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Evaluation of demand response actions in production logistics

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Abstract

Volatile electricity prices caused by an increase of renewable energy sources push producing companies towards taking in an active role in balancing the electricity grid. Possible actions at the customer side to actively adapt to volatile energy prices are called demand response actions. In production logistics such actions can be the modification of production schedules motivated by possible economic benefits. So far, the focus in scheduling problems has been the optimization in the dimensions of quality, time and costs. This paper presents the results of a simulation study on the economic benefits of demand response actions for a generic production system.

Keywords: Scheduling; job shop; Dispatching rules, Job release; demand response; energy-efficiency

1. Introduction

The German Federal Government aims at increasing the percentage of renewable energy sources within the gross electricity consumption from 20% as of today towards 80% in 2050 [1], [2]. The biggest challenge caused by the increase in renewable energy sources is considered to be the high volatility of the electrical energy generation. While conventional power plants are able to guarantee a constant level of electrical energy generation capacity, electrical energy generated by solar panels and wind turbines fluctuates due to weather conditions (see Fig. 1). Therefore, the growing inclusion of renewable energy sources causes weather and day-time dependent fluctuations within the electricity-grid which has to be compensated by expensive balancing energy. Existing regulating actions are classified into four categories. Primary and secondary balancing energy are quick-reacting control mechanisms that are being activated automatically due to fluctuations within the grid frequency. While primary and secondary balancing energy has to be provided within seconds the tertiary (minute reserve) and hourly reserve are being activated after 15 minutes or one hour respectively [3]. Since balancing power is very cost-intensive and fluctuations within

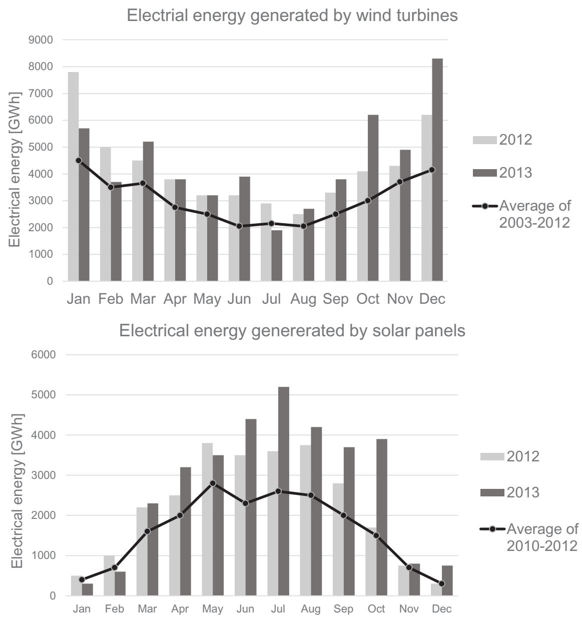

Fig. 1. Electrical energy generation from wind turbines and solar panels [7]

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the electrical energy supply are considered to increase due to the growing expansion of renewable energy sources market mechanisms have to be identified that reward balancing activities at the demand side. One option to incentive demand side actions at the customer side is to pass the volatile electricity prices on to the customer. Therefore, the German legislative passed a law (EnWG) to foster the implementation of load-dependent and day-time-dependent electricity tariffs on behalf of the electricity providers [4]. Therewith, variable electricity tariffs can be an instrument to incentive the shift of electrical energy consumption to low-demand times, to cut peak loads and to increase the forecast quality of the electricity-grid load.

Industry as a major consumer of electrical energy [5] can benefit from this situation in terms of electricity cost reduction. Since the year 2000 electricity prices of industrial consumers in Germany have increased tremendously therefore threatening the competiveness of the German industry (see Fig. 2) [6]. Companies of the German machinery and equipment industry regard rising energy costs in Germany to be a major threat in the future for which they are not well prepared for [9]. An average industrial consumer with an annual consumption of 100 GWh has to face a financial surplus load of over a million Euros for an increase of the electricity price of 1 Cent/kWh.

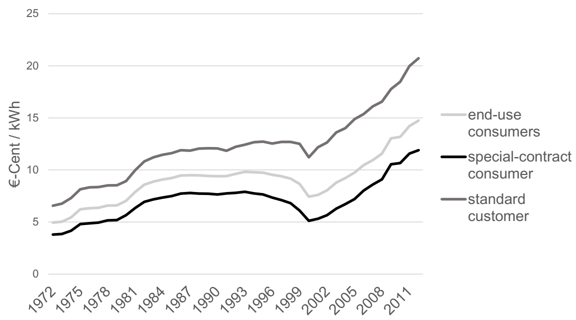

Fig. 2. Electricity price development in Germany for selected customers [8]

1.1. Problem Statement

This paper proposes an approach for integrating volatile electricity prices into production logistics for companies of the German machinery and equipment industry. The proposed method should enable companies to reduce electricity costs by shifting energy-intensive operations into periods of lower electricity prices.

The following section gives an overview of the main terminology used in this paper. Section 3 will present the State-of-the Art on sequencing problems and outline the research gap. Section 4 will present the simulation model developed to conduct the study. Section 5 will present the results and implications and section 6 will close the paper with a conclusion and further research needs.

2. Terminology

Demand Response (DR) can be defined as a change in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time or towards an activation of agreed reserved power capacity [10]. DR can be classified into two categories. Price-based DR refers to changes in usage by end-use customers in response to changes in electricity prices and includes real-time-pricing (RTP), critical-peak pricing (CPP), and time-of-use rates (TOU). Additionally, customers can participate in incentive-based DR instruments where they are given load-reduction incentives in addition to their normal tariffs.

Production logistics comprises all activities and processes within production that ensure the manufacturing, transportation and storage of products [11]. It is therefore a sub-discipline of logistics management where the planning and operation of production systems is in focus. At the core of production logistics production planning and control (PPC) covers all activities that need to be performed to ensure the delivery of a product within the right time, costs and quality [12]. Planning activities can be separated into long-range planning, intermediate-range planning and short-term control. Within this article the focus is on intermediate-range planning and short-term control which mainly consists of rough-cut capacity planning (RCCP), capacity requirements planning (CRP), lot-sizing, sequencing (order in which jobs are done), job release and job Dispatching [13]. These short-term activities completely define how, when and where electrical energy is used within production [14] and therefore play a significant role in reducing total electricity costs of a factory [15].

3. Literature Review

3.1. Sequencing in production logistics

Sequencing has been a topic in research for a long time and is considered a major tool for production logistics in order to optimize various production logistics targets such as minimizing throughput-times, maximizing on-time-delivery or balancing capacities [16]. In general, there are two categories of priority rules that can be used for sequencing - local and cause-based. Local rules focus on optimizing order-oriented targets without influencing the overall performance of the production system. Therefore, local rules prioritize jobs based on the earliest termination date, the shortest non-operational time or the shortest operation time in front of a machine. On the other hand cause-based priority rules focus on objectives which consider multiple machines or the whole production system, more precisely:

- Jobs are being allocated to machines with the shortest queue to optimize the overall machine utilization.
- Jobs with the shortest overall operation time are prioritized to reduce the average throughput-time.
- Jobs with the highest capital lockup are prioritized to reduce overall capital lockup.

- Jobs with the shortest buffer times and with the shortest due date are prioritized to increase overall delivery performance.

Although many of the sequencing rules are well documented and easy to implement companies still struggle with the discipline that is needed to implement sequencing rules [16].

In general sequencing problems can occur at two points of time within the order processing:

- 1. within a queue of jobs in front of a single machine.
- 2. before job release or
- 3. a combination of 1. and 2.

The research scope for sequencing can be classified into three categories [17], [18]:

- Flow shop: all jobs have the same amount of operational steps *m* which are being processed in a fixed sequence on machines 1, 2… m.
- Job shop: the number and character of operational steps are different for all jobs. The sequence of operational steps has to be fixed for every job and is not to be changed.
- Open shop: same as job shop but the sequence of operational steps is arbitrary.

Within our literature analysis we reviewed 33 relevant sources each on sequencing for flow-shop, job shop and open-shop based on a research on sciencedirect.com. We found that almost all reviewed literature dealt with problems in how to optimize conventional production logistics targets such as throughput-times and on-time-delivery. Among the many methods used the most popular where heuristic approaches such as shifting bottle-necks, particle swarm optimization, tabu-search, simulated-annealing and evolutionary algorithms.

3.2. Sequencing as a tool for demand response

Sequencing as a tool for demand response is a relatively new research area. In general, research for increasing energy-efficiency and thus reducing energy costs on a process level can be subdivided into three categories:

- Increasing the overall equipment utilization to reduce non-value-adding processes (e.g. idle machines)
- Avoiding peak-load, e.g. by using adequate ramp-up strategies or intelligent scheduling during production
- Shifting production from high-price periods (e.g. day-time) to low-price periods (e.g. night-time)

A common characteristic of energy-efficiency on the shop-floor is the lack of available information on electrical energy consumption of machines, facilities and other peripheral equipment. Especially data collection is crucial since it influences the quality of energetic analyses [19]. Therefore research focuses on the holistic collection of all energy data within a production system. An overview can be found at DUFLOU ET AL. [20].

Regarding the second category PECHMANN proposes a method to reduce electricity costs by an intelligent scheduling. Therefore, the production and the corresponding power demand for the next 24 hours are predicted. The scheduling algorithm aims at avoiding peak loads. This helps to reduce the total electricity costs by reducing the cost for peak loads but it neglects to shift power demand to low-price periods [21], [22]. HERMANN AND THIEDE are using simulation to show that electricity consumption and electricity costs can be optimized in production logistics measures [23].

WEINERT ET AL. present a so-called EnergyBlocks methodology which segregates production processes into operations each with its specific energy consumption. Within a case-study it is shown that the adaption of production schedules can reduce energy costs and consumption [24].

To summarize we found no relevant papers in our literature review that used sequencing as a tool to minimize electricity costs by shifting jobs from high-price periods to low-price-periods. Therefore, it is the objective of this article to present a simulation study that demonstrates the potential of load-shifting for reducing the electricity costs for a generic job shop production.

4. Experimental evaluation of demand response actions by simulation

4.1. Experimental conditions

Within the simulation study a job shop production consisting of a total number of 8 machines (milling, drilling, turning, grinding and sinking) is investigated*. An order contains products derived from customer orders or a forecast. Orders are transformed into jobs within the first step of the MRP II logic. The number of operations per job depends on the product and varies from 2 to 4. The routing of each job also depends on the product and is predefined. The simulation study covers a time-span of one month of production. A two-shift production is being investigated.

For each product a work plan determines the steps within production. Electricity-intensity of a product or a job is defined as the amount of electrical energy (electricity) consumed during machining. Electricity-intensity depends on the material and processing times (see also Appendix A.). After being released a job is transported to the first production step and consecutively to the next step according to its work plan. To evaluate the effectiveness of demand response actions two figures are regarded – total electricity costs and

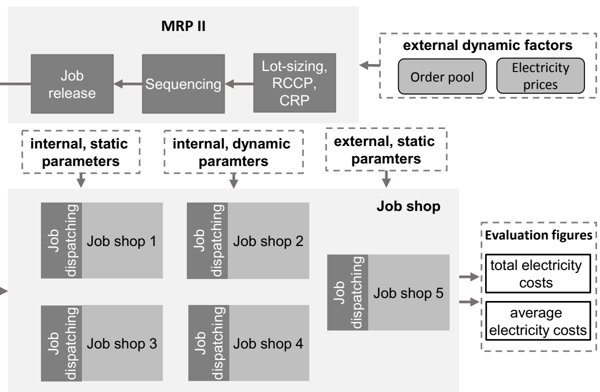

Fig. 3. Setup of the simulation model

* It has been demonstrated that six machines are adequate to represent the complex structure of a job shop and many researcher have considered job shops with less than 10 machines [25], [26].

average electricity costs. Total electricity costs [€] should be minimized by consuming more energy in low-price periods. Additionally, by shifting operational times of electricity-intensive jobs from high-price periods to low-price periods the average electricity costs [Cents/kWh] should decrease.

Fig. 3 gives an overview of the system under study. The simulation model represents a MRP II logic which is described in the following subsections.

4.2. Electricity price function

For the electricity price function electricity prices were drawn from the European Power Exchange EPEX Spot for a four weeks period in 2014. RTP was considered with an hourly fluctuating electricity price. Additional charges were added representing a wholesaler's services. The assumption was that customers are provided with the electricity price function on a day-ahead basis.

4.3. Master production scheduling

Jobs are picked randomly (based on the common random number technique) on a weekly basis (rectangular distribution) from the pool of orders to form a master production schedule. Orders can either represent an end-customer or be taken from a short-term forecast. By roughly adding up machining times based on the work plan and comparing them to the shift-plan a rough-cut capacity planning is simulated to ensure the feasibility of the master production schedule and to avoid a job overflow in the job shop. Within master production scheduling also lot-sizes for jobs are predetermined.

4.4. Job release

The job release function controls which jobs are allowed to enter the shop floor as well as how many jobs are on the floor thus controlling the level of Work-In-Progress (WIP). For the simulation studies the maximum number of jobs (MNJ) release mechanism was regarded [27]. In MNJ jobs will be released according to a priority given by the order sequence algorithm until the number of jobs in the job shop has reached a predefined value.

The algorithm calculates the average electricity price for the next 16 hours (two-shifts, one working day). The average electricity price is categorized as "low", "middle", or "high". Based on their expected electricity-intensity jobs are prioritized and released high priority first. For example, an electricity-intensive job in combination with low electricity prices will be prioritized against a job with low electricity-intensity. For comparison, two simple sequencing methods were also considered. The First-In-First-Out (FIFO) method simply prioritizes highest the job that arrives first in the queue and vice-versa Last-In-First-Out (LIFO) prioritizes highest the job that arrives last at the queue. Although these methods are not very sophisticated they may reflect common practice in the industry.

4.5. Job Dispatching

There is a buffer in front of each machine or group of machines where released jobs are accumulated. The algorithm first checks machine availability. Then, the algorithm checks the total processing time for each of the accumulated jobs and calculates the average electricity price for that period of time given by the electricity price function. For a low average electricity prices electricity-intense jobs are prioritized against jobs consuming less electricity. If all jobs have the same priority the algorithm calculates the changeover time based on the previously machined product and jobs with lower changeover times are prioritized. The magnitude of the job dispatching algorithm relies on the job release function. As the job release limits the number of jobs to be released to the job shop the job dispatching algorithm has fewer jobs to choose from.

4.6. Validation of the energy-aware algorithm

Validation for the energy-aware dispatching algorithm was conducted for the following scenario: A high maximum number of jobs (1000) were considered along with a high volatility of energy prices. The energy-aware dispatching algorithm is expected to deliver lower energy costs along with a distinctive curve for high energy consumption at periods of low energy prices. Fig. 4 illustrates the effectiveness of the algorithm in comparison to the FIFO dispatching strategy. As one can observe the total electricity costs were lower for the energy-aware algorithm in comparison to a FIFO dispatching. This was true for multiple days and observations.

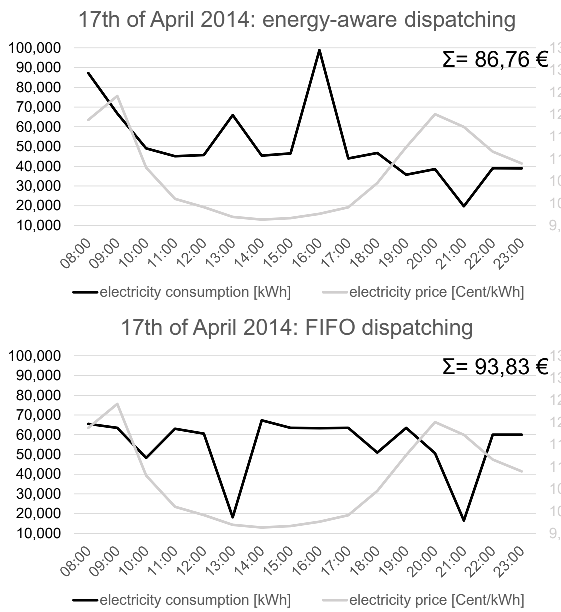

Fig. 4. Validation of the energy-aware dispatching algorithm

4.7. Simulation setup and execution

For each simulation study two scenarios have been considered (see Table 1). In scenario 1 an ideal situation is being investigated. The level of automation is considered to be high. This means that machines will automatically be set into a "stand-by" mode during idle times therefore consuming less electrical energy. Additionally, an ideal machine availability of 100% is defined. Scenario 2 is a more realistic situation therefore machines will remain in a "ready-to-operate" mode during idle times representing a semi-automated production system. –Additionally, machine availability in scenario 2 is considered to be 85% with a mean time to repair (MTTR) of 2 hours. For each scenario a maximum number of 12 and respectively 1000 are considered. Within the first simulation study actual electricity prices from a four weeks period in 2014 were considered. Within the second simulation study a combination of higher and more volatile energy prices is considered to further investigate the effectiveness of the presented algorithm. In order to give probability a fair chance 1000 observations are performed for every factor combination.

Table 1. Overview of scenarios and factor combinations

Variable (factor)	Scenario 1 (ideal)		Scenario 2 (real)	
Automation level	high-automation		semi-automation	
Machine availability	Availability 100%		Availability 85%, MTTR 2h	
Max. number of jobs in the job shop	12	1000	12	1000

5. Results

Two simulation studies were conducted to demonstrate the potential of the proposed algorithm. The first study investigates the potential for today's electricity prices. Within the second study higher and more volatile electricity prices were considered.

5.1. Simulation Study 1: Electricity prices for 2014

Fig. 5 illustrates the results of the simulation study with electricity prices from 2014. The average electricity costs for operational times could be reduced using the energy aware algorithm in comparison to the FIFO and LIFO sequencing. The reduction in average electricity costs also proved to be

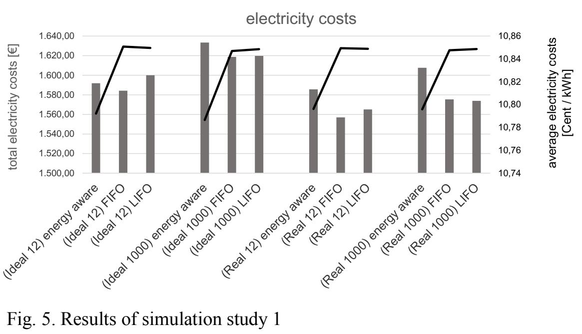

Fig. 5. Results of simulation study 1

true for the different scenarios under investigation. However, lower average electricity costs during operational times did not lead to lower total electricity costs since the total energy consumption was highest for the energy-aware dispatching.

The results prove that an energy-aware dispatching can lead to lower average electricity costs for operational times.

5.2. Simulation study 2: Combination of high and volatile electricity prices

Within the second simulation study the impact of alternating electricity prices of 1 Cent/kWh, 50 Cent/kWh and 100 Cent/kWh were considered, each valid for 16 hours (one working day). Fig. 6 illustrates the results for this simulation study. Again, average electricity costs could be minimized by using an energy-aware dispatching strategy but this time also total electricity costs could be minimized. Due to the higher

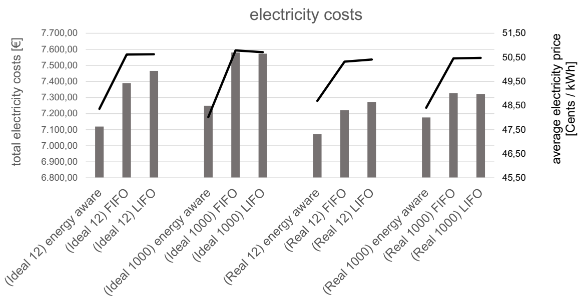

Fig. 6. Results of simulation study 2

electricity prices the energy-aware dispatching method proved to be more effective.

6. Conclusion and Outlook

The results of the two simulation studies show that a reduction of total electricity costs and average electricity costs based on an energy-aware dispatching algorithm is possible. The algorithm has shown to be more effective for higher and more volatile electricity prices and a higher WIP-level. Additionally, the algorithm works better for a heterogeneous product spectrum in terms of electricity-intensity of jobs. Further research should concentrate on combining methods for reducing electricity costs while considering other production logistic targets such as on-time delivery performance, capacity-utilization, and throughput-times simultaneously.

Additionally the investigation of a three-shift operation would be interesting. Possible savings in electricity costs have to be compared to the increasing labor costs caused by night-shifts surcharges.

Acknowledgements

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Appendix A. Assumptions of the simulation model

We present a summary of the assumptions made for the simulation model:

- Each machine is dedicated to one operation only (milling, drilling, turning, grinding and sinking).
- For milling and grinding parallel machines exist to balance the shop floor capacity and to limit bottle-necks.
- A job that is being processed has to be finished before another job can be set up. This means that no preemption is allowed.
- There are no two successive operations of a job on the same machine.
- Job operations have to be processed in a predefined order (work plan).
- Jobs that have not been processed in one week are transferred into the next.
- Other than machines there are no limiting factors such as material.
- The electricity price function is known to the end-customer on a day-ahead basis.
- Electricity intensity of the jobs is defined by their material (aluminum, steel, titanium) and machining times on each machine. The material defines the power consumption of the machines since e.g. aluminum can be machined with a higher feed-rate therefore consuming more electrical energy.

The simulation model considers a job shop with a total of 8 machines. The total time under investigation is five weeks of production. Statistics are drawn from the simulation model after it reaches a steady state (1 week).

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