Energy-Sensitive Production Control in Mixed Model Manufacturing Processes

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Abstract

Although energy efficient production is a topic of high interest both in industrial practice and research, the need for a comprehensive analysis of energy considerations in production control of manufacturing processes at manufacturing control level has been largely ignored until now. This holds true especially for mixed-model production. The paper at hand discusses selected production control tasks, methods, processes and strategies for this production type and aims at identifying the extent to which energy features can be implemented into use, new and existing approaches and controlling tools. Based on first research activities, basic cases of energy-sensitive production control have been derived.

Keywords:

Production control; Energy efficiency; Manufacturing execution system; Order scheduling

1 INTRODUCTION

Energy efficiency is defined in DIN EN 16001 as "ratio between the result of activities, goods or services of an organization and the energy consumed" [1]; in other words, a ratio between benefits and outlays. To stay competitive, manufacturers have to increase energy efficiency both for their products (i.e. through lightweight design) and for their processes. The latter can be achieved by implementing innovative technologies, tailored process controls or adapted interlinking and the automation of processes. With reference to the energy balance of a plant there are three basic fields of action for increasing energy efficiency (see figure 1).

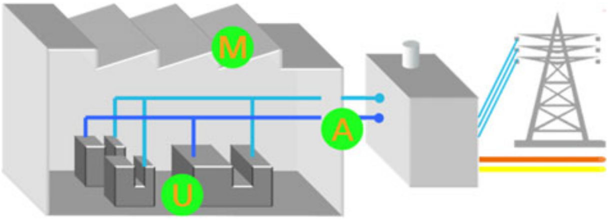

Figure 1: Research foci for energy efficient plants.

Allocation (A) handles the supply, feeding and transformation of energies required for the operation of the plant and the use of local and central energy storage systems. Increasing the efficiency of energy utilization (U) requires to deal with manufacturing technology as well as with production and logistic systems concerning drives, controls, mass reduction or decline of friction and heat losses. Efficiency potentials of energy management (M) should not be neglected. In addition to an energy-conscious predictive planning of the products, processes and resources, substantial improvements of energy efficiency can be made by an energy-sensitive control of material flows, machines and peripheral systems of a production system. In production control, visualization plays an important role.

2 SOFTWARE SOLUTIONS FOR ENERGY-SENSITIVE PRODUCTION CONTROL

As highlighted in section 1, business goals to reduce energy consumption and energy cost have to be taken into account at all levels of an organization. The management level of a factory can be divided into the enterprise control level, the manufacturing control level and, finally, the manufacturing level (see figure 2).

An examination of the software solutions used on the one hand for production planning and control and on the other hand for energy management at those levels paints the following picture:

At manufacturing level and, beyond the area of production, for building service equipment and other peripheral systems, energy data loggers (EDL) acquire performance and consumption data. The acquisition of these data is an indispensable prerequisite for an active energy management, but does not provide a targeted manipulation of energy demand by itself. Production management and control tasks are fulfilled by PLC and SCADA systems, which usually are unaware of aspects related to energy efficiency.

At enterprise control level, energy consumption data are cumulated in energy management systems (EMS) and allocated to accounting departments and specific cost carriers. This helps to generate a clear picture of power flows, sources of energy and consumption, especially for energy procurement purposes. Enterprise resource planning (ERP) software solutions at this level don't provide specific assistance in pursuing energy-related enterprise goals.

At the middle level, the manufacturing control level, load management systems (LMS) are used occasionally in order to profit from lower capacity costs by cutting peak energy demands. According to fixed supply profiles based on an hourly or quarter-hourly plan, these systems monitor energy usage and the adherence to limit values. If there is a danger of exceeding the connected load agreed upon with the energy supplier, LMS can actively shut-down energy consuming units, which are uncritical for current production processes. Load management systems are not supposed do influence the value-adding processes directly.

Manufacturing execution systems (MES) are used to control the material flows in the shop floor. Their functional scopes and features derive from traditional goals of manufacturing control [2] and comprise according to VDI 5600 [3] the following tasks:

- Detailed scheduling and process control,
- Performance analysis [4],
- Equipment, material and personnel management,
- Data acquisition and information management [5] and
- Quality management.

Within this, all tasks and features of an MES have to fulfill specific customer demands or requirements arising from factual circumstances like products, industry or production strategy. As an example, MES for mixed-model production lines have to provide functions like (re-) sequencing or merging and splitting. Enhanced features can be implemented as a part of an individual solution or a specific industry solution. Furthermore, it is common practice to provide those functions as dedicated software, which is able to communicate and operate with a specific or different MES to enhance or replace its or their functionalities.

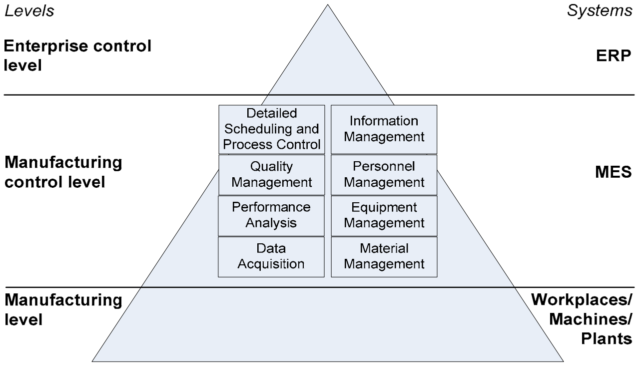

Figure 2: MES placement and tasks, taken from VDI5600. [3]

The “eniMES” concept presented in the following section can act as such an extension of a conventional MES in order to provide energy sensitive functions. A further intention is to provide a generic framework for software based energy-sensitive control solutions.

3 FRAMEWORK AND BASIC CASES OF ENERGY-SENSITIVE PRODUCTION CONTROL

In eniMES, three main modules (eniPLAN, eniCONTROL, eniVIEW) act for decision making and support. These modules are linked with each other and with further information sources by a fourth module (eniLINK), based on a semantic-web-based approach presented by WENZEL at LCE2011 [6]. All basic cases of energy-sensitive production control, as discussed in sections 3.1 to 3.3, are to be realized by eniPLAN and eniCONTROL (see figure 3).

Main functionalities of eniPLAN are an energy-sensitive order release according energy availability and costs at different times of a day/shift and the fine-tuning of station-specific shift plans to optimize operating times and modes. While the first function (see section 3.1) is only triggered at the beginning of each shift, station-specific shift plans (see section 3.2) can be alternated on-the-fly, taking the actual material flow and state of production into account.

The software module eniCONTROL (see section 3.3) realizes the on-demand operation of all manufacturing and peripheral systems like machinery, conveyors, power supplies, compressors, pumps, lightings, etc. by a model-based approach. Energy-saving operation conditions are determined and switched according to the material flow and the dependencies between above mentioned systems.

3.1 Energy-Sensitive Order Scheduling

Mixed-model Production is a production principle in which different products or product variants are custom manufactured in a single production system. This places high demands on the production planning and is therefore an extensive field of scientific research. However, optimization in terms of the energy consumption has rarely been the focus. The consideration of energy constraints in this planning can be taken at the levels

- order scheduling,
- station release,
- manufacturing equipment control.

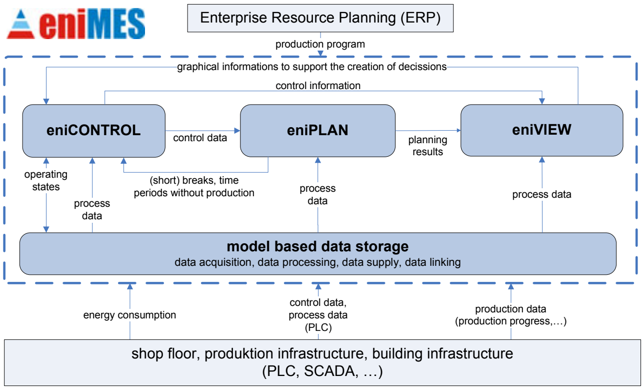

Figure 3: Framework eniMES.

The goal of order scheduling for a mixed-model production is a sorted list of selected jobs to be manufactured in an observation period. Out of a pool of received orders those are selected, whose production in the observation period serves best the company's business goals. So far criteria such as throughput times, equipment utilization and delivery reliability have been weighed against each other. If energy constraints should be included in this selection process, they must be formulated in a similar way as criteria.

It is assumed that the resource-scarce production is characterized by the following peculiarities:

1. Energy is not at any time unlimited available to the production system. The obtainable energy has a fluctuating hard limit over time.
2. Changing expenditures of energy production are expressed in fluctuations in energy prices, even in the short term.
3. The installed infrastructure is tightly dimensioned, so that it works more often with optimal efficiency. The operational safety is not given for any arbitrary procedure of operation.

Simply using energy-saving equipment is not sufficient in order to produce optimally in such an environment. Rather, the optimal procedures have to be determined continuously. In the following some of the necessary decision-making processes are briefly sketched.

The first point can be represented in the simplest way by a nominal scale with categories of Low-Energy-Supply (LES) and High-Energy-Supply (HES) conditions. These categories are initially assigned to the products and product variants according to the manufacturing equipment their production processes need. The observation period is divided into reasonable time intervals, which are rated according to their energy supply situation as LES- or HES-interval. As length of the intervals one can think of a single shift, a whole working day or a week of production. For example, it is conceivable that the production system draws a portion of its energy very efficiently from local sources, such as wind turbines or small cogeneration plants. Their deliveries cannot be controlled and only roughly be predicted. By considering the resulting LES and HES in order planning, the need of energy buffers is reduced and a more efficient production becomes possible.

The second point requires an assessment of the financial risks of different order scheduling. For deadlines and throughput times the measurable quantities are delay penalties, storage costs and capital commitment. PECHMANN [7] discusses the idea of using energy forecast for better negotiation positions with power suppliers. Though, the future price trend for energy is currently mapped on so called futures contracts and thus already made tradable. On the one hand, prices of these contracts can be considered as cost projections in the order scheduling, on the other hand acquiring them can hedge planning commitments with intended product prices. In both cases, production flexibility at free disposal will be transformed in higher revenues by appropriate order scheduling. So far as it is possible, energy intensive tasks would be carried out on times with low costs. Thus, energy costs can be optimized in conjunction with already established business evaluation parameters.

The last point generates restrictions that must be considered in the formation of sequences. Today, such restrictions already exist in assembly lines, where product variants with large work efforts may not directly follow each other in order not to overload workers. Narrow sized infrastructure components, such as air compressors and transformers, act similarly limiting as the capacity of available workers. For example, a restriction can be formulated, that orders with high compressed air requirements may not follow each other directly, so that compressed air buffers get a chance to replenish. Appropriate coordination of the sequences of several production lines could prevent the simultaneous use of highly energy-intensive equipment and thus ensure that transformers are not overloaded.

An agent – be it human or a software component like eniPLAN – wanting to perform an order scheduling for the upcoming shift would have to go through the following process. At first necessary information is gathered, which has to include at least:

- a pool with orders classified due to their energy demands,
- the knowledge whether it is a HES- or LES-shift,
- the cost of energy supply over the next few hours and
- restrictions on the sequence of formation.

Supposed it is a LES-shift, than exclusively LES-orders get selected using known scheduling methods like slack-time-regime or FIFO. In a second step these orders get sorted, so that large amounts of needed energy will be placed inversely to high energy costs on the time scale. Temporal flexible peripheral processes, like HVAC or charging of manufacturing equipment batteries are timed inversely to high energy costs in a similar way. Lastly the sequence of orders is adjusted so that no infrastructure constraints are violated. A resulting process schedule is depicted schematically in figure 4.

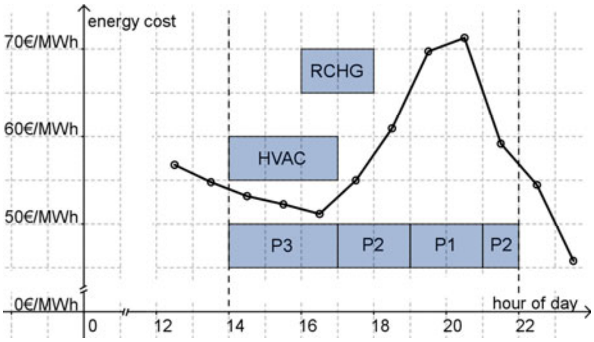

Figure 4: Energy costs of electricity (ELIX data from 2011-09-14) overlayed with schematic process schedule.

P1 to P3 are LES-products, but have ascending energy demands. The shift takes place from 14:00 to 22:00. The energy cost curve indicates a typical trend on a normal workday at an energy stock exchange. As can be seen, HVAC is suspended during high cost hours. A more detailed approach to optimization of HVAC-control is given in JUNGE [8]. Recharging of equipment is postponed as long as possible to still achieve a low price but also last the whole shift length. The orders are sequenced in a way so that the smallest possible amount of energy is consumed during cost peak time while ensuring a continuous workload. This production system would draw most of the needed energy during the hour with the lowest energy costs.

3.2 Energy-Sensitive Control of Material Flow

In the scope of consumption structure analysis, value-adding (operational) and non value-adding operation phases (e.g., ready for production or standby) can be identified for production resources through a priority analysis commensurate to their energy consumption. A more detailed way of describing participating energy consuming components of production resources is provided in DIETMAIR [9]. From an economical perspective, the energy demand during working phases is justified by its value-adding character. So production control should seek to reduce energy demand and energy peaks especially in non-value-adding phases [10]. One possible approach would be to bundle such time periods, by releasing lots at a working station specifically to compensate buffers upstream of High-Energy-Consumers (HEC), equipment that consumes energy on a large scale (e.g. lasers at welding stations in car body manufacturing), thus bundling non-value-adding time in blocks. Within these blocks it should be possible, from an organizational point of view, to operate machines and systems at a low energy level, or even to shut them down. The idle times would ideally be scheduled related to planned time periods without production (e.g. directly before or after work breaks, routine maintenance or other scheduled outages), so that these times are added to the downtime, lengthening the time block. By concatenating production flow related idle times to schedulable downtimes it is possible to tap the energy saving potential of even short idle times, whose particular transformation into downtimes would be inefficient due to required shut-down and recovery times, which may amount to several minutes per machine. Additionally, often the shut-down or recovery procedures comprise energy-consuming process steps for cleaning, calibration or heating, rendering short downtime cycles into a waste of energy. Downtime blocks, consisting of both idle times and f. e. a work break, only require a single shut-down and recovery procedure, saving energy and working time effectively. If there are no times of periods without production in the submitted schedules within a specific timeframe, the approach still can be used. Therefore, additional constraints need to be considered, to give advices for changing the operating state of a resource. A necessary condition is to keep and implement the knowledge of switch-off and ramp-time and the related energy consumption in the energy-sensitive algorithm. The required information of the resource and infrastructure models is deposited in the component eniLINK.

To explain how the algorithm is working, an example regarding to the case of planned time period without production will be provided:

For the use case a mixed model flow line simulation model has been built. The example is characterized by different production orders. On the same working station the orders need different working times to be manufactured. To every station we assigned the same shift plan. Products pass trough the production in a specific sequence. The critical points for the material flow are on the one hand the buffer downstream of the station in question (HEC), which would have to compensate any disruption in the flow of material to downstream workstations. Their scope must be calculated in advance from the current buffer inventory b_{Down} and the station working time $t_{HEC,SUCC}(o)$ of any order o in the production sequence, of the HEC-successor. This corresponds to the maximum possible downtime of the HEC before the successor is out of material. A second restriction for the maximum possible downtime is the buffer size upstream of the HEC, which would have to take up the parts from the material flow during the downtime. In this context, downtime of the HEC results in the addition of the order-related working time $t_{HEC,PRED}(o)$ for all the upcoming orders on the HEC-predecessor that can be additionally kept from the current point of view in the upstream buffer b_{UP} before the high energy consumer. The resulting formula yields the maximum possible downtime for the high energy consumer. System can be switched off when this possible downtime $t_{switch\text{-}off}$ is bigger than the residual time to the break t_{break} (see formula 1):

$$t_{switch-off} = \min\left\{\begin{array}{l} \sum\limits_{1}^{b_{down}} t_{HEC,SUCC}(o) \\ \sum\limits_{1}^{b_{up}} t_{HEC;PRED}(o) \end{array}\right. > t_{break} \tag{1}$$

The same procedure can be applied for many stations in the production line as long as the chosen working stations are not directly connected. In this example we adapted this algorithm in one working station for first investigations in a simulation of a mixed model production (see figure 5).

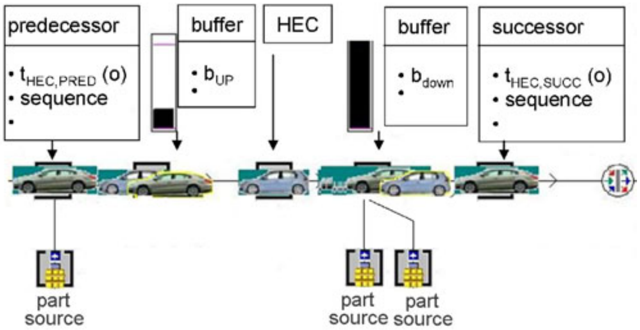

Figure 5: Energy sensitive station release (esSR) regarding to the buffer filling level.

By using the algorithm of the energy-sensitive station release (esSR) described above, rates of the machining states changed. Processing time increased in the same amount as the sum of waiting time and blocked time decreased (see Table 2). With the energy-sensitive station release we could raise the number of produced cars by 1.58 %, the cycle time by 2.39 % and at the same moment we could reduce the energy consumption per produced car body by 1.10 %.

state type	without esSR	with esSR	Δ t (absolute)
processing time	59.68 %	60.54 %	+ 3 hrs 3 min
waiting time	10.00 %	9.47 %	- 1 hr 54 min
blocked time	3.11 %	2.78 %	- 1 hr 9 min

Table 1: Comparison of state rates.

The fact of reducing energy consumption per produced part is influenced by two effects. First of all we can see the chosen work station is shutting down earlier in non value-adding phases. So we reduce over all energy consumption and thus energy consumption per part. Second effect of the algorithm can be seen in the buffer filling level. Because of the longer downtime of the work stations, the filling levels of the previous and the subsequent buffers are lower. That reduces the probability, that the station is blocked. With the station release algorithm we provided, the chosen work station is more often in a working state than in a blocked state. As a consequence the working station produces more car bodies and so the specific amount of energy consumption is lower.

With the provided approach one can consider real-time-orientated, station-related schedules to the contemplated resources. These contain information about the possible time span the states of the resource can be changed, if it will be changed immediately. In the field an additional instance needs to make the decision, whether a working station can be switched-off, without influencing the production system or the dependent peripheral equipment. From this point of view the algorithm can only offer recommendations as seen from the perspective of the material flow. In eniCONTROL this station-specific shift plans can be used to analyze the state-switching-recommendations and control the operating states of the resources as well as the operating states of the equipment.

3.3 Energy-Sensitive Control of Operating States

The results of order planning and order approval (see section 3.1 and 3.2) must be implemented during production/manufacturing in value-adding actions of the production technology – especially with respect to utilized machines and facilities. The presented approach for energy-sensitive control of operating states assumes that the underlying results of prior production planning with consideration of all available information represent energy-optimal defaults. In a running production, further influences exist which are unknown during production planning and thus, cannot be taken into consideration in the planning phase. To be able to also utilize the potentials of saving energy and resources in the running production, it must be possible to react on unpredictable events. For instance, such events are malfunctions regarding the material flow, technical failures, but also specific adjustments with respect to the material flow caused by a change of the current manufacturing situation. Those possible influences, inter alia, lead to an adapted behaviour of the machines and facilities involved in the production. Furthermore, they manifest themselves in different operating states. To decrease the demand of energy in the running production, one possibility is to be able to transfer machines and facilities to operating states with different energy respectively resource demand (see figure 6).

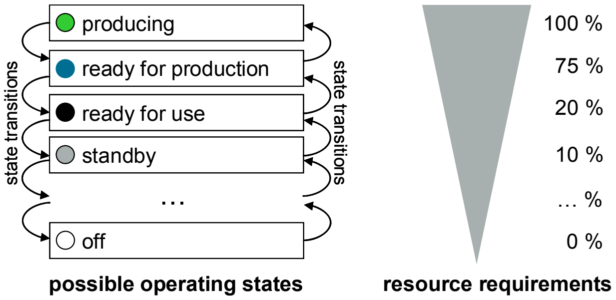

Figure 6: Exemplary illustration of possible operating states regarding their resource requirements.

The control of operating states with lower energy consumption currently only takes place to a limited amount and typically only for a subset of production systems, without considering components of the production infrastructure (e.g. compressed air, air extraction, cooling water) and the building infrastructure (e.g. light) [11]. Existing systems, controlling the individual domains of production, production infrastructure and building infrastructure, mostly operate independently from each other, so that saving potentials across these domains cannot be used. Thus, the main objective is to reduce the overall energy consumption with respect to the requirements of the production, by realizing a demand-actuated resource allocation by the production and building infrastructure.

The current considerations regarding section 3.3 focus especially on non-productive time periods. Such time periods, for instance, are unplanned shifts but also pauses in the shift plan and additionally added short breaks. Pauses and short breaks represent the results of the approach presented in section 3.2 for targeted station clearance and should, as subsequently described, be used for saving energy during the running production utilizing an energy-sensitive control of operating states. Furthermore, time periods are considered by this approach, in which the production system is not useable for production because of technical failure. According to the current state of the art, production systems are usually not transferred into operating states similar to standby in time periods without production. Thus, resources have to be provided furthermore at full extend by the infrastructure components, whereas no production takes place and they are possibly not required. A prototypically technical realization of the approach for the energy-sensitive control takes place as the part eniCONTROL of the framework for energy-sensitive production control presented in section 2.

To achieve an energy reduction across the mentioned domains, it is necessary to know and formally characterize all direct and indirect participating components of the production, but also the components of the production infrastructure and the building infrastructure, in a formal *component model*.

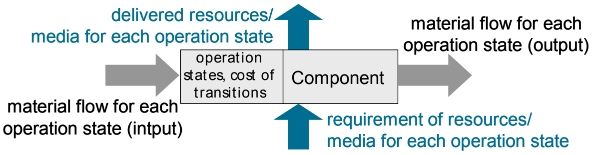

Figure 7: Characterized components of production, production infrastructure and building infrastructure.

In the component model it is distinguished between components of the facility structure and the infrastructure. Components of the facility structure realise the material flow, meaning the moving, storing and transforming of matter. Components of the infrastructure provide required energy, process matters or other infrastructure services (e.g. illumination or suction) required by those. Representatives of both component classes can be characterized as follows (see also figure 7):

- Set of operating states, that can be assumed by the characterized component, after it has been transferred using control commands via a dedicated interface,
- Costs/Effort (Time, Energy) arising for each possible operating state transition,
- Facility structure components: declaration of the provided respectively required material flow (input/output) per operating state, as well as required energy/matters per operating state and
- Infrastructure components: declaration of the provided respectively required energy/matters per operating state.

Using the characterized components, it is possible to determine structural dependencies as well as provision dependencies of necessary matters or resources in a *dependency graph* (see figure 8). The representation in this graph enables as well as the determination of resource relations between the components, the recognition of logically adjacent components.

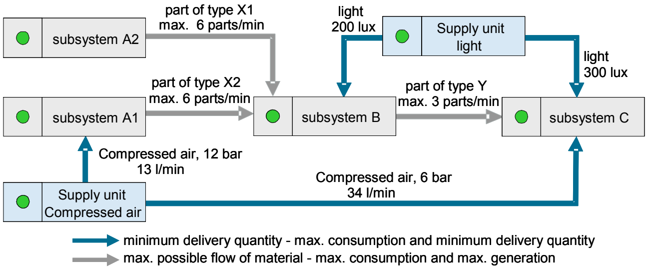

Figure 8: Example for a dependency graph containing different components in a factory building.

The dependency graph contains all components, which should be controlled energy-sensitively within a defined area such as a factory building. For the described approach, it is stated that time periods can be determined and provided, in which certain components of the production – for instance facilities or facility-parts – are not required for the production target. Those components can be transferred into an operating state with lower energy consumption – for instance into a standby state. Using the dependency definitions (see figure 8) between the components, adjacent components of the infrastructure, which provide resources and matters, can be considered recursively and also be transferred into an operating state with lower energy consumption.

To determine the matching operating states with lower energy consumption across components represented in the dependency graph, the system part eniCONTROL considers the following questions:

- What resource is when and how long utilized by which component to which extend?
- Which operating state results for the predecessor and successor components based on the calculated required resources?
- Which time is necessary to transfer a component from its current operating state to a defined target operating state?

For the transition of a component into an operating state with lower energy consumption, it has to be taken into consideration that therefore a defined time period is required. For a recovery (warm restart) of the production this also has to be considered. Thus, the described approach is only applicable for time periods with known duration. This is due to the fact that the components of the production and their resource providing infrastructure components have to be available for productive utilization again at a certain point in time.

From the point of view of the system part eniCONTROL it is furthermore distinguished, whether the controlled component is able to return to a production-ready operating state after a defined time period on its own, or therefore a punctual intervention of the system part eniCONTROL is necessary. Figure 9 depicts the processing of the energy-sensitive control graphically. A bidirectional communication between the system part eniCONTROL and the components of the factory building takes place over standardized interfaces like OPC UA respectively PROFIenergy. Therefore, on the one hand, operating states of the considered components – represented in the dependency graph – are continuously monitored and made available for the processing by the system part eniCONTROL. On the other hand, the selection of the operating states to be taken by the components is made by the continuous calculation and evaluation of possible operating state combinations.

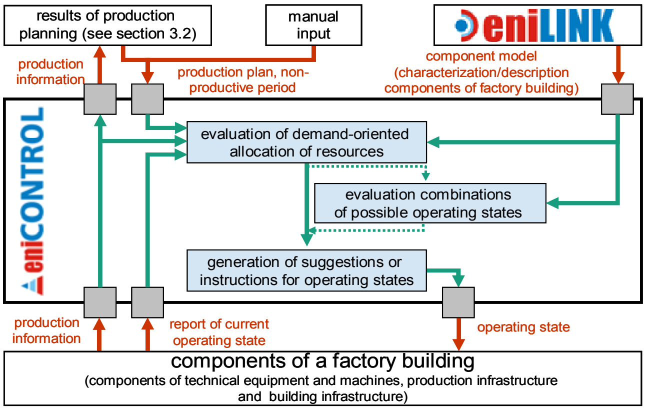

Figure 9: Approach of energy-sensitive control of operating states.

The calculation of possible state combinations includes the current situation of the manufacturing as well as superordinated systems, for instance of planning solutions close to the production (see section 3.2). It has especially to be taken into consideration, if the change of an operating state is reasonable from the point of view of saving energy and is realizable within the available amount of time.

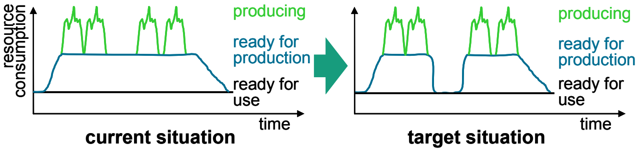

Figure 10: Reduction of total resource consumption in non-productive time periods using energy-sensitive production control.

By using an energy-sensitive control unnecessary energy respectively resource consumption in time periods without production can be reduced. Therefore the knowledge about material flow and resource dependencies is utilized to specifically control the operating states of infrastructure components. By consideration across components, a reduction of the overall energy consumption is achieved. Figure 10 demonstrates resulting saving possibilities exemplarily.

4 SUMMARY

Current work concentrates on tasks, methods and procedures in production control. For these, basic cases of energy-sensitive control have been investigated and evaluated. In order to implement these approaches into MES software components, special attention should be paid to the requirement, that new energy-sensitive control tasks must not lead to task overload of personnel responsible for scheduling manufacturing jobs at shop floor level. Additional energy-oriented target figures can be antagonistic to preexisting logistic target values or simply prone to misinterpretations. An adequate visualization of efficiency-related KPI's derived from energy data and of dependencies between energy consumption and production-related circumstances can lead to a fundamentally better understanding of the processes and to better decisions. That's why the next steps shall focus in particular on broadening the amount of the visualized data as well as the development and implementation of energy visualization methods.

Furthermore, the presented approach offers the possibility to link "live" acquired energy data with information regarding the resources (machines, etc.), processes and products. These enhanced data sets can then feed back into planning models and applications. By doing this, it becomes possible to progressively improve the planning quality, which will lead to better scheduling decisions, for example concerning energy-sensitive order release.

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