KPI-focused Simulation and Management System for Eco-Efficient Design of Energy-Intensive Production Systems

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Abstract

The optimal eco-efficient design of production processes guarantees sustainable and resource-efficient manufacturing systems. Within the scope of the European project “DAPhNE”, Fraunhofer IPA enables eco-efficient design with a new integrated system for the simulation and management of energy-intensive production systems as well as related key performance indicators (KPIs). The approach presented in this paper is based on a holistic production model and simulation system including dynamic KPIs with the focus on environmental, operational and economic aspects. A main objective of the developed system is to support the engineering and optimization phases to develop and maintain eco-efficient production systems.

Keywords: Eco-efficient design; key performance indicators; production simulation; integrated systems; production planning; production optimization; DAPhNE.

1. Introduction and Overview

Continuously growing energy demands and the consumption of primary resources along with the long-term increase of energy prices require new approaches and concepts for the sustainable economy of the future [1]. Therefore, enabling technologies and systems for the design and operation of energy-efficient production systems are required in order to effectively exploit the economic potential of energy savings, to conserve natural resources and to reduce emissions [2].

In this context, new factory design methods and tools which are based on digital models and coupled with instrumentation and monitoring data as well as new production applications, are key instruments or solutions to achieve eco-efficiency in production systems.

Previous research has addressed several aspects of integrated engineering systems or combined simulations for eco-efficient design from product development phases [3] to the planning and optimization of green factories [4] to factory operation considering production control and peripheral systems [5,6]. It has become increasingly evident that new planning solutions and methods have to go beyond stationary single simulation systems for experts or specific planning tasks, enabling wider support of all production and engineering stakeholders involved as well as the further integration of holistic tools or dynamic mobile applications to support the different phases of production planning.

This paper describes the development of an integrated production process simulation and KPI management system for the design and operation of eco-efficient production systems. Moreover, the research aims to provide further planning support and benefits by the integration of mobile production applications, providing the link from engineering and design phase to ramp-up and production operation. The focus is on eco-efficient design and production operation with...
special emphasis on economic, environmental and operational aspects. Besides environmental issues, which represent resource and emission-optimized production parameters, operational aspects are also taken into account. Therefore, the focus is to maintain or increase the equipment productivity or productiveness while reducing energy use. Moreover, economic aspects and costs are considered as well. The research work is part of the European Project “DAPhNE” that addresses the development of integrated solutions and new production systems based on high-temperature microwave heating technology of energy-intensive production systems. The main results of this project are comprised of new processing technologies, adaptive monitoring and control systems, as well as KPI management modules to simulate, evaluate and optimize production systems.

This paper is structured as follows: The first part introduces the conceptual framework and definitions to clarify the use of terms. This is followed by the description of the KPI-focused Simulation and Management System, the general architecture, methods and modules. Furthermore, the integration approach and results are presented based on an application scenario.

2. Terms and Definitions

This section addresses terms and definitions within the scope and concept of this article. At first, the terms of the simulation system and model are theoretically defined; secondly, the advanced software modules for the KPI-focused Simulation and Management System as well as the production system are described.

Simulation System and Model

The simulation process is primarily understood as the creation of an abstract model based on a real and complex system [7]. According to the VDI guideline 3633 [8] simulation is defined as modeling a dynamic process in a system by using an environment for experiments to gain optimized results which are transferable to reality. In general, the characteristics of a system are [9]:

- System boundaries
- Subsystems and non-separable elements as well as associated variables
- Transfer of material, energy and information
- Process as combination of subsystems/elements
- Logic and control of a system
- System conditions characterized by variables

Advanced Simulation and KPI-Dashboard

In this article, a software system refers to the developed KPI-focused Simulation and Management System as an integrated system of specific software modules. The first module is the Production Process Model and Simulation System called KPI-PMS. The main functionalities are scenario configuration, production simulation as well as results evaluation with a focus on energy-related process data and KPI values. The second module is the dynamic KPI mobile dashboard called KPI-MDB.

The objectives of the simulation systems in production are the improvement of the manufacturing processes and the early analysis of the modeled production system. In comparison to conventional objectives of simulation systems, such as bottleneck analysis, utilization, cycle or processing time optimization with KPI-PMS, additional parameters with the focus on eco-efficiency such as energy consumption or emissions are taken into account [8].

With respect to the second module, the KPI-MDB, current digital tools are monolithic and rigid. The dynamic factor to allow fast changes and adaptions of the software user interface is mostly missing [10]. Therefore, a dynamic KPI-MDB was developed to ensure fast adaptions by drag & drop functions [11]. The KPI-MDB uses aggregated information of data sources from a simulation system or a production object and presents the KPI data in a flexible user interface featuring an intuitive way of use as well as a variety of KPI compositions [12].

Production System

A production system is defined as a system for the fabrication of raw materials, parts or components to finish goods respectively completed products [13]. The system consists of organizational, structural and personnel fields as well as the production process and the associated resources. For the production process, it is necessary to provide space, energy and information [14]. The production process can mainly be divided into manufacturing, assembly, logistics, maintenance, and quality. Within the production process, equipment such as measurement, storage and transporting tools or facilities, etc. are involved [15].

Within the scope of the article, the considered production system focuses on energy-intensive production processes for manufacturing, such as new high-temperature microwave heating process technology and associated production resources and equipment.

3. KPI-focused Simulation and Management System

The developed KPI-focused Simulation and Management System called KPI-SMS described in this paper consists of a holistic production simulation system (KPI-PMS) and an integrated dynamic mobile application (KPI-MDB). The KPI-SMS focuses on environmental, operational and economic KPIs concerning eco-efficiency and process values of the modeled production system. Within this section, the two system modules, the KPI-PMS and the dynamic mobile KPI-MDB are described.

3.1. Production Process Model and Simulation System (KPI-PMS)

The architecture of the KPI-PMS is based on the modeled production system dealing with defined production processes and their system boundaries. Thus, upstream and downstream processes (e.g. supply of material, parts and products or
storage) will only be considered, if they do have an influence on the production process and its eco-efficiency.

The current KPI-PMS modeling approach is developed as a three-level architecture (see Fig. 1). At top level, the production system and its layout is configured and designed. Each production object has assigned parameters and a defined configuration set. The production objects are connected with their corresponding successors and predecessors through connection interfaces. At the second level, the configured production object representations consist of a detailed production parameter display with main processes and material variables, emissions, costs as well as available instrumentation devices, and sensor data. The programmed model elements, functions, and methods are integrated at the third level of the architecture.

3.2. Model Parameters and Data Handling

The data handling strategy concerning the KPI-PMS aims at representing all relevant data from the modeled production system and at enabling the consideration of real process data from the current production line in the model. Therefore, the KPI-PMS has two main data sources and interfaces implemented to integrate the production data within the KPI-PMS database.

The input data parameters are provided by “Data Profiles” that include process, material and energy data to configure predefined production scenarios. On the other hand, operational “Process Data” of production objects and their implemented instrumentation and monitoring devices are integrated (see Fig. 2). Further manual measurements can be made available for the KPI-PMS by integrating offline measurement data.

Concerning the factory engineering and design phase, the KPI-PMS will take the scenario configuration data for the different evaluation scenarios into account. This data can be revised and updated according to the simulation results. The data profiles, which are created in the engineering, development and design phases, are inserted into the internal module database for the scenario configuration. The data profiles include all defined and available production process parameters, involved material, products as well as their energy parameters.

For example, when considering energy-intensive material processing steps, the simulation model is configured by setting up the production, material and energy-specific parameters along with the boundary conditions. In particular, dimensional parameters such as the dimensions of each production object are defined and configured. Besides dimensional definitions, other technical production object specifications such as idle/standby power consumption, allowed equipment temperature, feed rates, planned maintenance times as well as economic specifications, such as different type of costs (equipment, maintenance or repair costs), can also be defined. The KPI-PMS model is adaptable to design revisions made during the subsequent development or engineering phases.
The material and temperature profiles along the process with material parameters, such as material density (bulk, pressed, sintered, molten) as well as material and temperature specific heat capacities, are configured. Moreover, emission and mass balances are set up for each material to be processed.

Energy costs can be specified per region or country. Energy sources concerning the share of electricity derived from renewable sources (energy mix) can also be defined. The defined production scenario configurations with actual production objects, their parameters, dimensions and material properties enable the simulation and evaluation of actual volumes and weights for each process along the production line and the associated material flow over time. Thus, process flow figures, material flow discrepancies or bottlenecks can be identified and the compliance with material processing specifications as well as residence times can be verified. Material flow characteristics, such as mass flow per hour or product weight per hour can be predicted and compared to the planned material flow or feed rates.

Moreover, energy consumption parameters are evaluated concerning the defined production scenario, which is based on the foreseen process configuration as well as the thermal characteristics and requirements of the processed material together with the applied energy profiles.

In addition to the simulation and analysis of preconfigured production scenarios as well as their integrated process data profiles, the detailed evaluation of eco-efficiency in the phase of production operation is considered. Thus, the KPI-PMS is designed to be able to import the process monitoring data via an interface connection in order to analyze the performance of the real production process. Data from implemented instrumentation and monitoring systems are collected within a dedicated process database and evaluated by the KPI-PMS (see Fig. 2).

A main focus of data monitoring and sensor capturing is on energy-related information concerning the production objects and the processed material or produced products. Energy data that represents the individual energy use of production objects can be obtained from integrated electricity meters to monitor the actual absorbed power and to analyze the data.

Energy-related material properties such as temperature data along the process and material flow characteristics within the production system are also taken into account. The availability and performance data of production objects are collected in order to determine the Overall Equipment Effectiveness (OEE). This includes information about operation and shutdown periods for each production object. Furthermore, data concerning emission flows can be accessed and analyzed within the KPI-PMS by using sensor data or theoretical calculations and mass balances.

The developed KPI-PMS enables the simulation of production processes, objects or systems, focusing on KPI evaluation and energy consumption. The KPIs defined are the decision variables of the configurable production scenarios and can be combined with conventional or existing factory KPI values. The main KPIs of the currently integrated production scenarios are:

- Economic KPIs, such as specific energy costs (fuel or electricity costs), expenses on material, maintenance and repair costs, total cost of ownership
- Environmental KPIs, such as emission data (CO2 emission) and share of energy from renewable or fossil sources
- Operational KPIs, such as energy and material consumption data or OEE data

Any further defined or revised KPI data can be supported and integrated. After simulation and visualization of the production process, the different scenarios are compared and the optimal eco-efficient design configuration can be identified. Therefore, key figures and charts are included to support the evaluation of the individual KPIs (see Fig. 3).

![Fig. 3. KPI-focused Simulation and Management Approach](image)

To make the simulated KPI information accessible from anywhere during subsequent engineering phases (e.g. ramp-up and production operation) within the Fraunhofer factory planning and operation environment “Application Center Industry 4.0”, a new app was designed and developed called the “Dynamic KPI Mobile Dashboard”, which is presented in the following chapters.

### 3.3. Dynamic KPI Mobile Dashboard (KPI-MDB)

The other main pillar of the new KPI-SMS is the KPI-MDB. This app is designed to integrate the scenario-specific simulation results, as well as the defined instrumentation and measurement values. The design of the human interface and the intuitive use of the app allow the user fast changes and flexible interface adaptations for KPI analyses and their possible correlations among dependent systems and production objects. Considering four phases of the production process life cycle, i.e. investment planning (1), engineering (2), ramp-up (3), and production optimization (4), the KPI-MDB is mainly applied in phase three and four. The context-
oriented backend of the KPI-MDB enables the users to create their own requested KPIs for each phase in the form of newly designed templates by reconfiguration of the human interface. Primarily, the user is enabled by the app to choose different production objects by drag & drop functionality. By using the same functionality, the user can then drag all associated KPIs for these objects. This results in a detailed KPI and production object composition of individually created templates for an individual evaluation.

4. Integration Approach and Application Scenario

The integration approach shows the structure and implementation of the KPI-PMS and KPI-MDB. The application scenario illustrates the data and information flow of the two implemented modules.

4.1. Integration Approach

The integration approach is based on the KPI-PMS and KPI-MDB as well as the considered production objects with instrumentation and monitoring devices. The data flow of instrumentation and monitoring data, energy, KPI data, as well as object data takes places through a MQTT-Broker (Message Queuing Telemetry Transport) [16] and HTTP-REST (Representational State Transfer) [17] interfaces (source). Besides, the simulation system database enables to store different scenario configurations for the optimization of the (digital) production models, see Fig. 4.

Fig. 4. Technical integration of the modules (Scenario-based)

In order to connect to the KPI-MDB, the KPI-PMS first has to generate the data with a predefined data format. For easy configuration and maintenance, the data format “csv” (comma-separated values) [18] is chosen because this format is well-known and users can manipulate the data by many data sheet tools already existing on the market. Secondly, a newly created communication component based on the internet of things standard “MQTT” supports data interchange between the KPI-PMS and the KPI-MDB. MQTT standard is the best fit for the dynamic KPI-MDB with a stable, reliable bidirectional communication protocol for minimal transmission overhead and common security aspects.

4.2. Application Scenario

Within the defined application scenario, a company has to fabricate a product, which requires an energy-intensive production process, such as the manufacturing of ceramic frits, cement or glass. Therefore, a new manufacturing process with high-temperature microwave heating technology was developed and composed of four main processing systems: Feeding system, pre-heating system, microwave heating system and microwave melting system. For each production object as well as for the entire production process, data are available concerning scenario configuration, monitoring and evaluation.

The modeling of the manufacturing process is performed in the KPI-PMS, which allows different configurations of the production processes by changing process, material and energy parameters. After running through various scenarios, the results can be evaluated by the simulated process values and the defined economic, environmental and operational KPIs concerning eco-efficiency. For this, either an evaluation report of the KPI-PMS or the dynamic analysis functionalities of the mobile KPI-MDB are available.

In contrast to a static parameter display in simulation programs, the KPI-MDB enables individual dynamic compositions and evaluations of figures and charts. For example, the plant managers are more interested in economic indicators, whereas the production engineers and plant operators are focusing more on operational metrics. Here again, the operator would like to know more about quality indicators, while the planner focuses on the OEE (see Fig. 5). By functions such as drag & drop, merging or drill-down charts, graphs or figures can be personalized as well as be put together individually with the KPI-MDB.

Fig. 5. Screenshot of KPI-MDB
4.3. Benefits

The KPI-SMS enables to model, simulate and optimize everything from production objects and processes up to the whole production system. The main benefits of the KPI-SMS are:

- Enhanced process optimization and production planning support along the factory life cycle with the focus on eco-efficient KPI target values.
- Advanced scenario configuration and comparison functionalities to evaluate the optimal production design.
- Customizable KPI-oriented analysis, KPI composition and connections, chart merging and configurations based on KPI formulas and targets.
- Correlations among dependent systems or production objects are explorable, resulting in a deeper understanding of complex systems.
- Fast integration of new technologies by working simultaneously during development and operation phase based on real and simulated data.

5. Conclusions

Within this paper, the developed KPI-SMS is described. It consists of two main modules: KPI-PMS and KPI-MDB. Their architecture, model parameters, data handling and integration aspects have been presented. The developed KPI-PMS enables the KPI-oriented, simulation-based evaluation of different production scenario configurations as well as the analysis of instrumentation and monitoring data from the real production line. Various production scenarios with different process configurations, production parameters, dimensions, and material and energy properties can be taken into account.

The objective of the KPI-SMS, i.e. to support the engineering and optimization phases to develop and maintain eco-efficient production systems, have been reached by integrating the advanced KPI-PMS simulation module with the dynamic mobile KPI-MDB module and the production objects. This allows every stakeholder in different planning phases to quickly receive optimized results. The analysis cycle of the simulation model parameter configuration, simulation experiment and result evaluation require less time.

Finally, an application scenario was established to demonstrate the system applicability and KPI-SMS benefits concerning engineering and optimization support for planning and maintenance of eco-efficient production systems. The application scenario indicated an optimized evaluation of KPIs for energy-intensive production systems, their production objects and processes.

However, different products, processes or new KPI targets may require the system to be further revised and adopted to the specific needs of an alternative production environment or industry sector. Therefore, further research and development work will be performed to enhance the flexibility and modularity of the whole system. The integration of the developed modules within the “Application Center Industry 4.0” at the Fraunhofer IPA and other operational environments will allow the further validation and application of the KPI-focused production simulation and management system in various industry applications.

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