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A REVIEW OF LITERATURE ON SIMULATION-BASED OPTIMIZATION OF THE ENERGY EFFICIENCY IN PRODUCTION

Anna Carina Roemer
Steffen Strassburger

Department for Industrial Information Systems
Ilmenau University of Technology
P.O. Box 100 565
98684 Ilmenau, GERMANY

ABSTRACT

Due to rising resource prices, the sustained use of energy has become a basic requirement for manufacturing companies to competitively perform on the market. Designing production processes therefore not only requires the consideration of logistical and technical production conditions but also the consistent optimization of resource consumption. As simulation technology has become a common tool for assessing dynamic production processes, the consideration of energy-related issues in this context is becoming a more frequent subject. The aim of this literature research is to summarize the current state-of-the-art in the field of energy management in production and its adjacent disciplines as well as to identify future research priorities for the simulation-based optimization of energy aspects. The accomplishment of this objective requires a methodological review focusing on the multidisciplinary combination of simulation technologies, including hybrid simulation, the integration of mathematical optimization approaches, and the domain-specific knowledge of energy-related subjects in production systems.

1 INTRODUCTION

The energy prices in Europe have been constantly rising within the last 20 years. In Germany, the electricity prices for industrial customers increased by nearly 80% from 2000 to 2015. Especially in the energy intensive industries, electricity has therefore become a major cost factor. Our research focuses on developing an application oriented and simulation-based procedure in order to allow for an optimum use of energy resources in manufacturing companies. For this purpose we intend to integrate energy variables into the decision-making system of production planning and control, in order to be able to affect the energy use of a production depending on the specific state of operation. The accomplishment of this aim requires the consideration of dynamically simulated energy flows in production simulations as well as sufficiently accurate procedures to predict process behaviors. By combining suitable modeling and simulation approaches with known optimization methods, the evaluation of the optimum use of energy would become possible without causing any restrictions regarding the flexibility of production, the process quality nor major changes in production output. Towards this research objective the literature review in this paper investigates different areas relevant for the simulation-based optimization of energy efficiency in manufacturing companies.

The paper is structured as follows. Section 2 outlines the concepts and techniques of simulation-based optimization of the energy efficiency as well as its adjacent disciplines. Section 3 describes the paper selection process as well as the grouping, the analysis, and the evaluation of the research approaches. Subsequently, section 4 discusses the findings and presents our results. Section 5 concludes with specific

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recommendations on future research in the context of simulation-based optimization approaches for the integration of energy efficiency goals in production.

2 SUBJECT AREAS OF THE LITERATURE REVIEW

The simulation-based optimization of energy efficiency combines concepts from Operations Management (OM), such as the integration of energy efficiency goals in production, Operations Research (OR), e.g. the use of integrated optimization algorithms as well as Modeling&Simulation (M&S), describing all techniques for model implementation and execution. By using a Venn diagram, Figure 1 illustrates the convergence of the involved disciplines. Being embodied in the areas of OM, the integration of energy efficiency goals in the normative, strategic, and operative production management is mandatory for following a holistic and sustainable consistent approach regarding material and energy use throughout all phases of a production (Dyckhoff and Souren 2008). While the problem formulation phase of including energy aspects in simulation approaches can be seen in the discipline of OM, the remaining steps of guiding a model builder through a simulation study are based in the discipline of M&S. The success of implementing and executing a simulation model directly depends on how extensively the steps of model conceptualization, data collection, model translation, experimental design, the production runs and analysis, and furthermore the reporting and documentation have been accomplished (Banks 2010, Wainer 2009). M&S techniques such as the discrete event simulation (DES), continuous system simulation (CSS), other specific classes to simulate dynamic system behavior (discrete time specified systems (DTSS), differential equation specified systems (DESS), discrete event specified systems (DEVS)) or a combination of different theories leading to a hybrid simulation approach are typically used (Zeigler, Praehofer, and Kim 2010). Located in the discipline of OR, optimization algorithms are required to come to appropriate business decisions as the complexity of production processes steadily increases. The use of optimization techniques aims at finding mathematical approaches that identify the optimum parameters for a predetermined analytical objective with constraints.

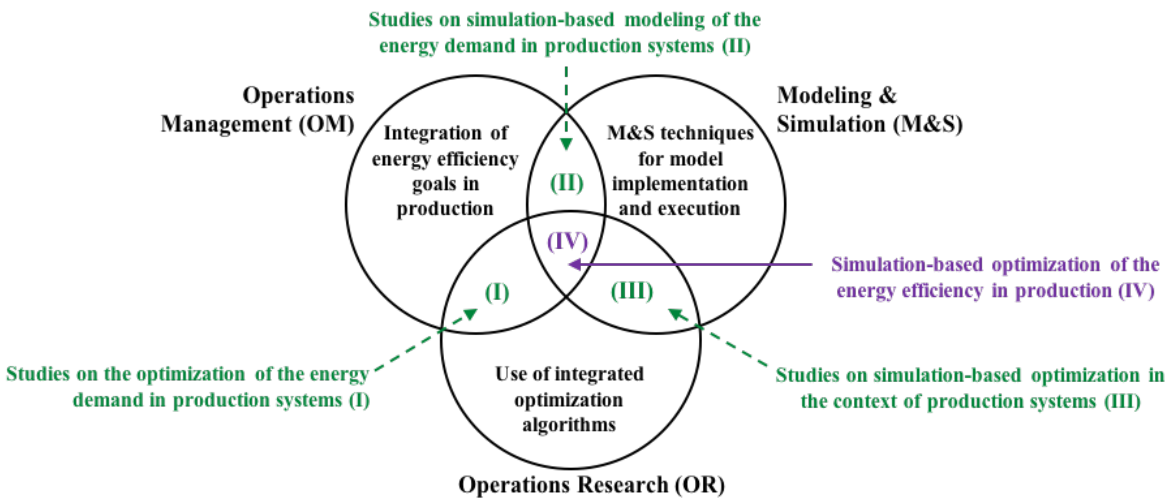

Figure 1: Convergence of disciplines in the context of energy efficiency in manufacturing companies.

Focusing on the convergence of all three described disciplines, only very few studies can be found in recent scientific discussions. Most studies identified as relevant in the selection process of the literature review converge only two of the three disciplines of OM, M&S, and OR and can therefore be found in the subsets of intersection in Figure 1.

- The optimization of the energy demand in production systems (intersection I in Figure 1) is sometimes performed without the use of simulation techniques. In the best case, such optimization studies can lead to an improvement of energy consumption even without detailed simulation models depicting all dynamic processes of the system. The overview of all existing machine processes and their decomposition into single operating states which can then be reproduced in form of mathematical models constitute the basis for the use of such optimization algorithms. By using different modeling accuracies, the mathematical models of the operating states are combined to depict the complete consumption profile of a production machine. Thus, the optimal solution improving energy efficiency in a production system can be determined.
- Studies in the field of simulation-based modeling of the energy demand in production systems (intersection II in Figure 1) primarily focus on the consideration of resource consumption based on physically measured operating states, which are expected to be constant over a defined period of time. The energy consumption of resources is assumed to be status based and presented as part of discrete event simulation approaches. Furthermore, some hybrid simulation approaches can be found. The hybrid simulation is merging the DES techniques for material flow simulations with the continuous approach for energy flow simulation to map the complex interactions between the material flow and the energy demand.
- Studies on simulation-based optimization in the context of production systems (intersection III in Figure 1) combine simulation techniques with optimization methods to find the best input variable values from among all possibilities without explicitly evaluating each possibility of a complex large-scale problem (Banks 2010). As the simulation-based optimization is well studied and publications in this intersection generally do not focus on energy-related topics, they are not considered in this literature review.
- Simulation-based optimization of the energy efficiency in production (intersection IV in Figure 1) requires the combination of discrete or hybrid simulation approaches with integrated optimization possibilities in order to achieve an improvement of measures in the relevant field of action. Modeling the diversity of energy flows in the context of the whole production system together with an integrated evaluation system can constitute a decisional support system for production planning and control in order to achieve an optimum use of energy in production systems.

The aforementioned intersections I and II as well as the convergence of all three concepts (intersection IV) provide the focus of this literature review.

3 ENERGY EFFICIENCY IN MANUFACTURING COMPANIES

The importance of the energy and commodity markets has steadily increased since the first oil crisis in the 1970s. Rising fossil fuel prices as well as debates on climate change and finite resources have triggered a mind change among politicians, entrepreneurs, and scientists. The sustained use of energy and other resources has become a basic requirement for a manufacturing company to competitively perform on the market. There are different options to improve the energy efficiency, from a technical point of view as well as from a processing point of view. Whereas our research is only focusing on an increase of energy efficiency through process improvements, Duflou et al. (2012) provide an overview of energy saving strategies, focusing on technical improvements, such as the use of energy-efficient components and the investment in innovative production techniques to significantly improve the energy consumption.

Within our literature review, a comprehensive research of available publications was conducted and assessed in order to provide an overview of the current state-of-the-art in the field of energy efficiency in production. It is research-based and includes journal articles, conference proceedings as well as theses and dissertations. Relevant literature has been found using the Institute of Electrical and Electronics Engineers (IEEE) Xplore Digital Library, the ACM Digital Library, the Web of Science®, as well as ScienceDirect®. The following search terms and key word combinations have been used: (“simulation-based optimization”

OR “simulation optimization” AND “energy efficiency”), (“simulation-based optimization” OR “simulation optimization” AND “energy efficiency” AND production OR manufacturing) as well as the German translations of the two combinations. The search results have been refined by considering only publications written in English and German language that have been published between 2000 and 2016. Additionally, cross-references and frequently quoted sources have been checked. The selected search criteria generated 128 relevant publications. The abstracts of all papers have been reviewed under the consideration of certain limitations (sub-section 3.1) and thus 73 papers for the full-text review have been selected. The full-text-review again concluded that several publications were not relevant for further investigations. This resulted in the consideration of 20 papers for this literature review. The limitations and criteria found to select and group the publications as well as the research approaches presented in the papers will be described in-depth in the following sub-sections.

3.1 General Limitations for the Selection of Research Approaches

Based on the selection process using the aforementioned search terms and key word combinations, the abstracts of the search results have been read and refined by means of the following factors:

- The approach focuses on the increase of energy efficiency of production processes by implementing process improvements rather than technological innovations
- The approach considers relevant energy consumption in an appropriate level of detail
- The approach considers simulation and/or optimization techniques
- The definition of system boundaries for the investigated scenarios is at least on the level of a multi-step production machine

Research approaches that did not match these criteria based on their abstract have not been considered for further investigation. Papers lacking information in the abstract, have been taken into account for the full-text review and have been sorted out afterwards. This selection process resulted in the consideration of 20 papers in total. All papers included in our literature review have been analyzed regarding the key aspects of the study, grouped corresponding to the previously defined intersections from Figure 1 and evaluated according to the group specific variables subsequently described.

3.2 Studies on the Optimization of the Energy Demand in Production Systems

Optimization covers a wide range of problems, aiming at finding the optimal solution for a certain problem, whereas the complexity of the approach depends on the objective function and constraints as well as on the design variables (Yang 2010). Several studies on optimization approaches in the context of improving energy consumption of productions processes can be found. Fulfilling the mentioned limitations for the paper selection process, 6 research papers could be identified as relevant for intersection I. The optimization approaches will be shortly summarized in chronological order according to the year of publication.

Devoldere et al. (2008) analyze the energy consumption of production systems in their different operating states in the fields of bending presses, milling, and laser cutting machines. Besides the productive operating states, non-productive phases such as stand-by, set-up, and shut down times are considered. Aiming at the detailed evaluation of the machine’s energy consumption and the ability to analyze process alternatives, time and energy studies are carried out to interpret the energy levels of single machines and their components in the terms of technical and process-based improvement of the resources (Devoldere et al. 2007; Devoldere et al. 2008). Devoldere et al. prove in several case studies that the main potential for energy savings can be found in the fields of non-productive operation phases and present results for savings in the laser cutting case of 12% and for bending presses of up to 60%.

Dietmair and Verl (2009) follow a machine control-based approach to determine the consumption forecasting of milling machines. The basic method for their study is the detailed breakdown of machine processes into individual operating states, which are represented as mathematical models and considered with different modeling accuracies. By additive linking, those single mathematical models are composed to form the production consumption profile. By combining the models with real operational data, Dietmair and Verl calculate reliable forecast values regarding the energy insensitivity of production machines. Thereby they can identify critical machine components, make improvements regarding the machine control or select process alternatives for inefficient machines.

Wang et al. (2012) present an approach for energy reduction based on an integrated optimization model for batch production load scheduling in energy-intensive enterprises (EIE) without violating existing constraints of the production processes. The reduction of energy use during peak hours, the time-shifting of energy use in off-peak times of the electricity tariff as well as reduction of the energy demand through optimal load scheduling are considered in the optimization approach. The formulation of the integrated optimization problem includes batch production loads and power generation scheduling, as the approach is addressing EIEs with self-generation power plants. After analyzing the production load curves and decomposing them into base loads and batch production loads, the operating parameters for rescheduling the batch production are formulated. Subsequently, the power generation scheduling problem is formulated, followed by the creation of the integrated optimization model containing integer variables as well as nonlinear constraints. In order to be able to convert the optimization problem into a mixed integer linear programming model (MILP), linearization techniques are introduced. Wang et al. conduct a case study in an iron and steel plant, proving the effectiveness of their approach.

Chen et al. (2013) analyze the effective control of machine startup and shutdown schedules to optimize the energy consumption considering given productivity requirements for serial production lines with Bernoulli machines and finite buffers. Besides using productivity performance measurements, an additional energy performance system is introduced. To calculate the performance measures of serial lines, Markovian analysis and a recursive procedure built on aggregation are used. Chen et al. validate their approach in an automotive paint shop line, proving that scheduling the startup and shutdown times of machines lead to significant improvements in energy efficiency.

Since 2009, the research group ECOMATION is focusing on approaches regarding the control of energy consumption in production facilities and the increase of energy efficiency by using automation techniques. As a part of this research team, Eberspaecher and Verl (2014) present a status-based approach focusing on the energy-optimal use of unproductive times in manufacturing. Combining two optimization algorithms, the Dijkstra-algorithm and the A*-algorithm, the most energy-efficient production state for the machine can be found. In order to be able to apply the optimization theory on machine tools, the energy consumption model had to be defined as a graph and was implemented in C# on the control's operating system. Eberspaecher and Verl prove during a prototypical implementation that the developed consumption graph-based energy optimization approach allows for a switching of energy saving modes during unproductive times to spend them in an energy-optimal state.

Swat (2015) presents an approach for the design of energy efficient processes in serial productions which enables the production planner to predict the energy requirements of production processes already in the early planning stages of a production. By building a business-related energy database, Swat creates the possibility to determine the total energy demand for all combinations of production equipment and machine parameters. Thus, the production planner has the option of selecting alternative process parameters and components to optimize the energy demand. Swat validates his methodology based on the processes of electrochemical machining and honing processes. The deviation between the predicted and the measured values for the energy consumption of the machine tools was only 4%.

Summarizing the research approaches in the field of optimization of the energy demand, two main methodological strategies of the researches can be identified. On the one hand, the effective scheduling and planning of machine start-ups and shutdowns as well as the usage of non-productive times is addressed as the main optimization potential. On the other hand the energy usage is minimized by analyzing energy consumption of single machines and components and choosing process alternatives for industrial processes.

3.3 Studies on Simulation-based Modeling of the Energy Demand in Production Systems

The simulation-based modeling of energy demand in production is a method for assessing the dynamics of production processes. To keep the production permanently on its optimum energy level, an ideal simulation approach has to consider all relevant energy flows with sufficient accuracy. Fulfilling the above mentioned limitations for the paper selection process, ten research papers remain relevant for the intersection II. All authors justify the selection of a simulation-based approach to model the energy use by the rising complexity of production processes that can hardly be evaluated in any other way. The reviewed publications aim at creating a pragmatic tool for supporting the production planning and control.

The majority of research approaches published in the field of energy flow simulation for production systems involve discrete event simulation approaches. They will be shortly summarized in chronological order according to the year of publication followed by hybrid simulation approaches later in this section.

Solding and Petku (2005) developed a methodology following the DES approach, focusing on the reduction of energy use as well as on avoidance of energy peaks in energy-intensive industries. They carried out several simulation studies in various industries modeling the state-based consumption behavior of machines by extending conventional simulators through additional programming within the simulation tool. By adding parameters to the simulation model, they created an accurate model for energy reduction, load management measures as well as the decision support for changing and combining different energy carriers.

Weinert (2010) presents a methodology focusing on the time-based structuring of the energy inputs depending on the operating state of the machine. Combining the time spend in a certain operating state and the associated specific energy consumption profile of a resource, he defines an own classification system. He assumes that similar resources have comparable energy consumption profiles and develops a mathematical functional description of the real consumption profiles. By combining the energy profiles to a sequence, the description of a process chain in an appropriate level of detail is reached. The grouping of individually modeled process chains leads to the description of the total energy consumption of a production. Weinert validates the concept in a case study in the field of a mechanical production comparing the forecast quality of his approach to reference measurements. He simulates the production processes using Visual Components 3DCreate and develops a prototype software to model the energy profiles. By introducing several interfaces, he enables the exchange of process data with the simulation software and thus creates a tool to support the modeling of energy use in production systems.

Berglund et al. (2011) present an approach to improve the production sustainability by measuring and evaluating the concerted effect of process energy from machine operations and the facility energy from building services. They invent a state-based DES model incorporating processes, process energy, and facility knowledge. Integrating real production data, process data, and facility energy data, Berglund et al. validate their approach in an engine block production. They prove that their approach has the potential to reduce manufacturing energy consumption even though the model generation is highly complex.

Wolff, Kulus, and Dreher (2012) present attempts to include energy aspects in the material flow simulation. Assuming that it is possible to model energy consumption as a constant or time-dependent status, they introduce a classification system for the machine states. To ensure that the functionality can be removed at any time for a model, the principle of modularity was adopted for elements of the energy simulation. Thus, the end user is able to switch the energy calculation modules on and off according to his requirements. Taking into account negative effects on the system performance, the energy simulation, and the material flow simulation are run in parallel. To realize the import of the energy consumption simulation, three modules are required: a module for parameterization and import, a calculation module, as well as a model for statistics and visualization. Conducting pilot studies in the automotive industry, the energy calculation module was validated. For further documentation purposes as well as the presentation and deeper analysis of the results, the researchers provide additional options for the visualization of the energy demand in form of diagrams, key performance indicators (KPIs), and statistic tools.

As part of the above mentioned ECOMATION research team, Haag (2013) developed a model-based planning and evaluation methodology to permanently keep the production processes in energetically favorable area. Using the methods of systems technology to merge the main processes and the production periphery, Haag extends the status-based approach of Dietmair and Verl (2009) by considering the time-based dimension and thus converting it from a static to a dynamic model. He integrates the areas of production planning and control and allows the evaluation of planning alternatives already in the early planning stages of production process planning. Haag implements a performance measurement system in the form of a computing system for assessing planning scenarios. He considers production targets (quality key figures, overall equipment effectiveness, and throughput times) to be able to use them as weighted factors for the evaluation of planning scenarios. Haag validates his approach on the example of a cutting production. The modeling and simulation is conducted in Plant Simulation version 10, the parametrization is done in an external database. Energy data, as well as setup times, and process data are taken over into the simulation model using an external interface. He proves that his approach is suitable for evaluating the influence of technological and organizational parameters on the overall energy consumption of production as well as for determining the optimal set of parameters.

Schlegel, Stoldt, and Putz (2013) present an approach integrating energy efficiency analysis in material flow simulations. Assuming status-based energy consumption patterns in the production, they develop a component model that is enlarged by a software package (eniBRIC). This allows for the consideration of energetically relevant inputs and outputs depending on the operating state of a machine. An evaluation module is used for data aggregation and data analysis. The approach is validated in the automotive industry. Despite the additional efforts for creating the simulation model as well as the increase of simulation time due to parameter variation, the methodology allows a comprehensive analysis of resource consumption, the comparison of process alternatives, and the dimensioning of infrastructure facilities. The simple parameterization of eniBRIC allows for the use in different industry sectors.

Using the discrete event simulator SIMIO, Cataldo, Taisch, and Stahl (2013) present an approach for evaluating the energy consumption of an automotive engine assembly line. To model the behavior of each production machine, they divide the mechanical functional behavior of a machine into small single steps characterized by parameters. Additionally, they implemented control functionalities based on finite state machine (FSM) control algorithms that have been translated into C# and thus integrated into the simulator. The energetic states of the machines have been modeled and integrated the same way. Thus, the energy behavior can be run in the simulator together with the mechanical behavior and the control functionality. Cataldo, Taisch, and Stahl validate their approach through a simulation study with a serial production line made of four machines. They prove that their method allows engineers to analyze the simulated production line and to evaluate the efficiency of the simulated layout.

The above mentioned approaches focus on the consideration of energy consumption based on measured operating states, describing them as constant over a fixed period of time. DES approaches do often not provide a sufficient accuracy for the modeling of highly dynamic production processes. To get a more detailed description of dynamic processes, hybrid simulation models are named as a possible solution in literature (Schmidt and Pawletta 2014). The hybrid simulation merges the DES techniques for material flow simulations with a continuous approach for energy flow simulation to map the complex interactions between the material flow and the energy demand. As the topic of hybrid simulation is quite new in the context of production simulation, only three publications have been identified for this literature review.

Rager (2009) developed a concept for an energy-oriented utilization of identical parallel machines with the objectives of minimizing the number of occupied machines to smooth the use of energy throughout the production time. By applying heuristic methods for solving the optimization problem based on hybrid evolutionary algorithms, Rager develops a decision model to support the energy oriented machine scheduling process. He proves the applicability of his approach in a case study of the textile industry. The discrete event simulation software eM-Plant is used for visualization purposes. Depending on the number of production orders, the simulation models execution shows, that energy cost savings between 10 and 20% and load peak reductions up to 30% can be achieved.

As a part of the “SimEnergy” research project, Peter and Wenzel (2013) develop an approach focusing on bidirectional interactions between discrete event production models and continuous energy models. Using a communication platform, the discrete event simulation tool for modeling the material flow is connected with the continuous simulator to map the energy aspects. The platform allows for the parameterization of the material and the energy flow model. Having a separate plug-in, the data exchange as well as the synchronization time are being controlled. Peter and Wenzel validate their approach using a practical example from the automotive industry sector. Executing several simulation runs, the influence of different shut-off temperatures on the output quantity is examined. It is shown that the interaction between production processes and energy flows through coupled simulation models can be analyzed and evaluated. Peter and Wenzel criticize that adjustments in production control to reduce energy consumption are only implemented in real industry cases, as long as they do not have a negative influence on output quantity.

Schmidt and Pawletta (2014) follow a research approach to describe hybrid production models in a purely discrete event simulation environment. Unlike Peter and Wenzel in their research, the combined consideration of the event discrete and the continuous modeling aspects is not realized through the coupling of two simulation models but through the use of the Discrete Event System and Differential Equation System Specification (DEV & DESS) approach from the field of systems theory. Schmidt and Pawletta use the discrete event simulator MATLAB/SimEvents without enabling the continuous model library to model their transaction-oriented process chains. To calculate the resource consumption of machines, a newly developed model library is used. It contains specific manufacturing processes and can submit its calculation results in form of state variable vectors to the simulation software. The hybrid simulation model consists of three parts, the material flow component, the state-based controller, and a subsystem for displaying time which are all validated using the example of a hardening furnace. The results show that the oven reaches the preset temperatures but the set time cannot be met. The approach can be used to validate technical data, to gain information for a proactive maintenance of machines as well as for the reduction of shut down times.

Summarizing the research approaches of intersection II, two main approaches can be distinguished. The majority of publications follows a DES-based model including the energy use of machines either as state-based variables or the energy use is included as a state-based consumption with cumulative load profiles. Only a few publications describe a hybrid simulation approach to realistically model the system of highly dynamic production processes. Regardless of the chosen approach, the simulation model generation is described as highly complex and time consuming. Often support software is required in order to manage, aggregate, and evaluate the collected energy data for the simulation models. The system boundaries of the considered production areas are therefore chosen very diversely among the approaches, ranging from the consideration of consumers that are only directly involved in the production process to the consideration of support processes and peripheral equipment.

3.4 Studies on Simulation-Based Optimization of the Energy Efficiency in Production

Studies on the simulation-based optimization of the energy efficiency in production converge the three disciplines of OR, OM, and M&S and therefore require a holistic view on manufacturing companies, an understanding of all processes, the relevant process in- and outputs, as well as their existing dynamic interactions. Aiming at the integration of energy efficiency goals in the decision system of a production, an approach combining simulation and optimization studies should be usable as a decision supporting tool in a complex and dynamic industrial environment. Fulfilling the above mentioned limitations for the paper selection process, only the subsequently listed four research papers can be identified as relevant.

Lorenz, Hesse, and Fischer (2012) present a DES-based approach to simulate and optimize energy consumption in complex automated production lines in the automotive industry using periodic time-expanded networks. Assuming the energy consumption behavior as being state-based, a consumption profile is assigned to each process of a robot in the simulation. Every ending simulation process as well as waiting processes create an entry into a data table, providing the basis for energy consumption analysis for single robots as well as the whole production line. To reduce peak-loads, a peak-load optimization process is added to the simulation model, calculating the optimal starting time for all processes whenever shifting execution periods is possible before starting the process. The approach is validated in a car body shop showing that the introduction of predetermined waiting periods causes a peak-load drop by nearly 20 %.

Aiming at the development of an energy-oriented simulation-based approach that enables every user in a manufacturing company to independently develop and assess simulation studies for the detection of potential energy efficiency improvements, Thiede (2012) presents a methodology consisting of ten process steps. Focusing on the general character of his concept, he specifies that the approach should neither be limited to a specific case in production or a particular industrial sector, nor to a specific simulation software. In addition, all energy flows and dependencies in production should be tracked. Thiede uses state-based energy profiles to picture the consumption behavior of a machine depending on its state of operation. To depict the interactions between the energy and the material flows, he follows a discrete-continuous simulation approach. Thiede validates his methodology in case studies from the automotive, the textile, and the electronic industries. He proves the applicability of his approach regardless of the size of production, the industry or the level of training of the executing employees and shows that numerous optimization approaches can be developed and evaluated based on his structured ten step plan. Through the use of the universally applicable optimization library OptQuest ™, Thiede includes optimization studies.

Heinzl et al. (2013) follow an interdisciplinary optimization approach for predicting the impact of energy saving measures by comparing different production plant scenarios. Combining the energy optimization of production processes with separately analyzed aspects of the fields “machine and production system”, “building” as well as the “energy system”, Heinzl et al. use the method of co-simulation to study the energetic interactions of the single subsystems. To cover all energy aspects, several simulation models, which are executable as standalone modeling environments, are developed. Heinzl et al. use different simulation tools (e.g. MATLAB, EnergyPlus, and Dymola), to ensure that the special requirements of every sub model are met by choosing the optimum software. To couple the different simulation models, the extensible open-source software platform ‘Building Controls Virtual Test Bed’ (BCVTB) is used. It allows the runtime coupling of different simulation software, supports data exchange and hierarchical combination of different modeling semantics. Proving the advantages of their co-simulation approach, the authors create different production scenarios varying the climatic and production conditions. The approach allows the user to make predictions regarding energy optimization measures in production systems.

Eberspaecher et al. (2014) present an approach combining power measurement data and control signal information with consumption data that has been generated using static and dynamic simulation models. In a second step a situation-based optimization is carried out to reduce energy consumption of machine tools. Eberspaecher et al. develop a general machine tool component library to be able to calculate with detailed electric load curves instead of using operating states. They combine their simulation approach to estimate the energy demand on machine and component level with a monitoring approach to allow real time energy demand monitoring. In combination with a component and an operating state optimizer the optimal parameter configuration for an energy-optimal production is found.

Summarizing the papers of intersection IV, different approaches to simulate the energy consumption in production systems combined with optimization techniques are presented. While the DES-based approach combined with a peak-load optimizer is suitable to calculate the optimum start and shut down times for robots, the hybrid simulation approach in combination with the optimization library OptQuest ™ focuses on the detection of potential energy improvements throughout the whole production process. The concept of simulation model coupling in combination with an operating state optimizer supports real time monitoring and parameter adaptations to optimize the energy use.

4 RESULTS AND DISCUSSION

All publications mentioned in this literature review, present new approaches in the research field of energy efficiency in production. Mentioned in all papers, the top motivation for the researchers is the changing importance towards the sustainable use of resources, mainly initiated by debates on global warming, rising energy costs, and resource depletion. For all approaches, the consideration of the energy consumption is generally based on measured operating states, which are considered to be constant over a defined period of time. The defined system boundaries are varying throughout the papers, reaching from the consideration of a multi-step production machine to a whole production facility including technical building services and peripheral production equipment. Regardless of the chosen system boundaries, the efforts of the data acquisition and evaluation as well as the model generation for all optimization and simulation models have been described as very complex and time-consuming.

After having analyzed all papers, three main approaches for the reduction of the energy use can be distinguished. Firstly, the optimization of machine control functionalities provides energy saving potentials, e.g. the efficient use of non-productive times or the peak-load avoidance. Secondly, by varying process parameters in the production, saving opportunities can be realized without influencing the production output negatively. The third category focuses on early planning phases in production planning. By the evaluation of process alternatives and the appropriate dimensioning of energy efficient components and machines, the production design can be influenced right from the beginning. In general terms, the evaluation methods in the approaches all focus on sub-areas of the production, following one perspective in order to optimize the energy use. This may lead to incomplete energy policies as well as conflicting goals within the production and may cause problem shifting from one to another area. Only by following an integrated view of production systems, considering all interdependencies between the production equipment, process parameters, relevant in- and outputs, as well as the building services, an appropriate method for assessing the energy consumption can be established.

The majority of studies has been validated using case studies from the automotive industry. Often, developed approaches are very case-specific and not transferrable to the production processes of other industries without high efforts. Several authors criticize that adjustments in production control to reduce energy consumption are only implemented in real industry cases, as long as they do not have a negative influence on output quantities. Although the main focus is on optimizing the energy use without causing any restrictions regarding the flexibility of production, the process quality nor major changes in production output, energy variables need to be integrated into the decision system of production planning and control to be able to accurately evaluate the energy cost savings in relation to additional costs incurring due to changes in output quantities caused by energy efficient production setups.

The utilization of optimization methods without the visualization of simulation techniques can hardly be used as an actual stand-alone decision support when following a holistic system perspective in production planning and control. A realistic presentation of energy consumption and its dynamics within the production system requires a significant visualization as the pure process description in form of mathematical models is rather a research topic than industrial practice. The simulation of energy use without integrated optimization algorithms can be considered as a tool to display material and energy flows, as well as machine states during run time. Due to highly complex and dynamic processes in nowadays production systems, manual process optimizations carried out by single persons are not goal-oriented when aiming towards an energy efficient production in all relevant fields of action. Therefore, a holistic approach combining simulation techniques with automated optimization algorithms is required to recognize systematic improvements.

5 SUMMARY AND FUTURE WORK

In this paper, we summarized the current state-of-the-art in the field of simulation-based optimization of energy efficiency in manufacturing companies as well as its adjacent disciplines. Following the elaborate paper selection process, we analyzed existing research approaches with the intention to identify main modeling and optimization techniques used to improve the energy consumption in productions in section 3 and evaluated them in section 4.

Our future research work relates to finding an approach that is not restricted to a case-specific production scenario but supports a wide range of production cases without causing high efforts for case-specific adaptations. As the hybrid simulation approaches are considered to reduce the efforts for data collection and offer a more flexible parametrization compared to DES techniques, a research approach that couples the hybrid modeling with mathematical optimization algorithms so far seems to be the most promising concept to evaluate the energy consumption in production systems. Furthermore, a continuous exchange of data between the simulation model and the energy monitoring system of a production could improve the model consistency.

REFERENCES

Banks, J., J. S. Carson, B. L. Nelson, and D. M. Nicol. 2010. *Discrete-Event System Simulation,* 4th ed., Upper Saddle River, New Jersey: Prentice Hall, Inc.

Berglund, J., J. Michaloski, S. Leong, G. Shao, F. Riddick, J. Arinez, and S. Biller. 2011. "Energy Efficiency Analysis for a Casting Production System" In *Proceedings of the 2011 Winter Simulation Conference,* edited by S. Jain, R. Creasey, J. Himmelspach, K. White, and M. Fu, 1060–1071. Piscataway, NJ: Institute of Electrical and Electronics Engineers, Inc..

Cataldo, A., M. Taisch, and B. Stahl. 2013. "Modelling, Simulation and Evaluation of Energy Consumptions for a Manufacturing Production Line." In *Proceedings IECON 2013 - 39th annual conference of the IEEE Industrial Electronics Society, Vienna*, 7537–7542. Piscataway, NJ: IEEE.

Chen, G., L. Zhang, J. Arinez, and S. Biller. 2013. "Energy-Efficient Production Systems Through Schedule-Based Operations." *IEEE Transactions on Automation Science and Engineering* 10:27–37.

Devoldere, T., W. Dewulf, W. Deprez, and J. Duflou. 2007. "Improvement Potential for Energy Consumption in Discrete Part Production Machines." In *Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses,* edited by S. Takata and Y. Umeda, 311–316. London: Springer-Verlag London Ltd.

Devoldere, T., W. Dewulf, W. Deprez, and P. Eberspächer. 2008. "Energy Related Life Cycle Impact and Cost Reduction Opportunities in Machine Design: The Laser Cutting Case." In *Applying Life Cycle Knowledge to Engineering Solutions,* edited by H. Kaebernick, 412–419. Sydney.

Dietmair, A., and A. Verl. 2009. "Energy Consumption Forecasting and Optimisation for Tool Machines". *MM Science Journal* 2009:63–67.

Duflou, J. R., J. W. Sutherland, D. Dornfeld, C. Herrmann, J. Jeswiet, S. Kara, M. Hauschild, and K. Kellens. 2012. "Towards Energy and Resource Efficient Manufacturing: A Processes and Systems Approach." *CIRP Annals - Manufacturing Technology* 61:587–609.

Dyckhoff, H. and R. Souren. 2008. *Nachhaltige Unternehmensführung. Grundzüge industriellen Umweltmanagements,* Berlin: Springer.

Eberspächer, P., P. Schraml, J. Schlechtendahl, A. Verl, and E. Abele. 2014. "A Model- and Signal-based Power Consumption Monitoring Concept for Energetic Optimization of Machine Tools." *Procedia CIRP* 15:44–49.

Eberspächer, P., and A. Verl. 2014. "Realizing Energy Reduction of Machine Tools Through a Control-integrated Consumption Graph-based Optimization Method." In *Economic Development and Wealth through Globally Competitive Manufacturing Systems,* edited by Cunha, Pedro Filipe do Carmo, 640–645. Red Hook, NY: Curran.

Haag, H. 2013. *Eine Methodik zur modellbasierten Planung und Bewertung der Energieeffizienz in der Produktion,* Stuttgart: Fraunhofer Verlag.

Heinzl, B., M. Rossler, N. Popper, I. Leobner, K. Ponweiser, W. Kastner, F. Dur, F. Bleicher, and F. Breitenecker. "Interdisciplinary Strategies for Simulation-Based Optimization of Energy Efficiency in Production Facilities." In *2013 UKSim 15th International Conference on Computer Modelling and Simulation (UKSim 2013),* edited by D. Al-Dabass, A. Y. J. Orsoni, R. Cand, and Z. Ibrahim, 304–309.

Lorenz, S., M. Hesse, and A. Fischer. 2012. "Simulation and Optimization of Robot driven Production Systems for Peak-Load Reduction." In *Proceedings of the 2012 Winter Simulation Conference (WSC),* edited by C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose, and A. M. Uhrmacher, 2875–2886. Piscataway, NJ: Institute of Electrical and Electronics Engineers, Inc.

Peter, T. and S. Wenzel. 2015. "Simulationsgestützte Planung und Bewertung der Energieeffizienz für Produktionssysteme in der Automobilindustrie". In *Simulation in Production und Logistics 2015,* edited by M. Rabe, and U. Clausen, 535-544. Stuttgart: Fraunhofer Verlag,

Rager, M. 2008. *Energieorientierte Produktionsplanung. Analyse, Konzeption und Umsetzung,* Wiesbaden: Betriebswirtschaftlicher Verlag Dr. Th. Gabler | GWV Fachverlage GmbH.

Schlegel, A., J. Stoldt, and M. Putz. 2013. "Erweiterte Integration energetischer Betrachtungen in der Materialflusssimulation: Advanced Integration of Energetic Consideration in Discrete Event Simulation." In *Simulation in Produktion und Logistik 2013,* edited by W. Dangelmaier, C. Laroque, and A. Klaas, 187–196. Paderborn: Heinz-Nixdorf-Inst. Univ. Paderborn.

Schmidt, A., and Pawletta T. 2014. "Hybride Modellierung fertigungstechnischer Prozessketten mit Energieaspekten in einer ereignisorientierten Simulationsumgebung." In *ASIM 2014, 22. Symposium Simulationstechnik, 3. bis 5. September 2014, HTW Berlin; Tagungsband*, edited by J. Wittmann and C. Deatcu, 109–116, Wien: ARGESIM / ASIM.

Solding, P. and D. Petku. 2005. "Applying Energy Aspects on Simulation of Energy Intensive Production Systems." In *Proceedings of the 2005 Winter Simulation Conference,* edited by M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, 1428–1432. Piscataway, NJ: IEEE.

Swat, M. 2015. *Methode zur Planung und Gestaltung energieeffizienter Prozessketten für die Serienfertigung am Beispiel ausgewählter Feinbearbeitungsverfahren*. Saarbrücken, dissertation.

Thiede, S. 2012. *Energy Efficiency in Manufacturing Systems*, Berlin: Springer Verlag.

Wainer, G. A. 2009. *Discrete-event Modeling and Simulation.* Boca Raton, Fla.: CRC Press.

Wang, Z., F. Gao, Q. Zhai, X. Guan, K. Liu, and D. Zhou. 2012. "An Integrated Optimization Model for Generation and Batch Production Load Scheduling in Energy Intensive Enterprise." In *IEEE Power and Energy Society General Meeting, 2012,* Piscataway, NJ: IEEE.

Weinert, N. 2010. *Vorgehensweise für Planung und Betrieb energieeffizienter Produktionssysteme*, Stuttgart: Fraunhofer-Verlag.

Wolff, D., D. Kulus, and S. Dreher. 2012. "Simulating Energy Consumption in Automotive Industries" In *Use Cases of Discrete Event Simulation, edited by S.* Bangsow, Berlin, Heidelberg: Springer, 59–86.

Zeigler, B. P., H. Praehofer, and T. G. Kim. 2010. *Theory of Modeling and Simulation. Integrating Discrete Event and Continuous Complex Dynamic Systems,* 2nd ed., Amsterdam: Academic Press.

AUTHOR BIOGRAPHIES

ANNA CARINA ROEMER holds a bachelor and a master degree in industrial engineering from the Ilmenau University of technology. She is currently working as an external PhD student at the Department of Industrial Information Systems of the Ilmenau University of Technology. Her research interests include simulation-based optimization approaches, hybrid simulation approaches as well as industrial simulations in general. Her email address is anna-carina.roemer@tu-ilmenau.de.

STEFFEN STRASSBURGER is a professor at the Ilmenau University of Technology and head of the Department for Industrial Information Systems. Previously he was head of the "Virtual Development" department at the Fraunhofer Institute in Magdeburg, Germany and a researcher at the DaimlerChrysler Research Center in Ulm, Germany. He holds a Doctoral and a Diploma degree in Computer Science from the University of Magdeburg, Germany. He is further an associate editor of the Journal of Simulation. His research interests include distributed simulation, automatic simulation model generation, and general interoperability topics within the digital factory context. He is also an active member of the Simulation Interoperability Standards Organization (SISO). His web page can be found via http://www.tuilmenau.de/wi1. His email is steffen.strassburger@tu-ilmenau.de.