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Automated production data integration for energy-oriented process chain design

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Abstract

Energy efficiency is an important aspect in automotive industry. While energy demand occurs during the operation phase of a production system, it is determined during the planning process. To enable a forecast of energy consumption during process chain design and a demand specific dimensioning of machine components, a modular framework consisting of specialized planning tools and an integrated database is developed. A seamless information flow based on OPC UA and AutomationML connects shop floor and planning environment and ensures data consistency. A database integrates available data sources and condenses acquired raw data to relevant reference data. The concept is prototypically implemented in a crank shaft production line.

Keywords: Energy efficiency, Production engineering, Production data acquistion

1. Introduction

Automotive manufacturers not only have to develop products fulfilling customer needs but also have to cope with legislative and environmental requirements and withstand an ongoing competition with other manufacturers. One success factor for manufacturers is the development of production systems which excel with high ecological and cost efficiency.

Consequently, production planners do not only have to take investment costs into consideration but - following the total cost of ownership (TCO) approach - also have to include the operating costs. An important share of the operating costs and the environmental impact of production systems can be allotted to the energy and media demands of the production machinery. The integration of environmental aspects into the planning process is still challenging. One reason for this is the lack of necessary information like the energy demand of existing productions systems. Other times information is not accessible with reasonable effort and required quality. Hence, the energy and media demand of planned production systems cannot be predicted accurately enough. [1]

Against this background, the authors developed a modular framework for the eco-efficient planning of process chains in automotive component manufacturing [2,3], whose structure and planning tools are briefly presented in the following section to form the motivation for an efficient data integration. In section 3, the state of the art and research with regard to data integration is discussed while section 4 presents the novel concept and application cycle for the integration of production and inventory data to support the planning process and tools. Subject of section 5 is its prototypical implementation on an existing crank shaft production system.

2. Framework for the eco-efficient planning of process chains in automotive component manufacturing

In the field of automotive component manufacturing, machining processes are currently predominant. Since the

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energy and media requirements of machine tools represent a significant cost factor, a planner can directly influence the operating costs through optimally dimensioned machine tools and machine components.

The basis for the modular framework consists of specific planning tools tailored to the respective planning phase, which are backed by the Data Provision module (see Fig. 1). The strength of this framework is that the planning tools are on the one hand able to create all relevant data based on forecasting functionalities. On the other hand, all planning tools are also designed to work efficiently with empirical data from the Data Provision module. [2,3]

The planning tools of the framework are briefly presented in sub-section 2.1; a more detailed description can be found in [2]. Sub-section 2.2 focuses on the detailed concept for the Data Provision module. The data flow within the framework is subject of sub-section 2.3 and includes the motivation for efficient data integration, which will be the focus of the following sections.

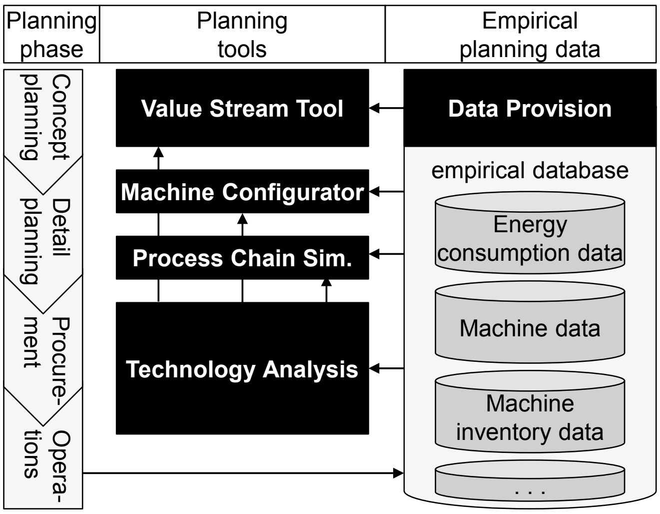

Fig. 1: Modular framework for process chain design

2.1. Planning tools

With the VALUE STREAM TOOL, the basic value stream of the process chain to be planned can be defined. Starting from raw and finished parts, the planner specifies the geometry and material data as well as the production process for each production step. The tool then calculates an approximation of the expected major cutting times and energy requirements.

The MACHINE TOOL CONFIGURATOR determines the optimum dimensioning of the machine components such as spindle, coolant system, cooling units, etc., depending on the manufacturing process and the process time which is limited by the value stream design. The energy requirement is calculated load-dependent for each relevant component.

The DYNAMIC PROCESS CHAIN SIMULATION was developed with a focus on ease of use by the planner via an Excel frontend. It serves for further planning of the process chain with regard to buffer dimensioning and design of the technical building equipment (e.g. compressed air system).

The TECHNOLOGY ANALYSIS module can, on demand, serve as a bridge between the process chain planning tools and the empirical data basis being represented by the Data Provision module. As such, it enables the planner to conduct technology and machine comparisons during all planning stages and hence supports decision processes. It comprises three main functionalities: First is the comparison of different manufacturing technologies based on criteria such as achievable process rates and specific energy consumption. Second is the functionality for a statistical evaluation of machine tool data coming from the Data Provision module to identify trends and correlations (e.g. actual energy demand vs. rated power for specific machine tool types). Third is a benchmarking functionality, which aims at identifying best-in-class machines.

2.2. Concept of Data Provision module

The DATA PROVISION module taps all relevant data sources such as energy and media measurement data from the energy management system, machine master data from inventory databases and operating data from machine data acquisition systems. This data is integrated to provide state-based energy and media demands that are correlated to the respective production job and parameters for each machine. Fig. 2 shows the realization of the Data Provision Module.

The main input is the energy consumption data from existing energy data acquisition systems. Since planning tools have no use for large data sets of power consumption as available in the database, a structured format for reference data needs to be provided. To achieve that, the data provision module structures consumption data according to the VDMA 34179 standard into four machine states: working, operational, standby and off [4].

Often, energy data acquisition is performed independently from other systems. To assign energy consumption values to the four machine states as described, the Data Provision module is connected to the database of a machine data acquisition system. For handing over the reference data including information about the machine and the production process, the Data Provision module is also connected to the machine inventory database.

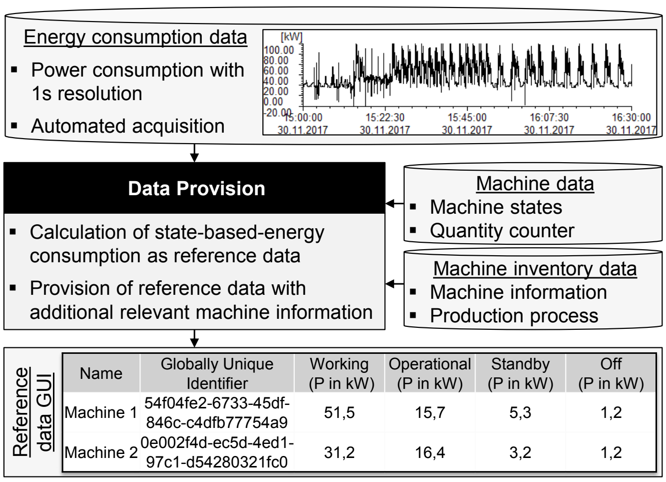

Fig. 2: Realization of Data Provision module

The Data Provision module itself is processing the data from these systems to calculate state based energy consumption values and hence provides reference data including necessary information about the machine and its manufacturing process for the planning tools.

2.3. Data flow within the framework

The planning tools Value Stream Tool, Machine Tool Configurator and Dynamic Process Chain Simulation form the core of the framework and are employed consecutively during the planning process. In doing so, the number of required machines and the resulting process times of the Value Stream Tool set the boundaries for the Machine Tool Configurator which in turn provides detailed load profiles and process times for the Dynamic Process Chain Simulation.

Additionally, these tools can benefit from empirical data coming from the Data Provision module. Based on the rough process data generated in the Value Stream Tool, the specific energy consumption of the processes can be extracted from empirical data to allow of a rough energy demand forecast. The detailed dimensioning of machines within the Machine Configurator can be skipped or shortened, if best-in-class machines for the given production job can be identified in the Technology Analysis module. In this case, machine characteristics can be imported and slightly modified in the Machine Tool Configurator or directly be adopted for the Dynamic Process Chain Simulation.

The individual tools and modules of this framework have been specifically designed for seamless collaboration and data exchange. However, for the integration of further (external) software tools, it becomes obvious that a homogeneous and standardized data management is essential for providing consistent inventory, process as well as energy and media consumption data. To-date, different company systems might not even use common machine identification numbers, for instance. This highlights the importance of a general concept for data integration between production and planning tools. To show possible solutions, section 3 will discuss state of the art approaches of data integration.

3. Approaches of Data Integration

Several authors have presented approaches to make use of the energy consumption of existing machines during planning phases to predict the consumption of future production systems (see e.g. [5,6,7]). A major obstacle for using these concepts is the lack of data consistency between production and planning software tools.

As outlined before, a prerequisite for planning tools is the availability of data from running productions. Machine and energy data acquisition systems are established in many manufacturing companies. That means the necessary data is already acquired, but is not yet easily usable for the suggested approach. Often, this is caused by the acquisition and storage of data in different systems without interfaces [8]. To give an example, the energy consumption of different machines is not comparable without knowledge of the machine type, the production process and the product. To provide relevant information for factory planning, these different information need to be condensed. Additionally, not only the planning process can profit from this information, but also potential improvements for running productions can be detected.

To establish the required data consistency between different software systems without just building one-on-one interfaces, standardized communication protocols are needed as well as common semantics. A concept of how these common interfaces could look like is offered by the Reference Architecture Model Industry 4.0 (RAMI). The initiative tries to define a general framework for the industrial internet of things and integrates the hierarchy levels and life cycle phases of a production system as well as software layers in a three-dimensional model [9].

To establish a standardized communication layer, the RAMI suggests OPC UA as a common communication protocol [10]. Another central element of the RAMI is the concept of the administration shell. It suggests that any relevant component contains self-descriptive information in its individual administration shell [11]. For the semantic description of information, various existing standards might offer case-specific solutions. One solution for the description of factory structures and engineering data is AutomationML (Automation Markup Language, AML). For classification of objects, eCl@ss is preferred [12].

AML was developed as an exchange data format for production planning information. It especially aims at connecting heterogeneous software tools. An important concept of AML are role classes, which define general meanings or functions of objects independently from a specific instance. These role classes are giving semantic information about the machine, independently from the realization in a specific software system [13].

As this is a file-based format, it is mainly used for asynchronous (offline) data exchange [14]. OPC UA on the other hand, is specialized in online data collection for control devices and IT systems. It defines the communication protocol, as well as an information model to structure data exchange [15].

As Henßen et al show, AML can be transformed into OPC UA information models [16]. This concept allows the integration of offline engineering data into online OPC UA information models. This can be used to accelerate the engineering processes by an automatic generation of OPC UA information models, simplifies virtual commissioning and could integrate engineering data into device controls. This interoperability between AML and OPC UA could also establish common semantics for production planning and operating systems and facilitate the data exchange between planning and production [16]. For the conversion process itself, the Fraunhofer IOSB Institute provides a web-based "AML2UA-Converter" which is used for the implementation of the prototype [17].

One example for the importance of this approach is a clear object identification. At the moment, different software systems often use different identifications for the same physical object. By creating an object in AML, a Global Unique Identifier (GUID) is generated automatically [14]. This GUID can also be integrated into the OPC UA information model to serve as an identifier. Thereby, the GUID also can identify the object e.g. in machine data acquisition, enabling acquired data to be compared to the relevant engineering data.

Besides the identification of an object, it also needs a semantic description of its function. One possibility for realization are standardized descriptions like eCl@ss. eCl@ss offers a hierarchical system for classification of materials, products and services. Therefore, the combination of AML and eCl@ss provides a structured format for engineering data with a clear definition of its objects [18].

Consequently, a combination of these three standards, AML, OPC UA and eCl@ss, might be a solution for the previously shown lack of data consistency between production planning and operation. In the following, a concept for data integration based on these three standards is presented.

4. Concept for integrated data provision

Fig. 3 shows the developed data provision concept. First step is the concept planning and detailed planning phase (1). The presented planning tools support the definition of the production system and the selection of most efficient manufacturing processes. To transfer the required engineering data such as process definitions and machine descriptions into different software tools, AML is used as a neutral data format (2).

During the automation and procurement phase (3), the AML models of the single machines are enriched with further details. Nevertheless, AML is not supposed to be a universal data storage format; instead, it is only used as an easily accessible exchange format.

To integrate basic engineering data into the machine control, the AML file is transferred to OPC UA, enriched with other OPC UA information models and implemented into the programmable logic control (PLC) of the machine (4). This information, integrated into the PLC, can be used as a basic administration shell (5).

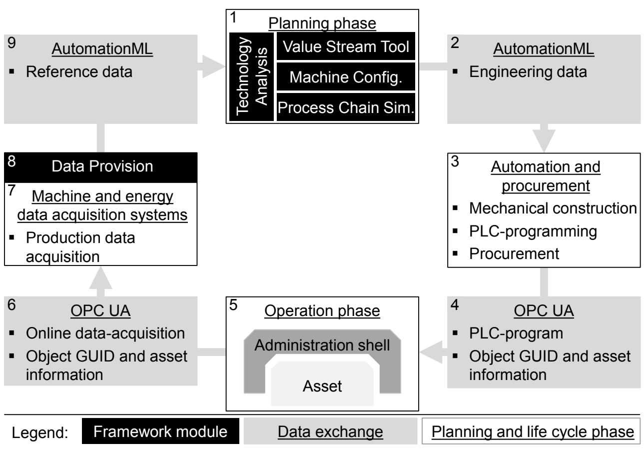

Fig. 3: Integrated data provision concept [3]

OPC UA is also employed to acquire production data as well as engineering information of the machine (6). For machine and energy data acquisition, established systems can be used. Additionally, for online production data, available engineering data like GUID and machine information can be used for data interpretation (7). As the planning tools are not supposed to interpret acquired energy raw data, the pre-processing of collected data is done by the Data Provision module (8).

Condensed to planning-relevant reference data, AML can also be used to make production data available for factory planning software (9). The described data provision concept enables data consistency between production planning and operation. Certainly, not all needed interfaces have been established in available software yet. Nevertheless, section 5 will describe a prototypical realization with available tools, illustrated at a case study for energy data transparency for a production line of automotive components.

5. Prototypical realization for a crank shaft production line

To prove the practicability of the discussed concept, two main aspects need to be examined. First, the technical realization of described interfaces via AML and OPC UA are analyzed and second, the generation of relevant reference data from acquired raw data, as described in 2.2, is investigated.

In the following, these aspects will be discussed in a case study, describing the prototypical concept realization within a production line for crank shafts of car engines. The considered line consists of 21 machines, mainly high automated machining centers. It carries out the mechanical processing of casted crank shafts in a large-batch production.

As state of the art software systems for machine and energy data acquisition are available for the examined production line, the acquisition process itself is not presented in the chapter. A further detailed validation of the developed planning tools, using provided reference data, can be found in [2].

5.1. Realization of data consistency via AML and OPC UA

To visualize the structure of the AML format, Fig. 4 shows a simplified example of a production line modeled in the AML Editor. It shows a hierarchically structured model of the production, beginning from the top level Engine Factory, over the Mechanical Production department and Crank Shaft Line 1 down to the machines. This example also shows some components of the Machine 2. In Fig 4, Machine 2 was assigned two supported role classes (SRC). First, a classification according to eCl@ss, identifying Machine 2 as a turning machine. Second, a classification according to DIN 8580 standard [19] defining the performed manufacturing process as turning.

Fig. 4 only shows a simplified model; however, more complex structures of a production system like product-process-resource relations can also be modeled (see e.g. [20]).

Besides this structure definition, any object contains attributes, describing necessary information about itself. As mentioned in section 3, any object also has a GUID for identification. As also discussed in 3, these AML structures can be converted into OPC UA information models to hand over the engineering information to officers and systems from the operation phase of the production system. As this concept is not established in the examined production line, a simplified method of data acquisition and pre-processing is needed.

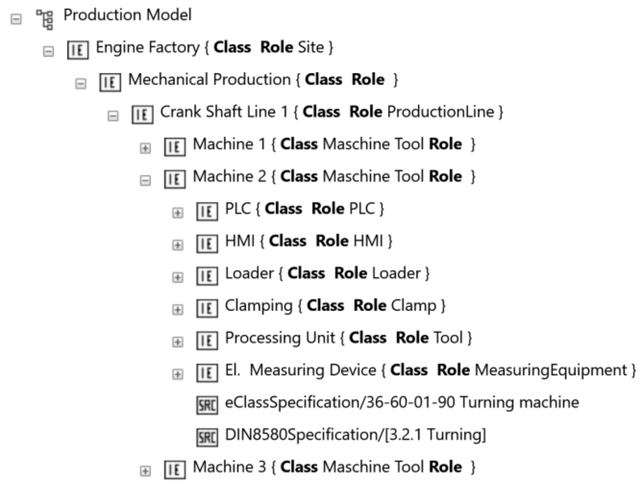

Fig. 4: Simplified model of a production line in AML Editor

5.2. Prototypical implementation of the Data Provision module

To face the demands of current production systems and heterogeneous software environments, a simplified model for Data Provision, based on available data sources is implemented to provide the presented planning tools with production reference data.

The main input is energy consumption data from the existing energy data acquisition system. For Crank Shaft Line 1, the power demand of every machine is monitored in one second intervals and saved in a database. The energy data acquisition system is independent from machine data and has no interface to the machine data inventory. As described in section 2.2, the Data Provision module connects the data from these three systems, by accessing the existing databases via Open Database Connectivity (ODBC) interfaces.

To integrate the different data models of the three systems, take into account the complex relations of objects within the production system and retain the possibility of further extensions, a graph-based data model was chosen. In order to keep the prototype compatible to existing software and IT infrastructure, it is realized as a Microsoft SQL database, although it is not fully suitable for graph databases. The developed data model is shown in Fig. 5. Each object within the production, independently if it is a physical object like a machine or logical like a cost center, is modeled as a node. These nodes are connected via edges that define the relationship between two nodes. A separated table defines the globalID of every database entry. To determine the function of a node or edge, it is classified by a type, e.g. as a machine, measuring device or material flow. Depending on the type of an object, various attributes can be assigned, like a machine type or manufacturer. The value of the attributes itself is stored in the values table. A special type of values are time series, like acquired energy data, which are stored in the Time Series table.

Certainly, this structure has noticeable drawbacks. Database queries are much more complex which reduces the performance. Moreover, the graph model reduces data integrity. However, the advantage of this model is its flexibility and simplicity, as a complex production system including all of its internal relations, is difficult to model in a relational database.

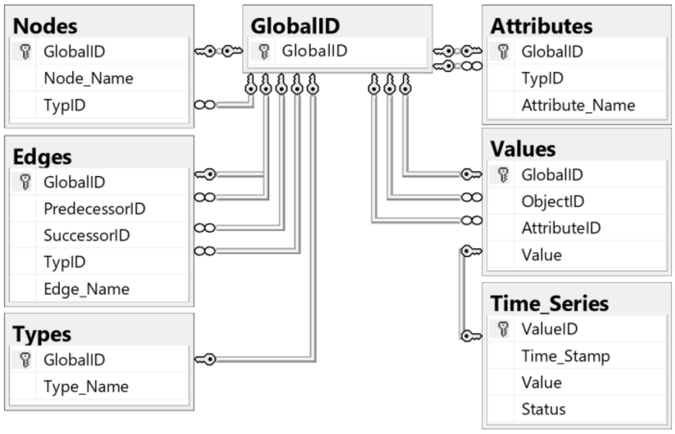

Fig. 5: Graph based data of the Data Provision Module

To access the database, a graphical user interface (GUI) is implemented. The main part of the GUI is the machine search, pictured in Fig. 6. It enables the search for machines in the database according to different attributes. Besides, a free, text-based search is possible to search for

- specific object type according to eCl@ss,
- manufacturing process according to DIN 8580,
- manufactured part,
- production unit and
- machine manufacturer.

Especially the search for eCl@ss and DIN 8580 is important as it enables the user to find similar and comparable machines. In the pictured example, two similar grinding machines from Crank Shaft Line 1 are displayed.

The calculation process itself starts with loading the machine states from the machine data acquisition system. To fulfill the measurement guidelines from VDMA 34179, transition times between states, ambiguous states like machine failure as well as too short working periods are not included in the calculations. To fulfill this, the algorithm analyzes the raw data and assigns machine states according to VDMA 34179 standard. E.g. working is only assigned, if the machine processes without disturbance for at least two cycle times. Micro stops like tool changes and loading procedures are included to the working state. For operational state, only failure free stops, like waiting for parts, are included, failure caused stops are excluded. In the next step, power consumption data is assigned to the relevant machine states. For the calculation of reference data itself, start and end date can be chosen to analyze a defined period. For this period, the average power consumption for the four states is calculated.

Consequently, external influences on the energy demand of a machine, like fluctuating utilization can be reduced. As the described production line manufactures only one product, it is not necessary to distinguish the consumption of different products, but could be added if machine data acquisition also acquires the manufactured product. The reference data is

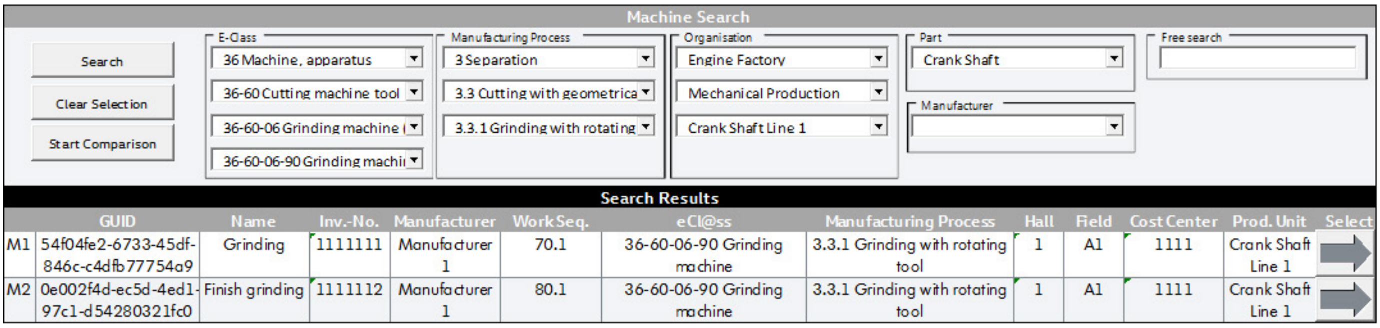

Fig. 6: Machine Search GUI

visualized in a GUI as shown in the lower part of fig. 2. These data can be post-processed in the Technology Analysis module and provided for the different planning tools in the next step just as presented in [2].

Consequently, a comprehensive data set including machine and process characteristics and energy consumption data is available for

- the tracking and validation of machine vendor specifications regarding the energy demand,
- the use in future planning processes with similar technologies,
- simulation studies within the continuous improvement process of the existing line and
- as a basis for all Industry 4.0 applications (e.g. digital shadow) to be implemented.

6. Conclusion and outlook

The presented integrated data provision concept is still under development and not completely implemented. To this point, only the generation of reference data from acquired raw data and the provision to developed planning tools is automated. The automated integration into the AML format to provide the reference data to other software tools with an AML interface is still under development.

All in all, the presented modular framework enables the planning of energy- and cost-efficient production systems. The developed planning tools allow factory planners to take the energy consumption of future production systems into account. The combination of model-based demand prediction and empirical production data can be used during different planning phases.

The concept for integrated data provision gives an outlook, how data consistency between planning and production can be realized based on open standards and existing technologies. At last, the prototypical realization shows how energy data from existing production systems can be used as reference data in production planning software.

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