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Anna Carina Römer

Simulation-based Optimization of Energy Efficiency in Production

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Anna Carina Römer

Simulation-based Optimization of Energy Efficiency in Production



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Preface

This book was written in the context of my work as an external PhD student at the Department Information Technology for Production and Logistics at the Technical University of Ilmenau.

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and patience, especially during the last very intensive months when finalizing this work.

January 2020

Anna Carina Römer

Zusammenfassung

Die vorliegende Arbeit beschäftigt sich mit der Integration von Energieaspekten in die Produktionssimulation. Ziel der Arbeit ist es, die Energieverbräuche von Produktionsanlagen realitätsnah in einem Simulationsmodell abzubilden, um diese anschließend für die simulationsbasierte Optimierung der Energieeffizienz nutzen zu können und damit eine umfassende Prozessqualität im Hinblick auf den optimalen Ressourceneinsatz des Faktors Energie im Produktionsprozess sicherzustellen.

Hierzu wird zunächst ein hybrider Simulationsansatz entwickelt, der verschiedene Simulationsparadigmen in einem Modell kombiniert. Die Hybridisierung von Simulationsmodellen bietet dem Modellersteller eine große Flexibilität bei der Erfassung von Problemen, die sich gleichzeitig auf diskrete (Materialfluss) und kontinuierliche (Energiefluss) Strukturen beziehen. In einem zweiten Schritt wird das Simulationsmodell für Optimierungsexperimente genutzt. Die Grundidee hinter diesem Ansatz ist es, durch mehrere Iterationen, die verschiedene Systemkonfigurationen simulieren, eine optimale Lösung für die zu variierenden Optimierungsparameter zu finden. Die Simulation wird durch die Optimierung gestartet, liefert die Ergebnisdaten und bildet die Grundlage für eine Beurteilung des dynamischen Verhaltens des abgebildeten Produktionssystems. Auf diese Weise lassen sich optimale Parameterkonfigurationen im Hinblick auf die gestellte Zielfunktion unter Nutzung des Simulationsmodells ermitteln.

Die in dieser Arbeit entwickelte Methodik gliedert sich damit in zwei Module, ein Simulations- und ein Optimierungsmodul. Das Simulationsmodul ist in drei Komponenten unterteilt, eine Materialfluss-, eine Maschinen- und eine Energiekomponente. Damit lassen sich die Produktionsprozesse auf allen notwendigen Ebenen in einem Modell abbilden. In Anlehnung an das in der Industrie übliche Vorgehen bei der Erstellung eines Produktionssimulationsmodells wird eine

Materialflusskomponente definiert, in der die Prozesse der Produktion diskret und prozessorientiert dargestellt werden. Das Materialfluss-Modell umfasst alle elektrischen Verbraucher, die unmittelbar an den Produktionsprozessen beteiligt sind. Um die Abläufe der Arbeitsschritte der einzelnen Maschinen exakt abzubilden, wird eine agentenbasierte Maschinenlogik definiert, die unter Nutzung von Zustandsdiagrammen die Prozesse darstellen kann. Dadurch lassen sich Maschinenzustände, Zustandsänderungen sowie Zustandsdauern unterschiedlich komplexer Maschinentypen realitätsnah modellieren. Die Verbindung zum Energieverhaltensverhalten wird über die Energiekomponente des Simulationsmoduls hergestellt. Die Energiekomponente beinhaltet die Modellierung kontinuierlicher Energielastprofile, die den einzelnen Maschinenzuständen zugeordnet werden und bei den Simulationsläufen entsprechend des Maschinenschaltverhaltens zur Ermittlung des Gesamtenergieverbrauchs der Produktionsprozesse genutzt werden.

Um die energetischen Aspekte in der Produktion nicht nur zu modellieren, sondern auch für Optimierungsszenarien zu nutzen, werden lexikographisch geordnete Zielfunktionen abgeleitet, die im Rahmen von simulationsbasierten Optimierungsexperimenten ideale Parameterkonfigurationen für den energieeffizienten Betrieb der Produktionslinien ermitteln. Der Schwerpunkt der Optimierung liegt dabei auf der Reduzierung des Gesamtenergieverbrauchs durch die Vermeidung nicht-wertschöpfender Maschinenzustände. In diesen Phasen verbrauchen die Produktionsanlagen unnötig Energie, werden aber nicht aktiv zur Wertschöpfung eingesetzt. Die Gesamtverbrauchsoptimierung zeigt auf, dass Unternehmen dieser Ressourcenverschwendung durch ein effizientes Schalten der Anlagen entgegenwirken können, ohne große finanzielle Investitionen in neue Technologien tätigen zu müssen. Neben der Optimierung des Gesamtenergiebedarfs beinhaltet die Methodik die Möglichkeit, im Rahmen einer Lastspitzen-Optimierung die Maschinenstarts innerhalb eines definierten Zeitraumes so zu verändern, dass auftretende Spitzenlasten reduziert werden.

Die entwickelte Methodik wird zunächst in einer fiktiven Fallstudie implementiert und verfeinert, bevor sie am Beispiel eines Automobilzulieferers in der industriellen Praxis Anwendung findet. Im Rahmen dieser Praxisversuche werden verschieden hoch aufgelöste Energiedaten getestet. Die praktische Anwendung der Methodik zeigt, dass es möglich ist, ein hybrides Simulationsmodell zur Darstellung des Energieverhaltens in der Produktion auf Basis historischer Verbrauchsdaten aufzubauen und in Kombination mit Prognosezahlen auch die zukünftigen Energieverbräuche mit den anstehenden Spitzenlasten und nicht wertschöpfenden Produktionsphasen sehr genau abzubilden. Aus den durchgeführten

Optimierungsversuchen ergeben sich damit Handlungsvorschläge zur energieeffizienten Steuerung von Maschinen, die in Produktionssituationen ähnlich des fiktiven Beispiels zu Energieverbrauchsreduzierungen von 10 % und in stark verketteten Produktionslinien zu Einsparungen von etwa 6 % führen.

Summary

This book presents a methodology for the integration of energy aspects into production simulation. The aim of this work is to realistically represent the energy consumption of production plants in a simulation model in order to be able to use it for the simulation-based optimization of energy efficiency and thus to ensure a comprehensive process quality with regard to the optimal use of the factor energy in the production process.

For this purpose, a hybrid simulation approach is developed, which combines different simulation paradigms in one single model. The hybridization of simulation models offers the model creator great flexibility in the detection of problems that are simultaneously related to discrete (material flow) and continuous (energy flow) structures. In a second step, the simulation model is used for optimization experiments. The basic idea behind this approach is to find an optimal solution for the optimization parameters being varied through several iterations to simulate different system configurations. The simulation is started by the optimization, delivers the result data and forms the basis for an evaluation of the dynamic behavior of the mapped production system. In this way, optimal parameter configurations can be determined with regard to the set target function using the simulation model.

The methodology developed in this work is thus divided into two modules, a simulation and an optimization module. The simulation module is divided into three components, a material flow, a machine and an energy component. This allows the production processes to be depicted on all necessary levels in one simulation model. Following the standard procedure in industry for the creation of a production simulation model, a material flow component is defined in which the production processes are represented discretely and process-oriented. The material flow model includes all electrical consumers that are directly involved in the

production processes. To map the work steps of the individual machines as accurate as possible, an agent-based machine logic is defined, which can represent the processes using status diagrams. This allows a realistic modeling of machine states, state changes and state durations of machine types of varying complexity. The connection to energy consumption behavior is made via the energy component of the simulation module. The energy component includes the modeling of continuous energy load profiles, which are assigned to the individual machine states and are used in the simulation runs according to the machine switching behavior to determine the total energy consumption of the production processes.

In order not only to model the energy aspects in production but also to use them for optimization scenarios, lexicographically ordered objective functions are derived, which determine ideal parameter configurations for the energy-efficient operation of the production lines in simulation-based optimization experiments. The focus of the optimization is on the reduction of the total energy consumption by avoiding non-value-adding machine states. In these phases, the production lines consume energy unnecessarily, but are not actively used to create value. The overall consumption optimization shows that companies can counteract this waste of resources by efficiently switching the machines without having to make large financial investments in new technologies. In addition to the optimization of the total energy demand, the methodology includes the possibility to change the machine starts within a defined period of time in order to reduce peak loads.

The developed methodology is first implemented and refined in a fictitious case study before it is applied to the example of an automotive supplier in industrial practice. Within the scope of these practical tests, energy data with different resolutions is tested. The practical application of the methodology shows that it is possible to build a hybrid simulation model for the representation of energy consumption behavior in production on the basis of historical consumption data and, in combination with forecast figures, to very accurately represent future energy consumption with upcoming peak loads and non-value-adding production phases. The conducted optimization experiments thus result in proposals for action for the energy-efficient control of machines, which in production situations similar to the fictitious example lead to energy consumption reductions of 10% and in strongly interlinked production lines to savings of about 6%.

Abbreviations

ABS	Agent-based Simulation
ATSA	Adaptive Thermo-Statistical Simulated Annealing
BCVTB	Building Controls Virtual Test Bed
CNC	Computerized Numerical Control
CSS	Continuous System Simulation
DES	Discrete Event Simulation
DESS	Differential Equation Specified Systems
DEVS	Discrete Event Specified Systems
DS	Dynamic Systems
DTSS	Discrete Time Specified Systems
EIE	Energy-Intensive Enterprises
EnPI	Energy Performance Indicator
ERP	Enterprise Resource Planning
GA	Genetic Algorithm
GEA	Global Energy Assessment
GHG	Greenhouse Gas
HSM	Hybrid Systems Modeling
IP	Interaction Points
IS	Information Systems
IT	Information Technology
FSM	Finite State Machine
KPI	Key Performance Indicator
LP	Linear Programming
LPC	Load Profile Clustering
MES	Manufacturing Execution System
MILP	Mixed Integer Linear Programming Model

MS	Management Science
M&S	Modeling and Simulation
MTTF	Meantime to Failure
MTTR	Meantime to Repair
NLP	Nonlinear Programming
ODE	Ordinary Differential Equation
OEE	Overall Equipment Effectiveness
OM	Operations Management
OR	Operations Research
OTC	Over the Counter
PDE	Partial Differential Equation
PLC	Programmable Logic Controller
PSO	Particle Swarm Optimization
QP	Quadratic Programming
RNN	Recurrent Neural Network
ROI	Return of Investment
SA	Simulated Annealing
SCM	Supply Chain Management
SD	System Dynamics

Symbols

Symbol	Unit	Description
E	Joule, kWh	energy
E_{state}	kWh	energy required to reach an operating state (standby, idle, run time, operating)
ξ		randomness of a system
f		objective function
F	N, kg*m/s ²	force
g	m/s ²	gravity
h	m	height
I	A	electric current
k	kJ/cm ³	machine specific constant
m	kg	mass
$m_{i_{op}}$	kW	energy consumption of machine operation (standby, idle, warmup, ...) of machine i
n		production volume
η_i		degree of efficiency
η_{system}		overall efficiency of a system
Θ		feasible region or constraint set
P	kW	power
ρ	bar	pressure
ρ_{am}	bar	ambient state pressure
\mathbb{R}^n		geometrical space of decision variables
s	mm	distance

Symbol	Unit	Description
t	sec	time
t_{warmup}	sec	warmup time
T	°C, K	temperature
T_{am}	°C	ambient state temperature
U	V	voltage
v	m/s, ms ⁻¹	speed
\dot{v}	cm ³ /sec	material processing rate
W	J, Ws	work
x		decision variable
X		design space of an optimization problem

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