

Forschungsberichte aus dem
wbk Institut für Produktionstechnik
Karlsruher Institut für Technologie (KIT)

Shun Yang

**Regionalized implementation
strategy of smart automation within
assembly systems in China**

Band 249



Forschungsberichte aus dem
wbk Institut für Produktionstechnik
Karlsruher Institut für Technologie (KIT)

Hrsg.: Prof. Dr.-Ing. Jürgen Fleischer
Prof. Dr.-Ing. Gisela Lanza
Prof. Dr.-Ing. habil. Volker Schulze

Shun Yang

**Regionalized implementation strategy of smart
automation within assembly systems in China**

Band 249

Regionalized implementation strategy of smart automation within assembly systems in China

Zur Erlangung des akademischen Grades eines
Doktors der Ingenieurwissenschaften (Dr.-Ing.)
von der KIT-Fakultät für Maschinenbau des
Karlsruher Instituts für Technologie (KIT)

angenommene

Dissertation

von

M.Sc. Shun Yang

Tag der mündlichen Prüfung: 14.04.2021
Hauptreferent: Prof. Dr.-Ing. Gisela Lanza
Korreferent: Prof. Dr.-Ing. Franz Dietrich

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the internet at <http://dnb.d-nb.de>.

Zugl.: Karlsruhe, Karlsruher Institut für Technologie, Diss., 2021

Copyright Shaker Verlag 2021

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-8330-9

ISSN 0724-4967

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren

Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9

Internet: www.shaker.de • e-mail: info@shaker.de

Vorwort des Herausgebers

Die schnelle und effiziente Umsetzung innovativer Technologien wird vor dem Hintergrund der Globalisierung der Wirtschaft der entscheidende Wirtschaftsfaktor für produzierende Unternehmen. Universitäten können als "Wertschöpfungspartner" einen wesentlichen Beitrag zur Wettbewerbsfähigkeit der Industrie leisten, indem sie wissenschaftliche Grundlagen sowie neue Methoden und Technologien erarbeiten und aktiv den Umsetzungsprozess in die praktische Anwendung unterstützen.

Vor diesem Hintergrund soll im Rahmen dieser Schriftenreihe über aktuelle Forschungsergebnisse des Instituts für Produktionstechnik (wbk) am Karlsruher Institut für Technologie (KIT) berichtet werden. Unsere Forschungsarbeiten beschäftigen sich sowohl mit der Leistungssteigerung von Fertigungsverfahren und zugehörigen Werkzeugmaschinen- und Handhabungstechnologien als auch mit der ganzheitlichen Betrachtung und Optimierung des gesamten Produktionssystems. Hierbei werden jeweils technologische wie auch organisatorische Aspekte betrachtet.

Prof. Dr.-Ing. Jürgen Fleischer

Prof. Dr.-Ing. Gisela Lanza

Prof. Dr.-Ing. habil. Volker Schulze

Vorwort des Verfassers

This dissertation is the result of my work as a research associate at the wbk Institute of Production Science of the Karlsruhe Institute of Technology (KIT). I would like to thank the entire board of management for its professional and personal support.

I am immensely grateful to my doctoral advisor Prof. Dr.-Ing. Gisela Lanza for her time, valuable input, and strong support. Her confidence and trust in me to work independently in research and industry projects has shaped my professional development and made this work possible. Particularly I appreciate for her great guidance to let me conduct the Sino-German cooperation projects, which helps me to form the unique global characteristics. Furthermore, I thank Prof. Dr.-Ing. Franz Dietrich for his interest in my work and for agreeing to be a co-supervisor. Likewise, I extend my thanks to Prof. Dr. Dr.-Ing. Dr. h. c. Jivka Ovtcharova for chairing the examination committee.

Additionally, I thank everyone at the wbk Institute of Production Science and in particular my colleagues in the group Production Systems for their friendly communication, cooperation and collaboration at work and outside of the institute. I especially thank Benjamin Häfner, Tobias Arndt, Christoph Liebrecht and Bastian Verhaelen for the technical discussions and the constructive comments on my work.

I would also like to thank everyone at the Global Advanced Manufacturing Institute and KIT China Branch. The memorable times is one of the wonderful periods in my life. I would like thank the colleagues from Beijing Plant for supporting validation of my research.

Very special thanks go to my family, who made this path possible for me and to my parents whose encouragement help me complete this work. My biggest thanks go to my wife, Siyin Pei, whose understanding, support, suggestion and faith in me were instrumental to the success of my dissertation. Last but not least, my special thanks to my daughter, Shuya Yang, whose smiling motivated me to keep moving.

Karlsruhe, 10.02.2021

Shun Yang

Kurzfassung

Produzierende Unternehmen in aufstrebenden Nationen wie China, sind bestrebt, die Produktivität der Produktion durch eine Verbesserung der Lean Produktion mit disruptiven Technologien zu erreichen. Smart Automation ist dabei eine vielversprechende Lösung, allerdings können Unternehmen aufgrund von mangelnden Ressourcen oft nicht alle Smart Automation Technologien gleichzeitig implementieren. Ebenso beeinflusst eine Vielzahl an Einflussfaktoren, wie z.B. Standortfaktoren. Dementsprechend herausfordernd ist die Auswahl und Priorisierung von Smart Automation Technologien in Form von Einführungsstrategien für produzierende Unternehmen.

Der Stand der Forschung untersucht nur unzureichend die Analyse der Interdependenzen zwischen Standortfaktoren, Smart Automation Technologien und Key Performance Indikatoren (KPIs). Darüber hinaus mangelt es an einer Methode zur Ableitung der Einführungsstrategie von Smart Automation Technologien unter Berücksichtigung dieser Interdependenzen.

Entsprechend trägt diese Arbeit dazu bei, eine regionalisierte Einführungsstrategie von Smart Automation Technologien in Montagesystemen zu ermöglichen. Zunächst werden die Standortfaktoren, Smart Automation Technologien und KPIs identifiziert. In einem zweiten Schritt werden, mit Hilfe von qualitativen und quantitativen Analysen, die Interdependenzen bestimmt. Anschließend werden diese Interdependenzen auf ein Montagesystem mittels hybrider Modellierung und Simulation übertragen. Im vierten Schritt wird eine regionalisierte Einführungsstrategie durch eine Optimierung und eine Monte-Carlo-Simulation abgeleitet. Die Methodik wurde im Rahmen des deutsch-chinesischen Forschungsprojekts I4TP entwickelt, das vom Bundesministerium für Bildung und Forschung (BMBF) unterstützt wird. Die Validierung wurde erfolgreich mit einem produzierenden Unternehmen in Beijing durchgeführt.

Die entwickelte Methodik stellt einen neuartigen Ansatz zur Entscheidungsunterstützung bei der Entwicklung einer regionalisierten Einführungsstrategie für Smart Automation Technologien in Montagesystemen dar. Dadurch sind produzierende Unternehmen in der Lage, individuelle Einführungsstrategien für disruptive Technologien auf Basis wissenschaftlicher und rationaler Analysen effektiv abzuleiten.

Contents

Contents	I
List of Abbreviations and Symbols	IV
1 Introduction	1
1.1 Background and Motivation	1
1.2 Scope of the Research	3
1.3 Objective of the Research	6
1.4 Structure of this Work	7
2 Basics	9
2.1 Assembly Systems	9
2.2 Key Performance Indicators	11
2.3 Advanced Manufacturing Concepts	12
2.3.1 Lean Production	12
2.3.2 Industry 4.0	14
2.3.3 Cyber-Physical Systems	14
2.3.4 Cyber-Physical Production Systems	15
2.3.5 Smart Automation	16
2.4 Location and Process Factors	20
2.4.1 Location Factors	20
2.4.2 Process Factors	21
2.4.3 Location Criteria	22
2.5 Implementation Strategy	23
2.6 Simulation	24
2.6.1 Hybrid Modeling and Simulation	26
2.6.2 Modular Simulation	29
2.6.3 Metamodeling	29
2.6.4 Randomness in Simulations	30
2.7 Uncertainty and Robustness	31

3	State of the Art	33
3.1	Requirements of the Methodology	33
3.2	Approaches for the Assessment of Lean Methods	34
3.3	Approaches for the Analysis of Smart Automation	35
3.3.1	Industry 4.0 Readiness Model	35
3.3.2	Interdependency Research	37
3.3.3	Implementation Strategy	38
3.4	Approaches for Role of Location Factors on Production	38
3.5	Approaches for Evaluation of Operations of Production System	41
3.6	Research Deficit	43
4	Methodology	45
4.1	Overview of Approach	45
4.2	Identification of Regionalized Catalogs of Influence Factors	46
4.2.1	Identification of the Catalog of Location Factors	47
4.2.2	Identification of the Catalog of Smart Automation Technologies	53
4.2.3	Identification of the Catalog of Key Performance Indicators	62
4.3	Interdependency Analysis	67
4.3.1	Typology of Assembly System Profile	67
4.3.2	Interdependency of Location Factors and Smart Automation	70
4.3.3	Interdependency of different smart automation technologies	77
4.3.4	Interdependency between Smart Automation and KPIs	82
4.3.5	Determination of the Interdependency of Location Factors and KPIs	87
4.3.6	Net of Bilateral Interdependencies	88
4.4	Modeling and Simulation	89
4.4.1	Preparation of Model	89
4.4.2	Modeling of Interdependencies of the Technologies with System Dynamics	92
4.4.3	Modeling of Assembly Systems with Discrete Event Simulation	96
4.4.4	Hybrid Modeling with Process Data	101
4.4.5	Experiment Design of Simulation	103

4.5	Derivation of Implementation Strategy	105
4.5.1	Description of Company Specific Assembly System in Simulation	105
4.5.2	Optimization of Implementation Strategy of Smart Automation	106
4.5.3	Evaluation of Implementation Strategy	108
5	Validation	110
5.1	Validation Setup and Procedure	110
5.2	Pilot Application with an International Manufacturing Business in China	111
5.2.1	Review of the Regionalized Catalogs	115
5.2.2	Adaption of Interdependencies	116
5.2.3	Adjustments to the Model	123
5.2.4	Derivation of Implementation Strategy for the Beijing Plant	140
6	Evaluation and Outlook	148
6.1	Evaluation	148
6.2	Outlook	149
7	Summary	151
8	Bibliography	153
	List of Figures	I
	List of Tables	VI
	Appendix	VIII
A1	Theory of reliability and validity of survey	VIII
A2	The questionnaire and results of location factors	IX
A3	Description of the generated application fields of CPPS	XX
A4	Description of smart automation	XXIII
A5	Investigation of KPIs	XXVIII
A6	Ranking of KPIs by importance	XXX
A7	Interdependency among different smart automation technologies	XXXI
A8	Result of Experiments in Testbed	XXXIII
A9	Optimization Result of Implementation Sequence	XXXV

List of Abbreviations and Symbols

Abbreviations	Description
ABS	Agent Based Simulation
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AM	Agile Manufacturing
AMSS	Advanced Manufacturing Systems
AMT	Advanced Manufacturing Technology
AR	Augmented Reality
AS	Available System
AS40	Assembly System 4.0
ATA	Automatic Torque Adjustment
BT	Break Time
CAFS	Chinese Academy of Fiscal Sciences
CIM	Computer-Integrated Manufacturing
CMfg	Cloud Manufacturing
Conc. eng.	Concurrent Engineering
CPS	Cyber-Physical Systems
CPPS	Cyber-Physical Production Systems
CS	Computer Science
Csourcing	Crowd-sourcing
C/O	Changeover Time
C/T	Cycle Time
DES	Discrete Event Simulation
DSFM	Digital Shopfloor Management
EE	Extended Enterprises
EPEI	Every Part Every Interval
ERP	Enterprise Resource Planning

ES	Effectiveness System
FMS	Flexible Manufacturing System
FPY	First Pass Yield
GAMI	Global Advanced Manufacturing Institute
GDP	Gross Domestic Product
GQC	Good Quantity Counted
HMI	Human Machine Interaction
HMS	Holonic Manufacturing System
I4.0	Industry 4.0
ICT	Information and Communication Technologies
IMF	International Monetary Fund
INS	Intelligent Screwdriver
IoT	Internet of Things
JIT	Just in Time
KPIs	Key Performance Indicators
LP	Lean Production
LM	Lean Management
LoFa	Location Factors
MAS	Multi-agent System
MES	Manufacturing Execution System
ML	Machine Learning
MS	Manufacturing Systems
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
MWIP	Mean Work In Process
NE	Number Of Employees
NM	Networked Manufacturing

NOWIP	Number Observations of Work In Process
ODT	Other Down Time
OEE	Overall Equipment Effectiveness
OLE	Overall Labor Effectiveness
PBL	Pick By Light
PBT	Planned Busy Time
PDT	Planned Down Time
PLM	Product Lifecycle Management
PMT	Preventive Maintenance Time
PN	Production Networks
POT	Planned Operation Time
PQ	Produced Quantity
PROD	Productivity
PSS	Product Service System
QCD	Quality, Cost And Delivery
QR	Quality Rate
QR Code	Quick Response Code
QRCS	Quality Ratio Counted System
RFID	Radio Frequency Identification
ROI	Return On Investment
SCM	Supply Chain Management
SCQ	Scrap Quantity
SD	System Dynamics
SG	Smart Gloves
SmAu	Smart Automation
SPSS	Statistical Package For The Social Science
TOAA	Time For Other Administrative Actions
TPS	Toyota Production Systems

VDI	Association Of German Engineers
VDMA	Association Of German Mechanical Engineering Industry
VR	Virtual Reality
VSM	Value Stream Mapping
VUCA	Volatility, Uncertainty, Complexity And Ambiguity
V&V	Verification & Validation
WCR	Workplace Carrier With RFID Tags
WIP	Work In Process
WN	Wireless Nutrunner
ZVEI	German Electrical And Electronic Manufacturers' Association

Symbols	Description	Unit
$a_{i,j}(n)$	Individual metrics between location factors and Smart Automation technologies, where i represents for row number, j for column number and n for each expert	-
A_i	Output state	-
$A_{i,j}$	Arithmetic average of corresponding values from expert interviews for location factors	-
AVA	KPI indicator – availability	-
$b_{i,j}(n)$	Individual metrics among different smart automation technologies, where i represents for row number, j for column number and n for each expert	-
$B_{i,j}$	Arithmetic average of corresponding values from expert interviews for Smart Automation	-
c_i	Value of key figure	-
c_i^{min}	Minimum value of key figure	-
c_i^{max}	Maximum value of key figure	-
Cof_n^{n-1}	mutual incentive coefficients between $Tech_n$ and $Tech_{n-1}$	-
$Const_{invest}$	Constraint value of investment cost	-
$Const_{days}$	Constraint value of implementation days	-
$Cost$	KPI indicator – cost	-
$Days_T$	Total implementation days of technologies	-
DEL	KPI indicator – delivery	-
Δu	Varying conditions	-
D_n	Implementation days of individual technology	-
γ_i	Normalization of key figure	-
i	Multi-purpose index used in several contexts, if just a single index is required	-
$invest_n$	Investment cost of individual technology	-
$Invest_T$	Total investment of technologies	-
j	Multi-purpose index used in several contexts, if just a single index is required	-
k	Total amount of technology available	-
$L(x, u)$	Stable target function value	-

n_{NE}	Number of employees	-
n_{GQC}	Number of produced good parts by first run	-
n_{SCQ}	Number of defect parts	-
n_{WIP}	Number of Work in Process	-
ω_i	Weight of KPIs	-
QUA	KPI indicator – quality	-
S_{Ai}	Score of corresponding aspect	-
S_i	Final score of each item	-
S_{ji}	Score gained of each item in its aspect	-
t_{AWUBT}	Actual work unit busy time	TU
t_{CT}	Cycle time	TU
t_{CToB}	Cycle time of bottleneck	TU
$Tech_i$	Technology i	-
t_i	Number of days already spent for the technology i	-
T_i	Total days the technology needs to be entirely implemented	-
t_{LDT}	Logistic delay time	TU
t_{ODT}	Other down time	TU
t_{PBT}	Planned busy time	TU
u	Influencing factors	-
v_{DF}	Defect rate	%
v_{FPY}	Value of First Pass Yield	%
v_{PROD}	Value of productivity	-
v_{UT}	Machine availability	%
x	Possible solution	-
y	Implementation effect level	-
$Z_{i,j}$	Number of individual metrics	-