GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

19.4 Monitoring production systems for energy-aware planning and design of process chains

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Abstract

Various energy-relevant data can be acquired from monitoring equipment and processes in production systems. Systematic analysis of these data is the basis for predicting the energy consumption of the production system and its energy-consuming elements. In order to continuously reduce the energy consumption in manufacturing, a new approach for the acquisition, aggregation and evaluation of these energy-relevant data throughout the production systems lifecycle is needed. This paper describes how energy-relevant data can be used for both the energy-efficient production planning and control and the energy-aware planning and design of the production system. Therefore, the comparability of equipment and processes in the data acquisition phase and the planning phase will be considered.

Keywords:

Energy consumption, predictive planning, methodology

1 INTRODUCTION

Climate change and other environmental consequences of human energy consumption are likely to be one of the most important challenges and threats to the global economic security in the next decades [1]. Therefore, several countries pursue a transition towards a sustainable energy provision and use. This comprises means such as renewable energy, energy efficiency and energy conversation. Industry is one of the keystones to realize this endeavor. Hence, the challenges for manufacturing companies are to increase energy efficiency and make energy consumption and the related energy costs a manageable resource in the future. Thereby, one focus is on electric energy which is widely used due to its flexibility and wide range of application [2]. In 2010, the industrial sector accounted for about 41 % of the electrical energy consumption worldwide [3].

In order to gain transparency, companies start to implement energy monitoring systems in their production systems. Therefore, more and more real-time measurement systems are used for monitoring the energy consumption on machine level. These energy consumption data can be the starting point for the energy-aware planning and design of the production system. During the actual use phase, the energy consumption data can be applied for the energy-aware control of the production system. Additional potential for long-term reduction of energy consumption promises the usage of the same pool of data for the design of the production system during the planning phase [4]. The objective of this paper is to show how the energy monitoring data can be used throughout the production systems lifecycle.

2 ENERGY-AWARE PLANNING AND DESIGN

2.1 Planning process and planning object

In production systems, energy, material and information are combined to realize the transformation of raw materials into desired end products [5]. Regarding electricity monitoring, the levels of application can be divided into the factory level, the department level and the unit process level according to [2]. This paper refers to the electricity monitoring on the level of unit processes that combine to process chains. Process chains describe the technical and organizational way how the transformation is achieved. In this sense they are the nucleus of a production system and build the starting point for the planning activities in the development of production systems for the series production. The planning can be separated into the activities that occur once in advance to the realization of the process chain and the recurring planning after the realization. All planning activities that occur once in advance to the realization are attributed to the technical production planning (TPP) [6]. In contrast, the production planning and control (PPC) is concerned with adjusting output and logistic performance with market demand by allocating customer orders and company resources over time [7].

The TPP comprises the selection of technologies and their combination to process chains, the selection of manufacturing equipment and the definition of process parameters [8]. There is a wide range of research activities to consider energy consumption aspects in these early steps of TPP. For example, the energy and resource efficiency has been compared for alternative process chains [9-10]. Another research field is the determination of energy-related lifecycle costs of machine tools in order to consider these as one criterion during the procurement [11]. The impact of alternative process parameters on the energy consumption has been investigated in [12] based on a discrete-event simulation. However, all approaches are challenged by the effort for the investigation and prediction of the energy consumption. A comprehensive approach for the use of energy monitoring data can help to overcome this obstacle.

Energy-aware PPC is basically addressed by two different approaches in current research. The first approach is simulation-orientated by using material-flow-simulation for the development and validation of various production strategies considering the energy consumption of the manufacturing equipment. The second approach is based on methods of

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

operational research. The methods in general set up multi-objective optimization problems. The objective function of these problems usually contains productivity as well as energy targets. Energy-aware simulation models of a production system in current research are set up on the basis of Energy Blocks [13] or integrated process modules with measured energy profiles [14] and consider the energy consumption of peripheral systems [15]. The objective functions of energy-aware multi-objective optimization are addressing the total energy consumption of a production system [16], the peak load [17] and electric power costs respectively the time-of-use electricity prices [18].

2.2 Methods to obtain energy planning data

The energy-related planning activities in TPP and PPC are based on the availability of power consumption and time parameters that allow the calculation of the energy consumption. There are three general methods for determining the energy consumption data of manufacturing equipment in process chains: *Experimental measurements* are discontinuous and one-time measurements. Such measurements are performed in laboratory or in production environments in order to gain insight into the energy consumption of unit processes or to determine the efficiency of manufacturing equipment [19]. In contrast, the *monitoring* of process chains is characterized by the continuous measurement and evaluation of the energy consumption. Thus, the energy monitoring is capable of creating energy awareness and foster energy efficiency by including the monitoring feedback in the manufacturing management system [20]. The frequency of the measurements for monitoring depends on the specific purpose. The *simulation* of the energy consumption with simulation models allows for determining the energy consumption without performing power measurements, once the models are available [12]. However, for building the simulation models, experimental measuring or monitoring is necessary. The more accurate the simulation model is intended to be, the more effort must be put into the previous measuring and modeling. Following, an approach for the energy-aware PPC and TPP based on the energy monitoring in process chains is presented.

3 APPROACH FOR ENERGY-AWARE PLANNING

3.1 Monitoring strategy

The definition of a monitoring strategy is the initial point for the energy-aware planning and design of process chains based on the energy monitoring of manufacturing equipment. Applying the defined monitoring strategy ensures consistency and transparency for the implementation of energy monitoring systems. The monitoring strategy depicted in Figure 1 comprises a strategy for measuring and evaluation of the energy consumption data.

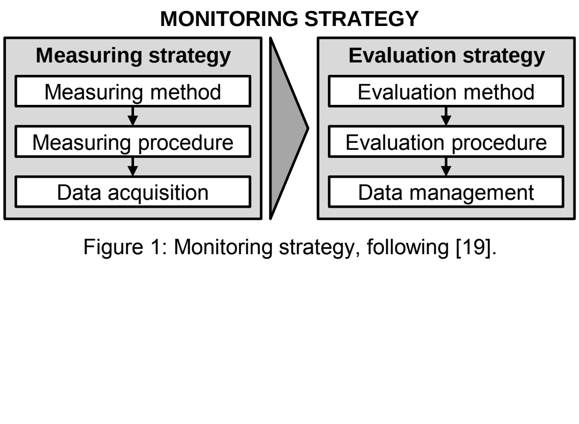

Figure 1: Monitoring strategy, following [19].

First, the *measuring method* is defined. This includes the definition of the traced quantity with the according unit, the definition of the applied measuring devices and the temporal output resolution. Measuring devices need to be selected according to the measuring task considering the cost, communication interfaces and the temporal output resolution. A temporal output resolution of 1 sample per second is sufficient in terms of accuracy of the measurement and the manageability of the data stream in further processing for low and highly dynamic manufacturing processes [2]. In the next step, the *measuring procedure* specifies what, where and when is to be measured. The system boundary ("what") of the measuring procedure is set to single unit processes that combine to process chains. The energy consumption of a unit process is composed of the energy consumed by the manufacturing equipment, e.g. lathe or milling machine, and the energy consumed by peripheral systems such as lubricant and compressed air supply. However, in a first step the energy consumption of peripheral systems is not considered. The main connection of the manufacturing equipment is defined as the measurement point ("where"). Hence, the equipment is characterized by its operational state and its state-related power demand. The measurement routine ("when") includes the length of measurements and the number of repeated measurements. In case of continuous measurements the routine is fully determined by the measurement output resolution of 1 sample per second. Finally, the *data acquisition* specifies the data capturing. This includes the definition of interfaces and mechanisms for the data communication [21]. For the subsequent evaluation of the measured data it is especially important to assign additional information such as a timestamp, the operational state, the equipment number, the product manufactured during the measurement and the set of applied process parameters.

The evaluation strategy provides instructions how the captured data are to be processed and made available for analysis and further application. The *evaluation method* describes how and which parameters are to be built and how they are derived from the captured data. Therefore, basic methods of descriptive statistics such as mean value, standard deviation and frequency distribution are applied [22]. Figure 2 displays a power consumption profile of the manufacturing equipment for a honing process.

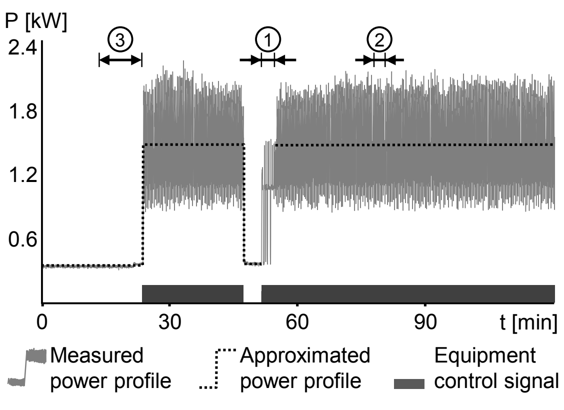

Figure 2: Evaluation of a captured consumption profile.

The chart shows the cutout of two hours from series production. A control signal of the equipment was tracked to document the operational state. The signal is activated with every start of a machining cycle and makes it possible to distinguish the operational state when the equipment is processing from the state when the equipment is waiting for parts. The chart shows two characteristic operational states in terms of the consumed power. In the state *process* the manufacturing equipment carries out the actual machining cycles. The state *idle* defines that the equipment is ready for operation. No machining is carried out, hence no control signal is tracked. A third operational state where the equipment is switched off does not appear in the shown profile.

Section 1 in the profile shows a power consumption different from the operation even though a machine signal was tracked. This presents an operational state that is caused by unpredictable manual interference. From time to time, those states can be observed. However, the occurrence is negligible for this investigation. Thus, the power consumption profile and the related power consumption can be approximated by averaged power consumption parameters and the frequency of occurrence of the operational states. An overview of the power consumption and time parameters is given in Table 1.

Table 1: Overview of power and time parameters.

Operational state	Power consumption parameter [kW]	Frequency of occurrence [%]
Off	P_{off}	$f_{off\,Ø}$
Idle	$P_{idle\,Ø}$	$f_{idle\,Ø}$
Processing	$P_{process\,Ø}$	$f_{process\,Ø}$

In the next step, the *evaluation procedure* determines how the parameters can be computed from the captured power consumption profiles. In Figure 2 it can be seen that the mean power consumption varies from cycle to cycle in the processing state. This is due to some random variations within the manufacturing equipment. Therefore, the average power consumption for the state *process* ($P_{process}$) is calculated for each cycle. When $P_{process}$ is averaged for the measured number of cycles, the desired power consumption parameter $P_{process\,Ø}$ can be derived. This was done for 10 cycles indicated by section 2 in Figure 2. Deviations in the power consumption during processing may also occur due to the wear of tools and components of the equipment. Provided systematically planned tool replacement and maintenance of the equipment, the parameter $P_{process\,Ø}$ is a reliable average power consumption value for manufacturing equipment. The associated standard deviation (SD) indicates the variability of the parameter. For the state *idle* there is no temporal reference given, that could be used for calculating the power consumption parameter $P_{idle\,Ø}$. Therefore, a reference interval of 60 s is chosen. Section 3 in Figure 2 indicates a segment of 10 such intervals, i.e. 10 minutes, in the power consumption profile. The calculation procedure for section 2 and 3 is exemplarily shown in Table 2. Obviously, the value for the third power consumption parameter P_{off}, when the equipment is switched off, is zero.

In the same way, the frequency parameters for the operational states can be calculated. In contrast to the power consumption, the frequency is not given in the absolute unit, i.e. hours, but it is expressed in percent from the total time period under consideration. Based on the weekly frequency of occurrence, a yearly average frequency of occurrence and a standard deviation can be calculated.

Table 2: Computation of power consumption parameters.

No. of interval	P_{idle} per interval [kW]	No. of cycle	$P_{process}$ per cycle [kW]
1	0.35	1	1.51
2	0.35	2	1.50
3	0.35	3	1.56
4	0.35	4	1.57
5	0.35	5	1.56
6	0.35	6	1.53
7	0.34	7	1.51
8	0.35	8	1.54
9	0.37	9	1.56
10	0.37	10	1.57
$P_{idle\,Ø}$	**0.35**	**$P_{process\,Ø}$**	**1.54**
SD	**0.01**	**SD**	**0.02**

It has to be mentioned that in comparison to the power consumption parameters these time parameters are highly influenced by the organizational conditions, i.e. the demand for the produced parts. However, the averaged parameters give a realistic picture of the past and they are therefore a good basis for future planning activities. Finally, the *data management* completes the monitoring strategy.

3.2 Data management

A key aspect for the efficient use of the data in the energy-aware PPC and TPP is a comprehensive concept for the management of the monitored data. There are three main determining factors that influence the energy consumption parameters: the manufacturing equipment, the machining task and the set of process parameters. The manufacturing equipment can be structured into classes according to the machine type, i.e. milling machines or honing machines. A further classification based on the power class, the type of construction and the model is advisable [13]. The manufacturing task comprises all operations that are carried out by the manufacturing equipment during one cycle. As differing machining tasks will affect the energy consumption parameters, a classification of the machining tasks is necessary according to the operations that are performed. The third determining factor is the set of process parameters that is applied, e.g. the number of revolutions, feed rate and depth of cut for a turning process. Looking at the influence of the three determining factors on the energy consumption parameters it is clear that the power consumption in the idle state ($P_{idle\,Ø}$) solely depends on the type of manufacturing equipment. In contrast, the power consumption for the processing state ($P_{process\,Ø}$) can significantly vary for a specified type of manufacturing equipment depending on the machining task and the set of process parameters. In order to provide sufficiently accurate planning data for different planning cases, a new data set is created for every distinct combination of these determining factors. The number of data sets will be reasonable in the particular case of a company and its particular product portfolio. The concept for the data management is illustrated in Figure 3 as a so-called EnergyCube. In the EnergyCube, each small cube can be thought of as a set of energy planning data including the power consumption parameters and the frequency of occurrence of the operational states. Note that the concept of the EnergyCube is independent from the method applied for the representation of the power consumption profile, i.e. the number and kind of operational states or the representation with another concept, e.g., the Energy Block concept [13].

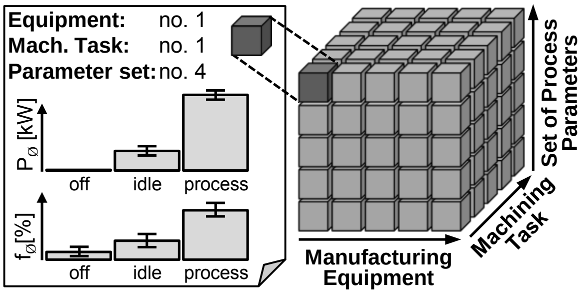

Figure 3: Concept for data management with the EnergyCube.

By means of the EnergyCube concept the monitored energy consumption data can be provided as planning data for the energy-aware PPC and TPP. While both planning tasks have different requirements, they can use the same data base. In case of a planning request for the energy-aware PPC, the planner selects the required information according to the manufacturing equipment, the machining task and the set of process parameters specified in the planning request. The planning request in the TPP is less detailed as the manufacturing equipment, the machining task and the set of process parameters may not have been fully defined. The more detailed the planning requests become, the more accurate the data sets can be selected. In the course of TPP also new technologies that have not yet been operated in the company may be considered for future process chains. In this case, lifecycle inventory data bases or the cooperation with the equipment manufacturer can be a practicable way to estimate and include the energy consumption of the planned process in the further planning. Figure 4 summarizes the approach for the data management.

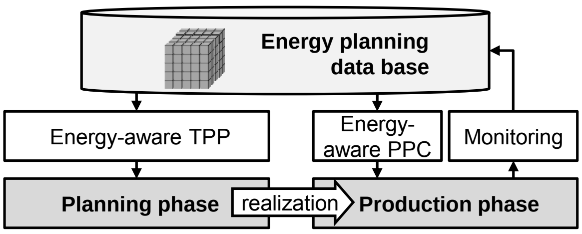

Figure 4: Management of monitoring data.

3.3 Energy-aware PPC

Within the scope of energy-aware PPC energy-based objectives are considered along with conventional productivity objectives such as short throughput time of a product, high utilization of manufacturing equipment and meeting target dates of customer orders. For instance, low energy consumption of manufacturing equipment, avoiding power peak loads within a production system and low energy costs of production based on volatile energy prices are taken into account. The first task for realizing energy-aware PPC is to combine each costumer's order as represented by a certain job with energy consumption. Each job is thereby characterized by a certain lot size and a specific process sequence for relevant manufacturing equipment. The sequence results from the equipment bill of material for the product. The deduction of the energy consumption from the process sequence of a job is shown in Figure 5. On each machine a job passes one determined machining task with predefined process parameters. The energy consumption for this machining task depending on process parameters and manufacturing equipment is represented by individual cubes within the EnergyCube. The average power consumption for the processing state $P_{process\,Ø}$ is revealed thereof. In addition, the average power consumption for the idle state $P_{idle\,Ø}$ of a machine is part of the parameter set.

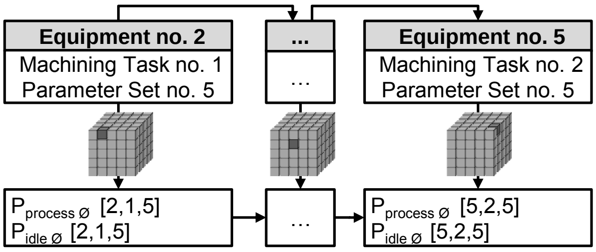

Figure 5: Example of a process sequence for equipment of a scheduling job with related machining tasks and parameters.

The second task for realizing energy-aware PPC is to set up the energy-based scheduling problem on the basis of $P_{process\,Ø}$ and $P_{idle\,Ø}$ of each machine. Figure 6 shows a scheduling chart for machine allocation taking the power consumption into account. Hereby, each order is dispatched to a machine according to its specific process sequence. In order to realize an energy-aware machine allocation, the following energy-based objectives and constraints for a multi-objective scheduling problem can be set up: (1) minimize the total idle time of the production system, (2) shut down machines at the right time, (3) minimize the total energy costs considering time-dependent energy prices, (4) avoid power peak loads and (5) meet the agreements of the energy contract by e.g. avoiding an overrun of a limit for the peak load.

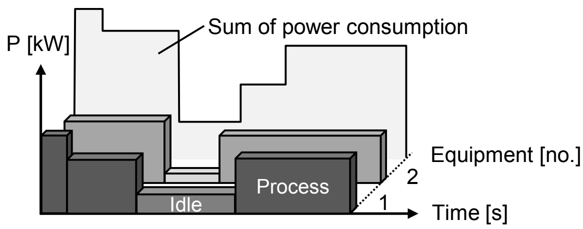

Figure 6: Machine allocations of scheduling jobs with related power consumption.

3.4 Energy-aware TPP

The planning objectives of the energy-aware TPP are the Technology Planning as well as the Configuration Planning for the design of a new process chain for the manufacture of one or different product(s), as presented in Figure 7. Thereby, the Technology Planning includes the energy-aware selection of manufacturing task, manufacturing equipment and process parameters for each production task needed to manufacture the product. The Configuration Planning contains the allocation of manufacturing equipment and machining tasks.

Additionally, it also implies the determination of the process sequence of the manufacturing equipment. Both planning objectives must be considered holistically and have to be matched with one another in order to realize the best possible level of target achievement.

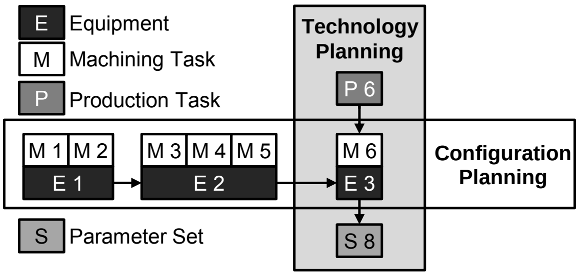

Figure 7: Planning levels for a holistic TPP.

The sequences of the Technology Planning steps are described in the following. The *Selection of Manufacturing Process* is the first planning step. The appropriate manufacturing process is allocated to the specific production task. The sequence of production tasks is derived from the design of the product and represents the fixed order of tasks to process the manufacturing of the product. Thereby, a production task is defined as a task for manufacturing a geometrically determined attribute of the product [23] by the implementation of a specific main group of manufacturing processes according to DIN 8580 [24]. A production task could be for instance: create a hole with the diameter 30 mm by using cutting. Now within the first planning step this productions task is allocated to a certain subgroup of manufacturing processes, e.g. drilling, countersinking, reaming. The second planning step is the *Determination of Machining Task*. The machining task is hereby the technology-based equivalent of the production task for one specific sub group of manufacturing processes, e.g. drilling a hole with the diameter 30 mm. Since this sub group is in addition represented by a specific EnergyCube, the appropriate machining task is determined within this EnergyCube. The fixed sequence of machining tasks for processing the manufacturing of the product is specified after this planning step has been executed for every production task. The third and fourth planning step *Selection of manufacturing equipment* and *Selection of Parameter set* must be matched with the Configuration Planning. For the defined machining task alternative suitable and available machines are selected. For each machine the parameter set is then chosen from the EnergyCube. Herewith two cases have to be considered. The first case occurs when a parameter set already exists within the EnergyCube which completely provides the machining boundary conditions for the considered machining task in dependency of the manufacturing equipment and the product. In this case, the defined parameter set and machining task determine the power consumption $P_{process\,\varnothing}$, $P_{idle\,\varnothing}$ and the time parameter $f_{process\,\varnothing}$, $f_{idle\,\varnothing}$ for the specific machine by the related cube. The second case describes the situation where no suitable parameter set can be ascertained for the planning task within the EnergyCube. In this situation, power consumption and time parameters have to be approximated from existing parameter sets. Finally, the processing time ($t_{process}$) for each machining task depending on a specific machine and parameter set has to be approximated. This processing time is then used together with the related power consumption and time parameters in order to calculate the energy consumption of a machining task:

$$E_{machinig\ task} = P_{process\,\varnothing} \cdot t_{process} + \\ + P_{idle\,\varnothing} \cdot \left(t_{process} \cdot \frac{f_{idle} + f_{process}}{f_{process}} - t_{process} \right) \quad (1)$$

The selection of alternative machines for every machining task with the dedicated energy consumption can then be used as input for the Configuration Planning. Within this scope, each machining task is finally allocated to one certain machine. Simultaneously, the process sequence of machines is set. These actions are carried out considering the abovementioned fixed sequence of machining tasks. In order to conduct the Configuration Planning, the following productivity and energy-based objectives can be considered in order to set up a multi-objective scheduling problem: (1) minimize the quantity of manufacturing equipment, (2) minimize the throughput time of the product, (3) minimize the total power consumption of the process chain. Furthermore the following productivity constrains have to be taken into account: (1) allocate all machining tasks and (2) meet the correct sequence of machining tasks.

4 INDUSTRY CASE

The industry case is derived from an ongoing research project with a manufacturing company in Europe. The company manufactures various components for the automotive industry in series production, e.g., crankshafts. The reduction of high energy consumption and energy-related costs was identified to be one measure to sustainably improve the company's economic and ecologic performance. In order to realize this goal, the company implemented a real-time measuring system for the energy consumption.

The measurements are executed on every machine of a process chain for the manufacture of the crankshafts. The monitoring infrastructure includes metering devices for the power measurement, a programmable logic controller (PLC) and an industrial PC connected to a server for analyzing the data stream. This real-time data stream of the power consumption for each machine is aggregated according to the presented monitoring strategy. In order to distinguish the operational states, the measured power data were matched with the data from a Supervisory Control and Data Acquisition system (SCADA). This matching of data is still a critical process because the data of the SCADA system are not necessarily consistent with the power consumption data. The application of the implemented monitoring system allows for deriving the EnergyCubes for the investigated process chain for crankshafts. These data are now available for the energy-aware PPC and can also be used for the TPP of a process chain for a new variant of crankshafts. Potential for the presented approach can be identified for the energy-aware TPP where the energy consumption can be included as one criterion for the design of manufacturing process chains, i.e., the selection of processes and manufacturing equipment.

5 SUMMARY

In this paper, energy monitoring in production systems was proposed as a starting point for the energy-aware planning and design of manufacturing process chains. In order to achieve this aim, a comprehensive approach was worked. The following results can be gained from this paper:

- A monitoring strategy for consistent and transparent implementation.
- Parameters for power and time consumption of manufacturing equipment using basic statistic methods.
- The framework of EnergyCubes for the management of the energy data sets.
- A procedure for a simultaneous energy-aware technology and configuration planning of process chains on the basis of EnergyCubes.
- A procedure for connecting EnergyCubes to scheduling jobs for subsequent energy-aware optimization of machine allocation

Finally, an industry case illustrated the chances and challenges of the presented approach. Future work will focus on a detailed description of the planning procedures for technical production planning (TPP) and production planning and control (PPC).

6 ACKNOWLEDGMENTS

This research was supported by the project *enPROchain* funded by the program “Zentrales Innovationsprogramm Mittelstand (ZIM)“ of the German Ministry of Economics (BMWi), by the *KAP* research project funded by the “Seventh Framework Programme” of the European Commission and supported by the Kadia Produktion GmbH + Co.

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