results . . . . . 200
7.3 Limitations . . . . . 205
References . . . . . 210

**8 Recapitulation** . . . . . 211
8.1 Conclusion . . . . . 211
8.2 Outlook and Future Work . . . . . 212
References . . . . . 214

**Annex** . . . . . 215

**Appreciation of Student Contribution** . . . . . 265

**About the Author** . . . . . 271

# Abbreviations

| | |
|---|---|
| AI | Artificial Intelligence |
| ANN | Artificial Neural Networks |
| APS | Advanced Planning Systems |
| BN | Bayesian Networks |
| BOL | Beginning of Life |
| C | Soft margin parameter of SVM |
| CAD | Computer-aided Design |
| CAE | Computer-aided Engineering |
| CAPP | Computer-aided Process Planning |
| CAQ | Computer-aided Quality |
| CBR | Case-based Reasoning |
| CHEM | Chemical Manufacturing |
| CIM | Computer Integrated Manufacturing |
| CSV | Comma-Separated Values |
| DM | Data Mining |
| DT | Decision Trees |
| EC | European Commission |
| EOL | End of Life |
| ERP | Enterprise Resource Planning |
| FDC | Fault Detection and Classification |
| FMEA | Failure Mode and Effects Analysis |
| FPR | False Positive Rate |
| FS | Feature Selection |
| GA | Genetic Algorithm |
| HMS | Holonic Manufacturing System |
| IBL | Instance-Based Learning |
| IM | Information Management |
| IMS | Intelligent Manufacturing System |
| KD | Knowledge Discovery |
| KDD | Knowledge Discovery from Databases |
| KM | Knowledge Management |

| | |
|---|---|
| KSF | Key Success Factor |
| MAR | Missing at Random |
| MBR | Memory-Based Reasoning |
| MCAR | Missing Completely At Random |
| MES | Manufacturing Execution System |
| MI | Multiple Imputation |
| ML | Machine Learning |
| MLH | Maximum Likelihood |
| MNAR | Missing Not At Random |
| MOL | Middle of Life |
| MRP | Manufacturing Resource Planning |
| MS | Manufacturing System |
| NaN | Not a Number |
| NB | Naïve Bayesian Networks |
| NN | Neural Networks |
| NP | Nondeterministic Polynomial (time) |
| PCA | Principal Component Analysis |
| PDM | Product Data Management |
| PEID | Product Embedded Information Device |
| PLM | Product Lifecycle Management |
| PLS | Partial Least Squares |
| PR | Pattern Recognition |
| QM | Quality Management |
| RFE | Recursive Feature Elimination |
| RFID | Radio Frequency Identification |
| RL | Reinforcement Learning |
| RR | Rolls-Royce |
| SCM | Supply Chain Management |
| SECOM | Semiconductor Manufacturing |
| SLT | Statistical Learning Theory |
| SME | Small- and Medium-sized Enterprise |
| SMOTE | Synthetic Minority Oversampling TEchnique |
| SQC | Statistical Quality Control |
| STEP | Standard for the Exchange of Product model data |
| SVM | Support Vector Machine |
| TPR | True Positive Rate |
| TQC | Total Quality Control |
| TQM | Total Quality Management |
| UPnP | Universal Plug and Play |