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IT-based Architecture for Power Market Oriented Optimization at Multiple Levels in Production Processes

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Abstract

Given the increasingly volatile prices on the power markets, it becomes economically more and more important for companies to develop and realize flexible strategies for energy consumption. A steady adaption of production processes which considers current power prices can take place on several levels of the automation pyramid, where each level has its own characteristics and requirements. In this paper, we present an optimization architecture based on an IT-platform which meets the challenges of complex multilayered production processes. We introduce layer-specific optimization strategies as well as an associated information flow, which facilitates creating holistic and well-coordinated optimizations.

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1. Motivation

Over the last decades, awareness of climate change in society has grown [1] and affected the political perception of the issue, leading to the series of United Nations Climate Change Conferences. These, regarding their degree of decisiveness and binding character, arguably culminated in the Paris Climate Agreement in 2015, which set the basis for a sustainable global energy system [2]. As a result, many countries steadily install renewable energies, especially in the

electricity sector [3]. Consequently, the number of wind turbines and photovoltaic plants, which exhibit a weather-dependent and thus volatile power generation, has increased significantly [4, 5]. This leads to a radical change of the energy system, as the balance between electricity generation and consumption must be guaranteed at all times [6]. In the past, conventional power plants were primarily responsible for ensuring this equilibrium [7]. However, the expanding share of renewable energies will displace conventional power plants from the so-called merit order. The merit order refers to the

ranking of power plants and renewable energies, whereby the order sequence depends on the marginal costs of the electricity generators. Thus, in the future, other participants have to provide the flexibility which is needed to keep electricity generation and consumption in balance [8]. This development is called the flexibility gap [8]. To close this gap, flexibility on the demand side – in particular so-called Demand Response – plays a decisive role besides new flexibility opportunities on the generation side and flexibility through storage [8]. As the industrial sector is responsible for a large proportion of global electricity consumption, it is crucial for a successful transition that companies deploy their flexibilities to raise their power consumption when supply from renewable energies is high and vice versa [9].

For companies, however, realizing flexible operation of their production has to be incentivized economically. Due to the aforementioned expansion of renewable energies, prices on the power markets are increasingly volatile [10] and thus leverage opportunities for optimized electricity purchasing and arbitrage on power markets. Electricity products with short duration, such as 15-minute products on the EPEX SPOT market, allow better coverage of consumption and production. The EPEX SPOT market is a European power exchange for short-term power trading. As a result, companies can also market smaller flexibilities [11].

Typically, production processes and supply systems are flexible to some extent. Nevertheless, first and foremost, compliance with delivery obligations has the highest priority for companies. Moreover, there are further objectives such as optimal machine utilization, consideration of machine maintenance, or availability of personnel that must be taken into account. Digitization provides powerful tools for performing optimizations under the aforementioned constraints and automatic adjustment as well as execution of the corresponding processes. However, due to the complexity described above, it is in general not possible to comprehensively optimize all processes of a company in a single step. Therefore, this paper suggests a decomposition of the overall optimization in the context of energy flexibility and shows how suitable sub-optimizations can be accomplished on different levels, taking into account that they should not counteract each other. We introduce an IT-based architecture that constitutes the basis for such optimizations in production processes. More precisely, we present layer-specific characteristics and strategies of optimization as well as the resulting information flow.

2. State of the Art

To a great extent, modern industrial companies focus on automation within their production processes in order to gain competitive advantages. In doing so, the hierarchical system of an automation pyramid characterizes automation in modern-day factories [12]. It generally consists of strictly separated levels of automation. Due to the wide range of applications and scope of interpretation, many types of automation pyramids have been developed. Following VDI 5600 [13], possible levels of automation are enterprise control level, manufacturing control level, and manufacturing level. Their corresponding automation systems are enterprise-resource-planning (ERP) as

well as production planning and control system (PPS) for long-term planning of production orders, manufacturing execution system (MES) for manufacturing schedules, and machine-oriented optimization (MOO) for short-term control of manufacturing processes.

In the future, decentralized and level-overlapping structures of communication in both horizontal and vertical direction will replace central management and control and, therefore, eliminate the automation pyramid [14]. Still, the above-mentioned systems on their respective hierarchical levels will not disappear completely but rather be closely connected within a network structure [15].

Every level of the automation pyramid has individual characteristics and attributes which have to be considered in an optimization. They include specific planning horizons, temporal resolutions, and maximum acceptable runtimes [13]. Furthermore, the complexity of constraints, derived from the degree of aggregation and abstraction level [16], grows with increasing level. Table 1 assigns these relevant characteristics for optimization to their respective level of the automation pyramid.

Table 1. Characteristics of optimizations and their respective levels of the automation pyramid.

	Enterprise Control Level	Manufacturing Control Level	Manufacturing Level
Time horizon	Weeks to months	Hours to days	Minutes to hours
Temporal resolution	Hours to days	Seconds to minutes	Seconds to hours
Maximum acceptable runtime	Planning period	Real-time	Seconds to hours
Degree of abstraction	Factory / line / orders	Orders, resources	Individual plants

On the other hand, there are already various Demand response programs associated within the existing different power markets [17]. Table 2 describes the most relevant power markets with regard to their corresponding time horizons [18].

The table shows that individual energy-related flexibility measures with specific planning horizons should therefore target particular power markets. However, modern IT-based frameworks on specific levels of the automation pyramid, which can address such energy flexibility measures, do not consider this circumstance. For example, PPS may nowadays calculate overall energy costs based on static market prices and include them in the total production costs, but does not take dynamic shifts of production planning to specifically consider power market forecasts [19] into account. Likewise, while energy monitoring and controlling realized by MES is known

to improve energy usage and consumption [13], adaption of production order to price signals on the power markets is not considered yet.

Table 2. Suitable power markets for different time horizons.

Time horizon	Power Market
Seconds	Control power markets
Minutes	Continuous intraday spot markets, control power markets
Hours	Intraday markets
Days	Day-ahead markets
Weeks to months	Futures markets, bilateral contracts
Years	Long-term bilateral contracts

Based on the individual levels of the automation pyramid with their aforementioned layer-specific characteristics, an optimization architecture for energy flexibility must respect the opportunity of trading on different power markets. Additionally, a well-adjusted energy oriented optimization needs to consider all the levels of the automation pyramid and take into account that the sub-optimizations stemming from the decomposition of the holistic optimization should not counteract each other. Therefore, it must ensure a consistent information flow between the incorporated layers.

The following chapters describe a suitable IT-based architecture as well as an associated information flow which meets those requirements.

3. Architecture

The proposed architecture was developed in the course of the work on a large national project (*Synchronized and Energy-Adaptive Production Technology for the Flexible Adjustment of Manufacturing Processes to a Volatile Energy Supply* - SynErgie) investigating the flexibilization of the industrial sector in Germany. SynErgie comprises more than 100 partners from science as well as industry. As already indicated, numerous examples from the production processes of the participating companies have shown that in order to obtain a holistic solution for power market oriented optimization, decomposition of the overall optimization problem is necessary. Fig. 1. Fig. 1 aggregates Table 1 and Table 2 and therefore shows how the different levels of the automation pyramid are connected to the corresponding power markets.

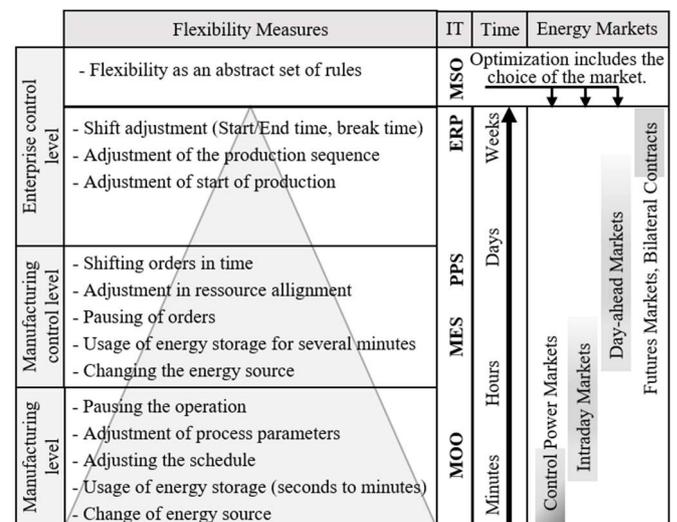
With respect to the mentioned temporal component, flexibility measures as well as the underlying systems can be distinguished, which is shown in the left part of the figure, inspired by the work of Rösch et al. [20]. While the degree of abstraction grows from the bottom to the top of the automation pyramid, the associated energy flexibility measures are targeting different specifications. For lower-level automation systems, especially machinery specific restrictions are important. On higher levels, energy-market oriented

optimizations must include logistic-related constraints. A market-side optimizer can further optimize on aggregated energy flexibility potentials, defined by the company as abstract energy packages. The underlying technical restrictions are no more explicitly considered, but already part of the abstract definition of flexibility measures.

Optimization on different levels or different systems on one level can be implemented dynamically, i.e. depending on the process under consideration, some of the optimization levels may be left out or split into further sub-optimizations. This offers the opportunity for adapting to various available interpretations of the automation pyramid as well as extending them with level-overlapping energy-oriented optimizations in horizontal and vertical direction. As a result, companies are therefore able to integrate their existing systems into the architecture and extend them based on the type and size of the individual loads.

The fact that only certain power markets are adequate for specific automation levels of a company can be illustrated by an application example from the SynErgie project. An industrial partner implemented an energy-oriented optimization for production planning which was conducted weekly, based on day-ahead prices. For this purpose, the production sequence was planned in such a way that expected energy costs were minimal. An ex post analysis with the actual day-ahead prices showed that the planning would not have changed significantly even with perfect information. The prediction error regarding electricity prices for a time horizon of one week on the day-ahead market was therefore small enough. However, if the forecast period goes far beyond one week, the error becomes too big to perform an optimization based on this prediction.

Furthermore, the prices on the day-ahead market are already known at noon of the previous day. Consequently, flexible adaption of production processes as reaction to volatile prices based on this market is no longer necessary from this moment on. Thus, this example shows how the temporal aspect of an optimization can interact with the appropriate market.



MSO = Market-side optimization, MOO = Machine-oriented optimization

Fig. 1. Allocation of power markets to corporate levels.

4. Information Flow

The communication in the described architecture is based on the conventional automation pyramid as pictured in Figure 2. This enables strategic decisions with the necessary foresight regarding the classic logistical as well as the energetic optimization goals, while keeping the complexity of the optimization problem low. Strategic decisions, which are made at a higher level, are passed on to lower levels as a fixed requirement. In the following, the necessary communication steps and the relevant information which must be exchanged between the different actors are described. Steps 1-7 are to be regarded as chronologically ordered. Each subsequent step must respect the restrictions resulting from the decisions made in the previous steps. Here, we assume that a company is able to procure electricity on all the relevant markets:

Step 1 - Trading at the derivatives market for electricity (level: PPS optimizer): In the first step, energy packages are procured, based on long-term production planning and expected developments on the futures markets. In this step, aspects such as energy efficiency can be incorporated into the optimization process, for example by fully utilizing batch processes or by taking into account environmental drivers that affect energy consumption. In addition to energy efficiency considerations, long-term fluctuations of electricity prices, e.g. due to seasonal characteristics of supply and demand, can play a central role for the overall energy costs. It might turn out that it can make sense to postpone energy-intensive orders to times when electricity prices are lower, even if this counteracts energy efficiency. One should note that also seemingly contradictory objectives, such as energy efficiency and low-cost energy procurement, can be represented in a single objective function.

Step 2 - Production planning (communication between ERP/PPS optimizer and MES optimizer): The production planning optimizer forwards the production orders to the MES-system. The consideration of energy costs in the objective function of the production planning optimization is based on the energy data provided in step 9 of previous optimization runs.

Step 3 - Trading at the day-ahead market (level: MES optimizer): The MES optimizer uses the previously defined specifications and price forecasts for the day-ahead market to calculate the optimal machine occupancy, which is then sent to the individual systems. The specifications of higher-level planning levels and past trading decisions of step 1 must always be adhered to. In addition to the energy efficiency of orders and the energy procurement costs, the energy flexibility of individual orders should also be taken into account. In this context, orders with a particularly large short-term flexibility potential should be placed in times of strong short-term price fluctuations on an adequate electricity market because then, their energy flexibility has the greatest value. This can be estimated by taking into account the average flexibility potential of an order and the average price fluctuation on the electricity exchange from historical data

Step 4 - Machine assignment (communication between MES optimizer and machine-oriented optimizer): The MES system forwards the production orders to the machines. Here, too, the energy consumption of individual machines is taken into account in the MES optimization via the information transferred in step 8 of previous optimization runs.

Step 5 - Trading at the day-ahead market (level: machine-oriented optimizer): In turn, the machine-oriented optimizer can use flexibility potentials at plant level to adjust operation according to price forecasts for the day-ahead market. At this level, storage systems for useful energies such

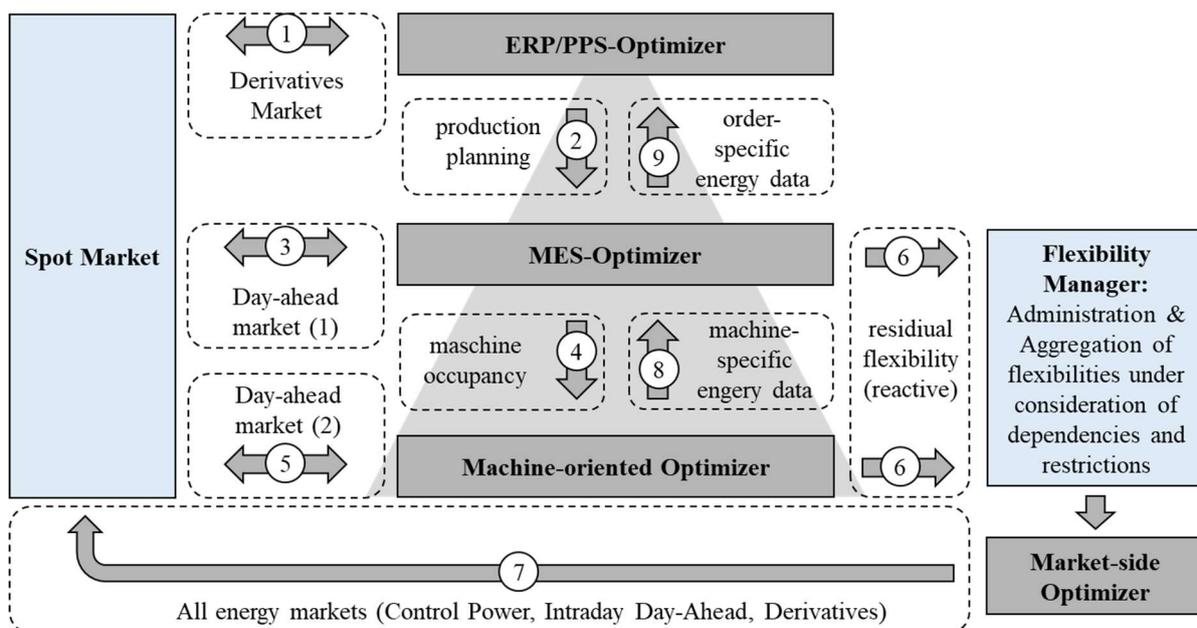


Fig. 2. Information Flow within the IT-Architecture.

as heat and cold or product storage systems, which are not used with full capacity can play an important role. Recall that at this stage, the product sequence has already been scheduled by the MES system in step 4 and cannot be changed at machine level anymore.

Step 6 - Residual flexibility (communication between MES optimizer / machine-oriented optimizer and flexibility manager): During operation, the machine-related flexibility potentials can be specified in the form of retrievable energy packages. A possible schedule has already been determined by the machine-oriented optimizer in step 4. However, since short-term fluctuations on the electricity market or unforeseeable events at machine level can occur during the day e.g. due to machine downtime, there is an additional need for short-term flexibility. In this context, flexibility potentials are defined as the opportunity to deviate from the load profile generated in machine-oriented optimization. These are the "residual flexibilities" which are passed on to the flexibility manager.

Step 7 - Trading at the intraday market (level: market-side optimizer): The flexibility manager takes dependencies between the individual flexibilities and other restrictions into account. For instance, changing an order at machine level can also lead to a change in the useful energy requirements and thus influence the flexibilities which can be used there. At this point, it can make sense to aggregate smaller flexibilities into a few larger ones in order to simplify the complexity of the flexibility conglomerate. The remaining flexibilities are then used for short instance optimization on the spot market.

Step 8 - Recirculation of machine-specific energy data: In order to enable optimization of machine utilization in terms of energy efficiency and energy flexibility, information on the energy requirements associated with the performance of a particular process step for a corresponding product is required. After a process step has been performed, the respective data is forwarded from the machine to the MES optimizer, where it is available for future optimizations.

Step 9 - Recirculation of order-specific energy data: For an optimization of long-term production planning, energy-relevant data which is linked to the execution of a complete order is required. This data is then collected at MES level and finally forwarded to the PPS optimizer.

Based on the presented information flow, energy-oriented optimization on all levels of the automation pyramid is possible without violating constraints located at a respective higher level. Optimization on different levels can target different power markets and a market side optimizer can further optimize residual aggregated energy flexibility potentials. Finally, each automation level can use information on the energy data provided by the level underneath for future optimization.

5. Conclusion and Outlook

Our IT-based architecture for energy-oriented optimization of production processes allows the decomposition of the overall optimization problem into smaller packages. We demonstrate that a well-coordinated optimization over all layers of the automation pyramid can be achieved. The

associated information flow guarantees that the sub-optimizations do not interfere with the input requirements specified on their respective higher levels.

In the course of the SynErgie project, the IT-based architecture will be implemented, as described in [21]. Optimization services for multiple levels in production processes can be incorporated dynamically to meet the particular requirements of individual companies. In future works, the IT-based architecture will be connected to companies to enable a flexible production in regard of power market oriented optimization.

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