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Integrating Energy Flexibility in Production Planning and Control - An Energy Flexibility Data Model-Based Approach

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Abstract

Production companies face the challenge of reducing energy costs and carbon emissions while achieving the logistical objectives at the same time. Active management of electricity demand, also known as Demand Side Management (DSM) or Energy Flexibility (EF), has been recognized as an effective approach to minimize energy procurement costs for example by reducing peak loads. Additionally, it helps to integrate (self-generated, volatile) renewable energies to reduce carbon emissions and has the ability to stabilize the power grid, if the incentives are set appropriately. Although production companies possess great potential for EF, implementation is not yet common. Approaches to practical implementation for integrating energy flexibility into production planning and control (PPC) to dynamically adapt the consumption to the electricity supply are scarce to non-existent due to the high complexity of such approaches. Therefore, this paper presents an approach to integrate EF into PPC. Based on the energy-oriented PPC, the approach identifies and models EF of processes in a generic energy flexibility data model (EFDM) which is subsequently integrated in the energy-oriented production plan and further optimised on the market side. An application-oriented use case in the chemical industry is presented to evaluate the approach. The implementation of the approach shows that EF can have a variety of characteristics in production systems and a clear, structured, and applicable method can help companies to an automated EF. Finally, based on the results of the use case, it is recommended to introduce EF in production companies stepwise by extending existing planning and scheduling systems with the presented approach to achieve a realization of flexibility measures and a reduction of energy costs.

Keywords

Demand Side Management (DSM); Energy Flexibility (EF); Production Planning and Control (PPC); Energy-Flexible PPC; Energy Flexibility Data Model (EFDM)

1. Introduction

In order to achieve the goals of the international climate agreement, the German government has decided to phase out coal and nuclear power generation [1,2]. Meanwhile, the share of electricity generation from wind and solar energy has to increase to achieve greenhouse gas neutrality of the electricity generated and

consumed in Germany by 2050 [3]. As power generation from renewable energy sources such as wind and solar energy is limited in its ability to adjust to current energy demand, the associated fluctuating power generation poses major challenges for power grids and a significant increase in electricity price volatility is to be expected [5]. One possible solution to address these challenges is the increase in industrial Demand Side Management (DSM) also known as energy flexibility (EF). The concept of the energy-flexible factory takes advantage of being able to adapt quickly to price changes in the energy or balancing power markets with very little financial effort, thus derive an economic benefit [4,5]. Production planning and control (PPC) plays a central role in the context of the energy-flexible factory [6], as production is the main power consumer of a factory [7]. A large number of publications have dealt with energy-oriented PPC, in which production is optimised according to electricity price forecasts with regard to minimum electricity costs [8]. The PPC includes production planning, which plans the operations in long to medium term, and production control, which releases and controls the orders based on the previous planning [9]. Due to unavoidable disturbances such as machine breakdowns, a complete realization of the production plan is almost impossible. Therefore, the task of production control is to implement the production plan in the best possible way. The focus of PPC is to achieve logistical objectives, such as the timely completion of customer orders or machine capacity utilization [9]. With increasing awareness of sustainable aspects and pressure to optimise costs, additional objectives such as minimizing electricity costs or avoiding peak loads have been considered in PPC under the term energy-oriented PPC in recent years [10]. The approaches used to the present are either very rigid because they are based on forecasts and thus cannot react flexibly to short-term changes in different energy markets or are very complex.

EF must be considered without jeopardizing logistical objectives. In order to be able to react to changing energy prices at a later point in time and to be able to use EF, an approach is pursued in which EF measures are already taken into account in the planning phase, so that they can be taken when required. The approach thus offers two advantages. First, a company can adapt to a changing energy market without having to make unplanned changes to its production schedule. On the other hand, companies without energy-oriented planning can use this simple approach to at least consider EF measures and thus participate in the market. In doing so, the approach can be integrated into existing PPC methods, as they can be scheduled as additional orders, so to speak. Furthermore, by using an energy flexibility data model (EFDM), a description of the flexibility is used that is also suitable for marketing the flexibility, thus creating a continuous flow of information from production to the energy market. As publications usually stem from production or energy related domains, the interface between these domains has been insufficiently considered so far. In addition to the possibility of a reactive influence in the production control, due to market signals, this procedure also enables trading with EF for example via Intraday, Day-Ahead or the balance markets. Our approach is, therefore, to be understood explicitly as an extension of existing PPC solutions.

In addition to reviewing previous work and describing our own methodological concept, a use case from the German chemical industry is considered in order to validate and exemplify the application of the approach.

2. State of the Art

There is a variety of research in the domain of energy-oriented PPC and ongoing digitalization in manufacturing companies [11–16]. These works are usually based on electricity price forecasts with the goal of minimizing electricity cost due to production activities. Heinzl [11] and Wang et al. [16], as representatives for considering energy costs in production planning, use optimisation methods to combine the logistic and energy objectives. Süße et al. [15] additionally consider a battery storage system to account for the energy demand of production by means of a suitable battery charging management system. Even though the electricity load profile is altered in [15], energy flexibilities other than batteries are not yet considered.

In production control, they may react to short-term changes in electricity prices or due to changes in expected power consumption. Or they may react when the actual electricity price deviates significantly from the electricity price forecast [17,14]. In Schulz et al. [18] a closed-loop control was developed which is based on an algorithm with several data inputs such as production process data, environmental and energy data. The goal was the minimization of residual loads in the factory, but market interactions were not taken into account. Summarizing, none of the previous publications enable for flexibility trading.

Previous approaches do not take the information requirements of energy markets into account because, as mentioned, they treat energy prices as a given input variable. However, a continuous view from production to energy market requires the possibility of a uniform and simple description of energy flexibility that is still accurate. Different energy sources, dependencies between the production infrastructure and the supply technology, and restrictions due to logistical objectives as well as the involvement of different IT systems are just some of the general conditions that have to be considered when dealing with EF in production [19]. An energy flexibility model which addresses all these points is published by Schott et al. [20]. EFDM provides the framework for generically describing flexibilities and flexibility measures using key figures and technical parameters. A flexibility describes the potential possibilities of an energy flexible system to vary its performance compared to the reference operation. EFDM uses the classes *flexible load*, *dependency*, *storage*, and *flexible load measure*. The degrees of freedom of the EF – respective the flexibility potential – are defined by the characteristics of the key figures of the mentioned classes. A flexible load models a technical system or the interaction of different technical systems that have the potential to evoke a change in energetic performance. The *dependency class* is used to model constraints and dependencies for the interaction of multiple flexible loads. The use of a flexible load can, for example, imply or exclude the use of another flexible load. A storage system is a technical system or the interaction of different technical systems that have the potential to store energy. Basically, in addition to direct energy storage systems, such as heat or battery storages, inherent storages are possible [21]. Especially in complex production systems, modelling dependencies is particularly important to be able to model flexibility realistically and to limit the flexibility space to the variants that can actually be implemented. The class *flexible load measure* describes a concrete power change of the system within its flexibility space defined by the flexible loads, dependencies, and storages. However, the described model has not yet been used in PPS applications.

Consequently, there is no procedure to potentially plan deployments of energy flexibilities without knowing the actual implementation in advance and at the same time not jeopardizing the achievement of logistical objectives. In addition, there is a lack of a holistic process that meaningfully encompasses the consideration of EF from machine to market and back again. Based on the aforementioned points, the aim of this paper is to present a generic process for the machine-, plant- and market-independent consideration of EF in PPC which considers EF in production planning and provides preconceived options for production control.

3. Methodological approach

With the help of the EFDM, we are developing an approach that allows the integration of EF into existing PPC systems, thus providing an easy-to-use solution for practical applications. Our approach can be divided into five steps as illustrated in Figure 1.

In a first initial step, possible flexibilities are identified and characterized in a flexibility audit before subsequently being modelled in an EFDM. For the identification and characterization of flexibilities, the methodology proposed by Tristan et al. [22] can be used, which examines both production systems directly performing the production tasks and the supply systems performing supporting tasks or tasks necessary for the operation of these production systems. If changes are made to the production infrastructure, processes or product portfolio, a renewed flexibility audit is recommended to leverage the highest possible flexibility potential. After the initial flexibility audit, steps two to five address the operational PPC.

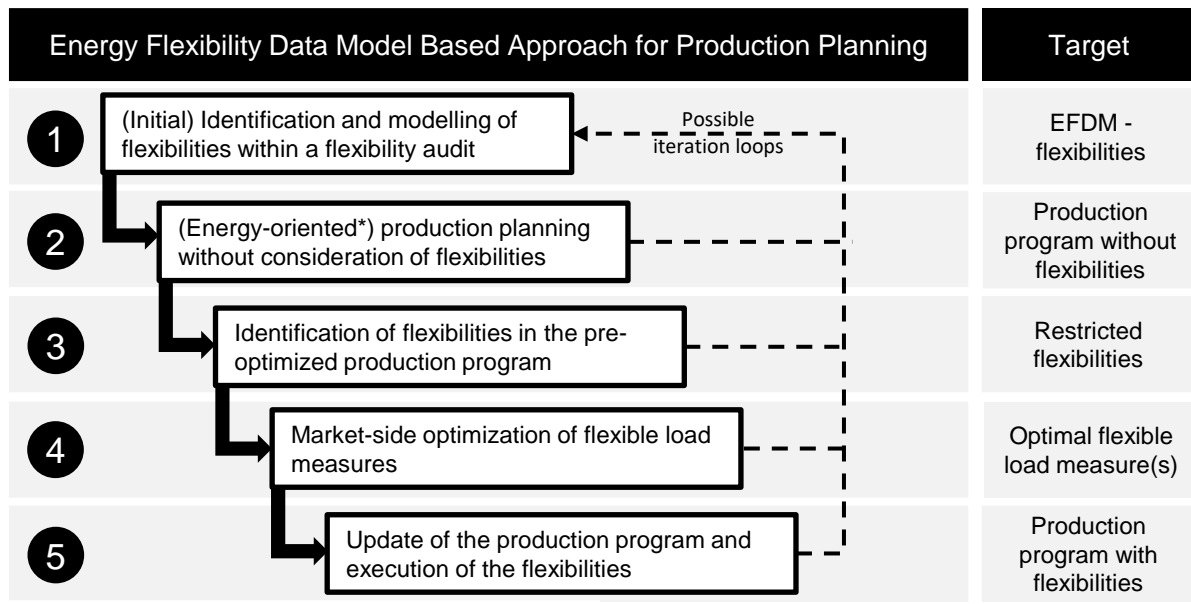


Figure 1: Five-step approach for flexible production planning with an EFDM

In step two, energy-oriented PPC is carried out using conventional software tools without considering the flexibilities previously modelled. An optimisation of logistic objective variables under consideration of a price time series (typically day-ahead prices) for energy-oriented production planning towards a more efficient production is not mandatory for our approach. Conventional PPC software that cannot integrate price time series do not need to be replaced. Our approach is therefore to be understood explicitly as an extension of existing PPC solutions. The result of the second step is consequently a production plan without flexibilities, representing today's standard in advanced production planning systems.

In the third step, the flexibilities modelled in the EFDM are concretized into restricted flexibilities based on the previously created production plan. Restricted flexibilities can only be used and scheduled at positions with free production capacity in the previously created production plan. This procedure ensures that the logistical objectives considered in step two are not violated. In addition, the flexibility space created by the flexibilities modelled in the EFDM is reduced by the restrictions and, as a result, the optimisation carried out in the next step is simplified and more performant.

In the fourth step, the identified restricted flexibilities are optimised regarding the market side. In contrast to energy-oriented production planning, which usually only considers a single price time series of one energy carrier, the nature of flexibilities offers a significantly broader spectrum of marketing options and an associated higher revenue. Thus, in the market-side optimisation the flexible load measures with the highest expected revenues or savings on different possible energy or capacity markets are identified. Here, typically the energy-only markets (day-ahead and intraday) and balancing power markets are integrated in the optimisation [23]. Note here, that the EFDM contains costs of each flexibility (e.g. higher wear of machines or opportunity costs) and allows us to evaluate within the optimisation if the use of flexibilities is advantageous from an economic perspective. Individual costs of flexibilities can be modelled for example with the help of a cost-model initially introduced by Rösch et al. [24] as the quantification of costs for flexibilities in a DSM context might be a challenging task. In addition, the effect of using flexibilities on a company's load profile can also be taken into account, as high load peaks negatively influence the economics by increasing grid charges. Note here, that after the market-side optimisation of flexibilities, marketing steps must be initiated in parallel, which, however, are not the focus of this work. These steps enable the combination of external marketing opportunities and the use of flexibilities for peak shaving. After

identifying the optimal flexible load measures to be allocated, the previous production plan from step two can be updated and adjusted with the flexible load measures and associated production tasks determined before the production plan is executed. In the period between the generation of the production plan and its execution, changes in energy and balancing power markets can be monitored and, if necessary, flexible load measures that have already been scheduled can be drawn without major impact on the production plan.

With step five we receive a production plan with flexibilities considered – thus, a more economic production plan. Further iterative loops to dynamically react on machine failures or changes in orders are proposed and applicable for each step allowing for rescheduled production plan.

4. Conceptual application

We demonstrate our five-step approach for energy flexible PPC by conceptually applying it to a use case from a German company in the graphite production. We address both production planning and production control with machine scheduling at the intersection of the two disciplines to optimise the use of EF. Graphitization is the most energy-intensive and last chemical production step in the fabrication of graphite products. The amorphous carbon bodies are heated up to the required temperature of around 2,600 to 3,000°C by resistance heating requiring several megawatts of electrical power [25]. In our case, eight identical furnaces are available for this process step. The furnaces are fed with electrical energy by two transformers, which are moved towards and connected with the specific furnace (see Figure 2 (b)), allowing a maximum of two of them to be operated simultaneously. The heating process is characterized by material specific heating curves and can be divided into two phases (see Figure 2 (a)). In phase one the material is preheated to ensure a constant temperature distribution. After a holding time the target temperature is reached in phase two. Note, one of the transformers has only limited power and therefore cannot cover the entire graphitization process. This transformer can only be used for preheating and thus, its use can partially parallelize two heating processes. For a more detailed process description we refer to Bank et al. [26].

By conceptually applying our approach, in the first step, possible flexibilities have been identified and modelled in an EFDM. The flexibilities identified in the use case can be classified as measures for shifting individual orders and measures for customizing heating curves and thus adapting individual graphitizing processes. For the former, due to the fact that the graphitization process includes a cooling phase, in which the material remains in the furnace, capacities for shifting start times of individual orders are offered in production planning. For the latter, further flexibilities in the form of an adaption of the heating curves are feasible. These include temporary shutdowns as well as load reductions and increases. The flexibilities were modelled in an EFDM and two of them are hereafter used to demonstrate our approach.

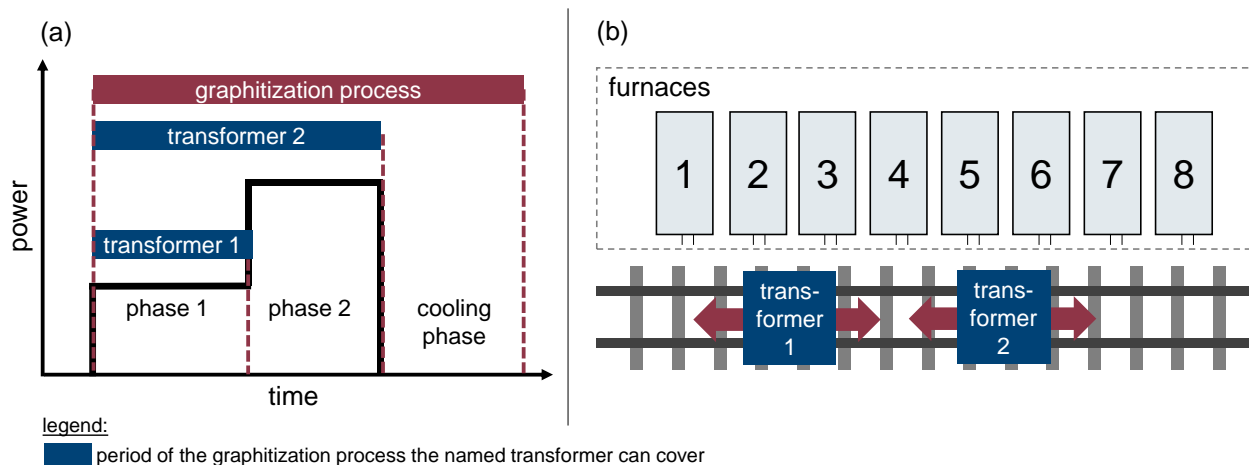


Figure 2: Load curve of the graphitization process (a), layout of the use case (b)

The flexibility “load reduction/shedding by 100% in phase one (flexibility 1 (F1))” can be held for a duration of up to one hour (see Table 1). F1 is coupled with another compensatory flexibility (F2), where (heating) phase two is extended to the extent that compensates for the energy consumption previously missed by F1, thus ensuring that the required total energy demand is met. The flexibilities are not restricted in their validity, i.e. the period in which they can be used. Table 1 shows some additional key figures from the EFDm for the identified flexibilities F1 and F2 exemplarily.

Table 1: Key figures of the identified flexibilities (based on Schott et al. [20])

ID	Description	F1	F2
validity T_G	period in which the flexibility is available	[00:00, 24:00]	[00:00, 24:00]
reaction duration t_D	time between the command to activate until the start of the change in power	{900s}	{900s}
power states P	power levels during holding periods ((+) increase in power consumption, (-) decrease in power consumption)	{-3 MW}	{+6 MW}
holding duration t_H	length of the period in which the flexible load is held in its power state	{[15min, 60min]}	$\frac{\int_{i=0}^T p_{F1,i} di}{p_{F2,i}}$
dependencies	impact of an activation of a measure on another measure	EFM1 implies EFM2	EFM2 implies EFM1

In step two, energy-oriented production planning is carried out. Therefore, the identified flexibilities are used as degrees of freedom in the optimisation of logistic objective variables under consideration of a day-ahead electricity price prognosis. For this purpose, energy-oriented machine scheduling was implemented in an optimisation tool [26]. Six to seven orders are scheduled for a planning period of seven days in compliance with logistical objectives. The result of the second step is an energy-oriented production plan where orders are planned according to the energy cost forecast without the possibility of additional flexibilities (see Figure 3 (top)).

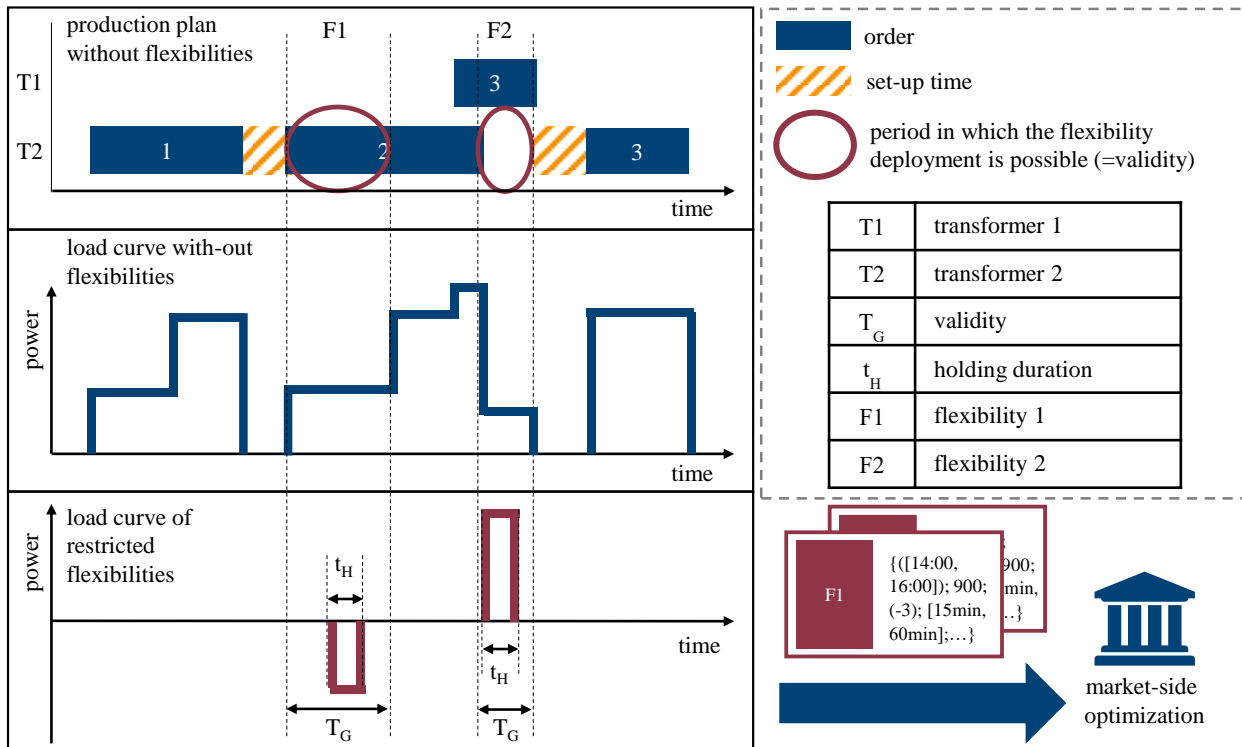


Figure 3: Identification of (restricted) flexibilities in the pre-optimised production plan

In the third step, possible flexibilities in the previously created energy-oriented production plan are identified. For this purpose, the EFDm flexibilities modelled in step one are restricted based on the

constraints of the production plan. To ensure that logistical objectives are not affected, flexibilities can only be scheduled in times with free capacity. Key figures of the EFDM such as the holding duration and validity are specified by the restrictions of the production plan. Figure 3 shows the determined production plan (top), its corresponding load curve (middle), and two exemplary flexibilities that can be scheduled based on the available capacities (bottom). The free capacity following order two allows the scheduling of the flexibilities F1 and F2. The holding period of the flexibility spaces is not yet restricted in this step. However, the validity of F1 is restricted to the duration of phase 1 of the heating curve and a specific start time is defined for F2 being the end time of order two.

In the fourth step, the identified restricted flexibilities can be optimised within their remaining degrees of freedom on the market side towards the highest expected revenues of various possible energy or balancing power markets resulting in optimal flexible load measures (FLM) with specific holding durations and starting times. After market side optimisation the production plan from step two can be updated and adjusted with the flexible load measures receiving a production plan with flexibilities considered (see Figure 4). Further iterative loops with dynamically changing planning horizons are applicable. In addition to marketing the (restricted) flexibilities, the pre-planned flexibility options can then also be used in response to the short-term state of production (e.g. in reaction to machine failures) in production control.

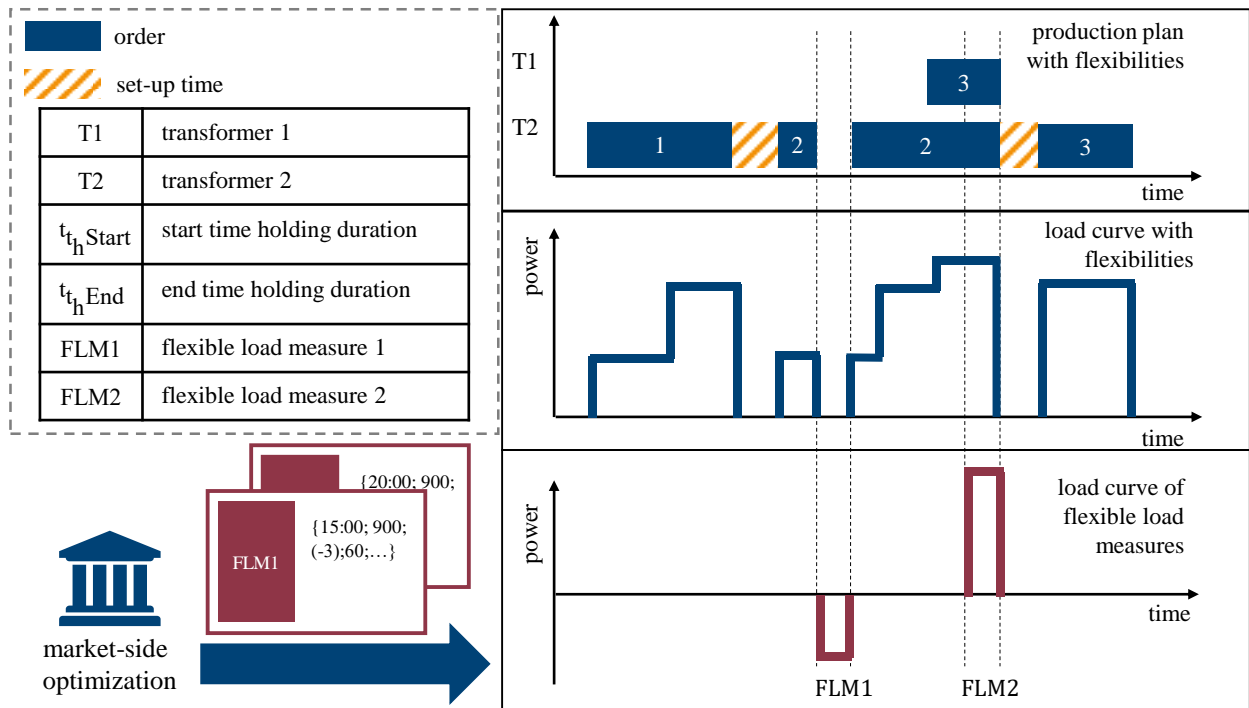


Figure 4: Production plan with flexibilities post market side optimisation

5. Discussion and Outlook

We have developed a five-step approach that considers EF in production planning without compromising the logistical objectives of production. Despite the consideration of EF in planning, only the production control currently decides whether a particular marketing option is taken, based on the corresponding short-term state of production as well as the energy and capacity markets. Thus, the approach closes the existing gap between energy-oriented PPC and flexibility trading as it is described as a building block of a future and sustainable energy system. However, the use case also indicates a limiting factor for practice since flexibility can only be scheduled if free capacities are available. A further monetary advantage can be achieved in addition to the energy-oriented PPC or, in the case of unforeseen events, it is possible to react accordingly and to fall back on flexibility measures that have already been prepared.

The preparation of possible flexibilities closes the gap between production planning and production control which arises in energy-oriented PPC, since different markets and marketing opportunities have different lead times due to individual market designs [27]. Furthermore, due to short-term tradable flexibilities and associated price volatility, deterministic planning of flexibilities in advance is not always possible. In addition, the use of a defined description of EF in the PPC closes the gap between production and energy management because it creates a unified language that can describe flexibility end-to-end from the machine to the energy and capacity markets. To make the procedure more applicable in practice, further automation is necessary. For this purpose, the restricted flexibilities in step three should be automatically generated based on one-time modelled EFDM-flexibilities (step one) and the specific production plan without flexibilities (step two). It is also conceivable to incorporate the revenues to be expected as a result of the flexibility as anticipated values in the planning and to carry out a stochastic optimisation in order to design freedoms in the production plan not only on the basis of the current price curve.

Despite these limitations, with this study we demonstrated a viable approach for integrating EF into existing PPCs, helping to optimise energy costs. Our method is particularly suitable due to the step-by-step extension of existing methods and approaches and can also be integrated into approaches that do not yet consider energy as a target variable. In any case, by using the described approach, marketing can take place on different markets, so that a high monetary potential can be achieved in the use of energy flexibility.

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