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Increasing energy efficiency in production environments through an optimized, hybrid simulation-based planning of production and its periphery

Thomas Sobottka[ab]*, Felix Kamhuber[ab], Wilfried Sihn[ab]

[a]Fraunhofer Austria Research GmbH, Theresianumgasse 27, Vienna 1040; Austria
[b]Vienna University of Technology, Theresianumgasse 27, Vienna 1040; Austria

* Corresponding author. Tel.: +43-676-888-61626; fax: +43-1-504-6910-90. *E-mail address:* thomas.sobottka@fraunhofer.at

Abstract

This research aims to develop a novel planning tool able to increase both the energy efficiency and general performance of production systems using a hybrid-simulation based, multi-criteria optimization, with this particular paper focusing on the optimization method. Lacking necessary planning tools for an energy aware production planning and control, companies are unable harness the associated optimization potential. State-of-the-art tools are not able to sufficiently consider interactions between the discrete system behavior of material flow and the continuous thermal-physical behavior of equipment. This paper presents a planning method addressing this deficiency. The developed genetic-algorithm based optimization module optimally fits the requirements.

Keywords: energy efficiency; production planning; optimization; hybrid simulation; multi-criteria metaheuristic optimization

1. Introduction

Long term trends of rising energy costs, together with a societal drive towards notions of sustainable living plus pressure from the political domain, facilitate the need to increase the energy efficiency of production processes. The basic definition of energy efficiency in the context of production is the ratio between the value-added output of a production system and the necessary energy input [1]. The industrial sector is currently responsible for 31% of the annual energy demand and 36% of the CO_2 emissions globally [2], rendering energy efficiency an important goal. Thus, sustainable manufacturing has become a new paradigm for manufacturing enterprises [3].

Thus, planning tools providing decision support for this new set of goals are necessary [4]. A demand analysis by a large EU-FP7 research project has identified a need for ICT tools that enable companies to effectively reduce CO_2 emissions. Market research by McKinsey has estimated the global market for Information and Communications Technology (ICT) solutions supporting the energy aware planning to be around 15 billion EUR by 2020 [5].

Studies show that energy efficiency considerations should be an in integral part of Enterprise-Resource-Planning (ERP) and Manufacturing Execution Systems (MES), with simulation based approaches suggested to be the most promising methods [6]. However, currently there is a lack of practically applicable planning methods.

In order to address this deficiency, this research is meant to develop a novel planning tool that increases both the energy efficiency and general performance of production systems using a hybrid simulation-based optimization approach. This particular paper focuses on the optimization method. The research is embedded within a larger research project comprising multiple academic fields as well as implementation partners for software development and industrial enterprises as application partners.

The paper is structured as follows: First a summary of the requirements for a software planning tool for production planning and control (PPC) purposes is presented, followed by

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a brief overview of related work. After that, the results concerning the underlying methods for the planning tool, hybrid simulation and the optimization – the main focus of this paper –, are presented. Finally, the results are conflated and discussed.

2. Requirements for the planning tool

The requirements for a planning tool have been deducted from an analysis of relevant literature, supplemented by expert interviews with managers from the application partners within the research project. According to the findings of a large EU research project, based on interviews with 106 international experts, the tools will have to consider both conventional economic planning goals and energy and resource efficiency simultaneously. The planning should be integrated into the existing ICT and the use of detailed simulation models is recommended [5]. Li [7] stresses the necessity for a generic structure to make the tools available for different application environments. He [3] also emphasizes the need to consider all relevant energy flows and their interdependencies. Concerning the underlying methods, Thiede – among others – declares simulation to be the method best suited to provide the necessary planning support [8]. An automatic decision support function, i.e. in the form of an optimization module, is another major request from prospective industry users.

3. Related Work

In this chapter, a brief overview of related work will be introduced. This comprises two major aspects: the hybrid simulation and the optimization.

3.1. Simulation & simulation based Planning approaches

The basic concept of a dynamic simulation is to create a digital model of a real-life system, featuring all relevant characteristics, and to then use that model to conduct experiments in order to gain insights into the system behavior or to optimize and develop plans for the system [9]. Material flow and the processing of orders is simulated utilizing a discrete event simulation (DES), while the thermal-physical behavior of machines and equipment is simulated in continuous simulation environments that basically solve differential equations (Differential Equation System Specification – DESS). One of the most advanced simulation based concepts for planning tools in the field of energy aware planning is Thiede’s approach based on a multilevel-simulation [10]. This concept combines multiple simulation environments in a co-simulation, in which the subsystems are modelled either in a DES or DESS environment. The sub-simulations are coupled at certain points during the simulation run and provide a certain level of integrated modelling. However, the level of integration necessary to comprehensively represent the interactions between the energy system and the production and material flow is practically impossible to achieve with a co-simulation. This requires an integrated hybrid simulation, enabling both a continuous and discrete behavior simultaneously.

3.2. Optimization & simulation based optimization

Optimization methods comprise optimization algorithms that are able to find optimal solutions for problems with a limited complexity and optimization heuristics that are able to find approximate solutions, if exact solutions cannot be found; these are called NP-hard problems. Within heuristics, there are special heuristics dedicated to a certain problem category in operations management and metaheuristics that serve as generic algorithms for a broader range of applications when dedicated heuristics are not available [11]. Most complex optimization tasks, especially if the optimization utilizes a simulation as an evaluation function, as in this research, feature multiple local optima. This requires the algorithms to not „get stuck” in local optima, in order to arrive at better solutions eventually [12]. The metaheuristics can be discerned in algorithms based on iterative local search (LS) and generative population based methods (PS) [13]. Most of these heuristics mimic natural processes, i.e. imitating animal behavior, evolution in biology or the cooling of materials.

The optimization problem in this research is mainly the *scheduling and sequencing of orders*, thus representing a permutation flow shop sequencing problem (PFSSP), extended by the optimal control of production equipment and equipment in the periphery. For optimization in production scheduling applications without the energy aspect, Pochet gives an overview of approaches based on mixed integer programming [14]. Due to the increased model complexity in the case of energy aware planning, there are examples of approaches based on the Genetic Algorithm (GA) [15] and Rager [16] utilizing the GA for a simulation based approach in a case similar to the projected application of this paper. None of the existing optimization methods features the more complex hybrid simulation developed and used in this research, thus a customized optimization method has to be developed.

4. Hybrid Simulation

The characteristics of the simulation determine the requirements for the optimization, which will utilize the simulation as an evaluation function, thus the following will give a brief overview of the development of the hybrid simulation, although the main focus of this paper is on the development of a suitable optimization method.

Originating from the work of Zeigler, system specifications for a hybrid simulation have been developed – DEV&DESS and hybrid Parallel Discrete Event System Specification (PDEVS) [17]. These specifications provide a hierarchical and modular system definition, consisting of *atomics* – the basic building blocks describing dynamic system behavior – and *coupled* – describing a system behavior with interacting components that can either be “atomics” or other “coupled”. The formalisms describe, how events are to be handled and how ordinary differential equation solvers (ODE) are called, to model both the discrete and continuous system behavior. The approaches have been evaluated in the simulation development phase of this research and the PDEVS formalism turned out to be the most suitable option [18].