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Approach for Dynamic Price-Based Demand Side Management in Cyber-Physical Production Systems

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Abstract

Nowadays, the potential of intelligent energy management concepts varies in many areas, e.g. smart energy usage. Trends in the energy sector for electricity depend on various factors. One factor is the fluctuating supply and distribution of renewable energy, leading to a necessary load control of smart grids. Another one is the need for a more flexible demand side management, especially for the manufacturing industry. Based on the increasing connectivity of modular Cyber-Physical Production Systems (CPPS), new opportunities of demand side management concepts can be identified. The aim of this paper is to show an approach for a dynamic price-based Demand Side Management (DSM) in CPPS, with regards to economic and technological aspects. We focus on DSM and dynamic pricing for a CPPS-side interaction with smart grids and markets in the energy sector for electricity. Furthermore, the meaning of collecting, transforming and learning from data about energy consumption by using CPPS and the resulting possibilities for DSM will be shown. Based on these findings, possible impacts for manufacturers will be identified, e.g. possibilities for a better resource adaptation of electrical energy, which is related to production planning data or the identification for reconfiguration of production processes.

Keywords: demand side management; cyber-physical production systems; dynamic pricing; energy consumption data; resource adaptation

1. Introduction

The scope of Demand Side Management (DSM) is to improve electric energy systems on the consumption side, which can include different measures [1]. Reasons for this can be found in the potentials to react with DSM of industrial energy consumption with a dynamic price-based usage of renewable energy [2] or the opportunities of DSM for charging electric cars [3]. The approach for dynamic price-based DSM with Cyber-Physical Production Systems (CPPS) is to show how the concepts of DSM and CPPS can participate at system level to raise the potential of DSM.

This paper describes an information system approach for DSM with CPPS and their system elements and relations. The term energy is used in the context of this paper mainly in relation to electrical energy. The scope is to show how the potential for an increasing changeability of production lines can be used for the requirements of a fluctuating energy supply. Therefore, a system overview will be shown, how dynamic energy prices or energy market interactions can be integrated into production planning and reconfiguration at plant level.

In section 2 the current state of the art of smart energy, DSM and its usage in industrial sectors is introduced. Furthermore, CPPS and the advantages of flexible production configuration on a modular level are described. Nowadays, as a combination between the areas of energy and production, the inclusion of energy and production planning takes place and leads to a potential of dynamic energy pricing. Section 3 describes the approach of a CPPS-based information system for DSM. The approach offers an overview about necessary sys-

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tem elements and their relations. Therefore, the architecture of CPPS will be extended with information system elements which are necessary for the integration of DSM. In section 4, the system elements and their relations are described in more detail. The importance of information models will be shown, especially concerning energy consumption data of modular production modules and the added value by combining them with production planning information to create an energy forecast. At least, the relevancy of price-related information and market interactions in this system approach is discussed. Section 5 summarizes the paper and describes an outlook for further research. Additionally, the development of components and methods in CPPS to implement the system approach for DSM are considered. Related to the system approach, possibilities for further research are shown.

2. State of the Art

To describe the system approach for DSM with CPPS, the basics of the areas of smart energy and DSM will be introduced. Furthermore, the concept of CPPS and the possibilities of modular production lines for flexible manufacturing are explained. Finally, the relevance of energy for production planning and dynamic pricing is presented.

2.1. Smart Energy, Smart Grids and Demand Side Management

Europe's energy markets are changing since liberalization and deregulation through requirements from the European Union and their implementation in national regulations and laws. On the way to smart energy as a great vision of predominantly renewable energy generation in many central and decentralized units, various developments must be considered. Therefore, electricity markets and the development of electricity prices are key components. In relation to the increasing share of renewable energies and the resulting increase for more information, there is a rising demand for digital meters. [4]

Smart grids are a paradigm to meet these requirements of energy supply and usage. The definition of smart grids encompasses various aspects and meanings. These definitions include the integration of enabling information and communication technology as well as other advanced technologies with large-scale power networks. Main scope is to enable a more efficient, effective, economic and environmentally sustainable generation, transmission, distribution and usage of energy. Therefore, the concept of Cyber-Physical Systems (CPS) is seen as a technology platform to improve the integration and interaction with smart grids. [5]

Demand Side Management is defined as planning, implementing and monitoring of utility activities to influence the energy consumption behavior on the customer's side. The scope is to adjust the consumption, e.g. to consume less power in peak times or shift the energy use to off-peak periods. [6] Due to the challenges of intelligent networking of decentralized units, considering developments in smart energy, Industry 4.0 and DSM offers potential for interconnection.

2.2. Cyber-Physical Production Systems

One approach that has proven to realize a more flexible production environment is the modularization of production equipment. This modular production approach can be explained with the example of the SmartFactory-KL, that comes with a vendor-independent modular production environment where research partners as well as industrial companies work together to create the production environment of the future. [7]

A flexible, modular production environment is seen in this context as a CPPS, which consists of Cyber-Physical Production Modules (CPPM). Each of these modules can be from a different vendor and has a specific production function that can be used for the production process. Therefore, a faster response to changes in production due to interchangeable modules can be realized. Following this concept, CPPM are built out of smart components like CPS. This allows a flexible composition of CPS to CPPM and furthermore CPPM to CPPS. [8] Figure 1 summarizes this modularization approach.

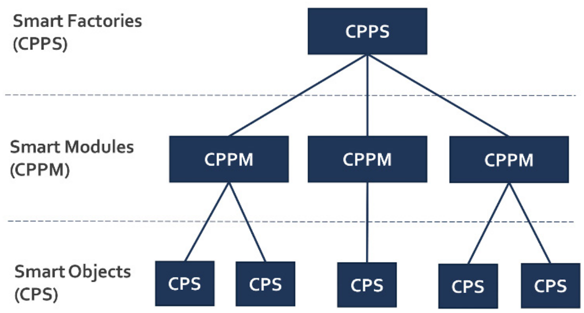

Figure 1: Concept of a modular production environment, based on [7] [8]

Overall, the SmartFactory-KL is creating an interoperable and modular production line. The objective is to create a modular production environment where CPPM can be aggregated to CPPS. This interoperable and flexible character creates a customer-oriented production environment for individualized products [7] [9]. Moreover, the future vision is to reach the autonomous production including the human in a central role [8]. The aspect of sustainability is also of major importance in the subject of smart factories, which includes the area of energy management and the use of energy data in production planning [10].

The future concept of production will be autonomy. An autonomous production which is flexible, modular and interoperable is the objective. Such a system can in future consist of many autonomous subsystems that are interacting with each other. In relation to DSM, there are various potentials to use the flexibility and the possibilities of modular CPPS to fit to changing energy demands. This means that the advantages of this flexibility can be used on the customer side in the form of individualized products as well as on the procurement side in form of flexible energy supply for CPPS.

2.3. Energy-related production planning and dynamic pricing

The importance of energy to production planning systems is pointed out. Therefore, energy must be considered as a limited resource in the production process. As components of an energy-related production planning system it is necessary to establish an energy-oriented information management, and a monitoring and forecast for energy demands by using load profiles with the inclusion of the costs of energy consumption. [11]

To promote implementations of cleaner production strategies, it is necessary to provide an architecture for a management of energy-intensive manufacturing industries, which can be enabled with Energy-Cyber-Physical Systems (ECPS). The architecture for an ECPS can be based on advanced technologies like cloud manufacturing, Internet of Things and CPS and enables a green manufacturing model for the future smart factory. [12]

Related to various production processes, the potential for using DSM differs. As main factors to realize the energy saving potential, different criteria must be considered, like the schedulable capability, the production capability, the inventory capability and the size of price variations over a time period. [13]

System designs for resource adaptation by using an energy-oriented production planning are necessary to link the potential of DSM with the flexibility of CPPS. To realize DSM in production planning, there is an additional need to participate to dynamic pricing concepts from utility companies, which depends on a flexible production configuration of CPPS. An energy-related production planning system must be able to manage energy information to handle flexible loads combined with expected energy savings and reconfiguration costs.

Due to the challenges of smart energy and the reliability of smart grids, the possibility for real-time pricing as mechanism for DSM is essential. Therefore, the possibilities of changing and shifting energy consumption plays a major role. Related to primarily focused interaction concepts between one utility company and energy consumers, also new approaches considering cooperation concepts between many retailers are discussed, to realize the highest individual or combined revenues. [14]

Another option for commercial energy consumers is to use dynamic electricity tariffs to interact with a smart grid. These tariffs can be divided into load-variable and time-variable tariffs. The possibilities of such tariffs are based on the integration of renewable energy sources to provide flexible and dynamic approaches. As success factors for participating with dynamic tariffs an established technical infrastructure and information management, based on smart meters that are integrated in a smart grid, the consumer's acceptance, defined contract design and economy also as further technical developments are defined. [15]

3. Approach for Dynamic Price-Based Demand Side Management in Cyber-Physical Production Systems

To link the thematic areas of DSM and CPPS from the point of view of an information system architecture, an overview of the corresponding system elements is necessary. The main scope of this approach is to use the flexibility and changeability of CPPS, which is mainly used to fulfill changing and individualized customer demands also for the purchase of electrical energy. Furthermore, it is used to meet the requirements of a changing or volatile energy supply or to participate with the energy market.

The system approach contains an overview of cyber-physical system elements and information system elements for DSM with a suggested classification to the suitable CPPS-related architecture level as seen as in figure 2. The information system elements, which are belonging to the corresponding elements of the structures of CPPS, are assigned to these architecture levels. The elements of the system approach are assigned to the following levels (description from bottom-up point of view):

- Cyber-Physical Production Modules (CPPM)
  - Energy Information Models
  - Consumption Management
- Cyber-Physical Production Systems (CPPS)
  - Production Planning
  - Energy Forecast
- Market Platforms
  - Energy Price
  - Energy Market

In this approach, energy consumption data will be collected on the CPPM level. Related to the architecture, a CPPM summarizes the consumption data of all their belonging CPS. To get and to provide this information, smart meters must be added to each CPPM, or to the corresponding infrastructure nodes, which supply energy and data communication for related CPPM. The provided smart meter data can be prepared by using predefined energy-related information models.

As a data basis for changeable energy-related production planning and dynamic pricing concepts, it is necessary to establish a system element for consumption management which collects, historizes and manages the consumption data of all units on the CPPM-level, which contains CPPM and CPPM that are supplied by infrastructure nodes. Therefore, the consumption data must be provided by using energy information models of each CPPM or infrastructure node. The scope of the consumption management information system element is to store this data and provide this information to other system elements, e.g. the production planning or energy forecast. The main benefit can be found in a modularized and elementary granularity of consumption data.

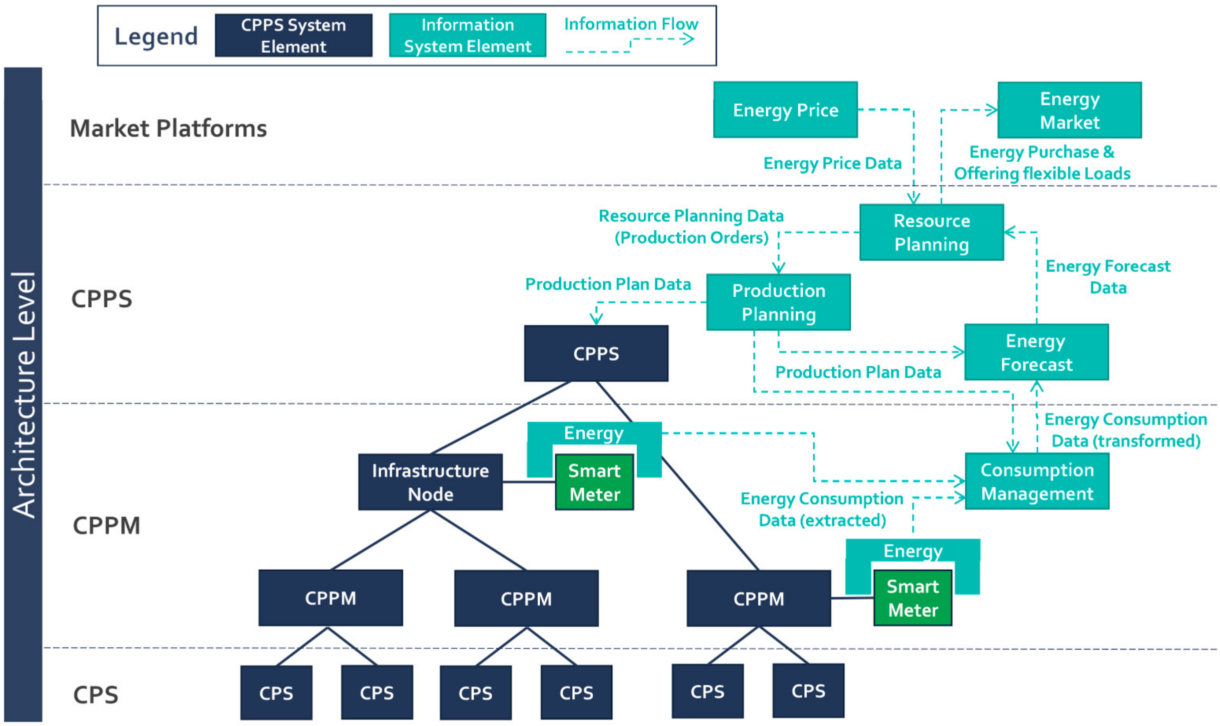

Figure 2: Approach for Dynamic Price-Based Demand Side Management in Cyber-Physical Production Systems

The system element that is responsible for the production planning provides the production plan data for CPPS and its derived suggested process sequences for CPPM. Related to the energy consumption data, which can be found in the system element for consumption management, the production plan data can be combined in two ways, to provide a point of view that differ in terms of time:

1) Historical consumption data
2) Expected consumption data in the future

As basis for historical and expected consumption data, the modular-related information must be extended with a process-related dimension. Therefore, the historical consumption data of CPPM and infrastructure nodes must be combined with the time-related historical process sequence data from a production plan. Based on these historical process-related consumption data, this information can be used for future production planning to create a process-based energy consumption forecast on the CPPS level. The result is a modular and process-related load profile with future perspective.

To interact with concepts of DSM, the belonging production planning on the CPPS level must be able to consider corresponding signals from a smart grid. One signal form can be sent in form of flexible energy prices for energy demands, e.g. to move flexible loads to another point in time. To use the potentials of DSM, the flexibility of a modular CPPS should be used in combination with production planning and enterprise resource planning systems, to consider dynamic energy prices as an optimization variable. Furthermore, the energy forecast information from the production planning and the current configuration of a CPPS can be used, to offer flexible loads by using energy markets.

Like the requirements of changing and more individual customer demands, it can be expected that a flexible system such as a CPPS can use its potential to react to changing conditions in form of dynamic energy price signals or energy consumption faults in single modules, which can lead to production reconfigurations. The scope of the corresponding system elements for this system approach will be described in more detail in the next section.

4. Information system elements of the approach

Related to the system approach, the information system elements will be described from bottom to top. As a basis for the collection of energy data, the meaning of information models for energy consumption will be described and linked to the dimensions of product, process and resource. Based on the consumption management, the relevance of this data for production planning and energy load forecasts will be shown as an enabling basis to the aspects of pricing and market interactions.

4.1. Information models for energy consumption data

To collect energy-related data from CPPM, energy information models must be defined with a standardized software interface. Therefore, the Plattform Industrie 4.0 provides a detailed metamodel of the Asset Administration Shell (AAS) and their related submodels for Industry 4.0 components in manufacturing companies [16]. For energy-related data, a specific submodel for energy efficiency, containing consumption data, has been predefined [17]. The implementation of this submodel can be used to make the data from energy consumption available for other system elements, e.g. consumption management or production planning. In relation to the ECPS architecture, the energy consumption data is related to a cyber-energy layer, in which the data is processed [12].

To set up the energy information models for CPPM, the predefined aspects of energy-related submodels of the AAS can be used. Each CPPM or infrastructure node can implement the AAS to provide an instance of this energy-related submodel. This instance could be used to offer modular energy consumption data for the other system elements, belonging to the total systems consumption management. The module-based information reference model can thus be used to collect energy consumption data with a predefined interface.

Smart factories contribute to a better understanding of the behavior of energy consumption, e.g. for decision-making systems in production management, where the consumption data of the machines and their corresponding configuration can be analyzed and assigned to products and processes [10]. The energy consumption data of CPPM can thus be assigned to the corresponding consumption data dimensions of products and production processes, which are related to current production plans of CPPS. Therefore, the information system element for production planning can directly provide the information about the corresponding processes and products to the system element of consumption management, to enable a new point of view of consumed energy during the manufacturing. Figure 3 gives an overview of the consumption dimensions and suggested data elements, which are to be linked to the consumption data of a CPPM to provide these dimensions.

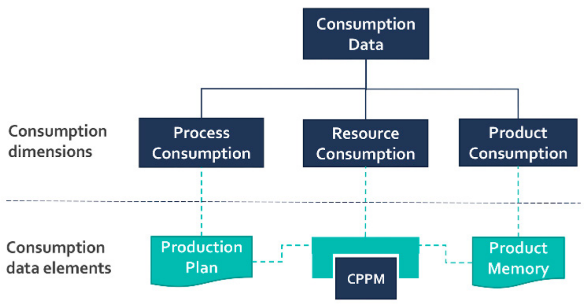

Figure 3: Consumption dimensions and suggested consumption data elements

The model-based preparation of energy consumption data of CPPM, which is seen here as a production resource, can be used to assign the module-related information to the manufactured products. The product-related consumption data can further be used to create an ecological footprint [18]. The possibility to assign collected product-related consumption data directly to products can also be provided by an AAS, to store consumption data of completed production steps, that have been executed on the product, in digital form.

The possibility to interact with an AAS of a product during a production process of a product-driven manufacturing can be realized by using a digital product memory, which can contain product and manufacturing data [19]. The implementation of information models with the AAS can be used to make the energy-related part of such a digital product memory available for updates from different manufacturers along the supply chain. The allocation of the consumption data of a production resource to the product can be used to create consumption patterns and to compare it in future with similar product variants.

The assignment of energy-related data to processes is necessary to identify correlations between process planning and energy consumption on the CPPS level. Especially the modular structure setup of CPPS can lead to various setups on the level of CPPM. To identify the process-related consumption data in a more detailed way, executable actions of a CPPM must be provided in a capability-based manner. The benefits of preparation of energy consumption data to belonging processes can be found in connection with the use of production planning systems.

4.2. Energy as part of production planning systems

The interaction of production planning systems with CPPS and the resulting scheduling is an essential part of optimizing the resource adaptation of a factory. One aspect of this resource adaptation can be seen in an optimized way to adapt energy in planned production processes. Therefore, collected and prepared consumption data of processes, products and resources can be provided. The main scope is the creation of an energy-related energy forecast on CPPS level about the different dimensions of consumption.

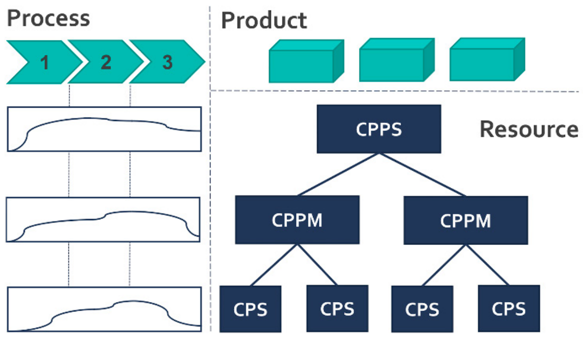

Figure 4: Combined consumption dimensions for production planning

Especially the possibilities of reconfiguration and resource adaptation of CPPS enables advantages for production planning systems. During the production planning, energy optimization potential can be considered, and the collected data of different configurations can be used to find out reconfiguration effects. Furthermore, this data can be used for simulation approaches of production planning, resulting in energy load profile forecasts of expected consumptions on CPPS level. Combined with the dynamic pricing of energy, the estimated energy costs of a production plan can be prepared.

In combination with strategies of DSM, there are various possibilities of reconfiguration, leading to a more holistic view of production resources. Energy-intensive processes that can be postponed can be identified and shifted to periods with less workload or cheaper energy prices. To realize flexible reconfiguration, the production planning can schedule reconfiguration processes for CPPS, to reduce down-times and times to set up the machines.

It can be assumed, that the creation of historical load profiles for production resources have an impact, if the dimensions of the consumption data will be considered together. In detail, the total of process, product and resource as consumption data dimensions can provide a differentiated perspective for load forecasts. New combinations of process, product and resource are leading to new entities of consumption data, which can again be collected and measured by using the CPPM energy-related information models. Furthermore, this approach can be used to improve an energy-related feedback loop.

4.3. Energy pricing and market interactions

Energy prices from utility companies and market interactions are necessary to realize DSM with CPPS. Therefore, for pricing and market interactions, these tasks are designed in the system approach as several system elements with an interface to interact with smart grids and energy markets.

To ensure a reliable supply of electrical energy for energy and households, all actors participating in electricity markets must forecast their generation and loads, to ensure a balanced power supply and demand. Individual forecasts of all actors are used for scheduling for the entire market. Therefore, and to participate with energy markets, suitable industrial processes which can be used for the implementation of DSM have to be identified. Related to the DSM potential in balancing markets, energy-intensive industries have the potential to change production processes with the shifting or shedding of loads or to sell DSM potentials in spot and balancing markets. [20]

Dynamic pricing and the usage of load-variable and time-variable tariffs offers potential for commercial customers if the business factors and general conditions allows an execution of a load shifting of electricity-intensive activities. Therefore, the usage of performance measurements or the use of intelligent smart meters is required. [15]

The opportunities of DSM with CPPS can be seen in the possibility to provide the necessary requirements and consumption data of production processes and the further identification of flexible loads, which is also needed for market interactions.

With the implementation of smart meters in CPPM or infrastructure nodes, the measurement-related infrastructure can be provided to enable the possibility to react and to use dynamic energy prices. Furthermore, the storage of energy by using dynamic prices to refill empty energy storage units and the possibility to consume them, can be used as solution to bride a period, where no direct alignment to the planned consumption of a CPPS is possible.

The system element that should handle dynamic prices must interact with the resource planning and production planning of the CPPS, to check if a production reconfiguration is possible and should be executed. Therefore, the current load profile forecast on CPPS level and the effects of rescheduling must be known. Due to the need of energy demand forecasts to interact with energy markets, the information system element for the CPPS energy forecast can be used together with the elements of resource planning and production planning.

5. Conclusion and outlook

This paper describes a dynamic price-based approach for DSM with CPPS. An overview of the main system elements and their relations has been shown and the main system elements have been introduced. For future research, the structure, the processes and the behavior of each information system element must be explored and defined in detail to fulfill the requirements of a flexible CPPS, which can interact with smart grids and energy markets with the mechanisms of DSM. Based on the system approach, the design for the several information system elements must be done.

It can be explored, how predefined concepts of DSM [21] can be integrated in the system approach of DSM with CPPS. Furthermore, the possibilities for integrating energy storage units as own CPS can be explored in this context [22]. Especially the concepts of load shifting and load clipping by using production planning systems, combined with historical consumption data and the opportunity of process-based load profile forecasts can be used to react more flexible to smart grids. The integration of energy storage units as separate CPS could be used in a CPPS to temporarily store energy for production. The capacities of these energy storage units can be considered with their actual and expected forecast state of charge in the concept of DSM in CPPS. The additional use of such energy storage units could provide a greater flexibility in resource adaptation of electrical energy, for reconfigurations in production and thus in participation with dynamic energy prices.

In terms of distributed control systems in modern manufacturing and production systems, the usage of skills in combination with OPC UA as generic interface are discussed [23]. The usage of skill-based CPS and CPPM offers possibilities to collect consumption data, combined with the time-related skill-execution, e.g. from a manufacturing execution system. The concept of a skill-based consumption data measurement, especially in terms of different skill parameterizations, offers new approaches in decentralized systems.

Related to new concepts like Production as a Service (PaaS) [24], where manufacturing capacities can be shared, it can be assumed that the possibilities of DSM and energy market interactions can be researched in the future. In relation to PaaS, the concept can be extended with an electrical energy-related point of view. Identified flexible energy loads in production planning can then be offered by smart factories. This makes it possible to adapt energy more flexibly in future production and to respond to load fluctuations in smart grids and thus to contribute to their stability.

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