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Advanced use of data as an enabler for adaptive production control using mathematical optimization – an application of Industry 4.0 principles

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Abstract

This paper deals with the need for more advanced and mathematically based planning and scheduling tools for production systems with complex flows which are subjected to constant change. To develop and utilise such tools, better data acquisition and aggregation from the operational level on the shop floor is needed. An information infrastructure has been proposed to enable this novel type of optimized adaptive scheduling to achieve significant improvements in production efficiency. The solution is based on a system architecture and an information infrastructure with a middleware that provides a specific production cell with all the data relevant for scheduling.

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Keywords: Industry 4.0; Adaptive production planning; Optimization; Information architecture

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1. Introduction

For a long time, it has been a well known fact that variation leads to production inefficiency. The reduction of variations has therefore been one of the starting points for successful production control strategies such as Lean and variants of the Toyota Production System. Some businesses do not, however, lend itself easily to this type of standards and logic. An example is the production of jet engine and aircraft components that often are produced in functional workshops. GKN Aerospace Engine Systems is a company that develops and manufactures a wide range of different components for jet engines. For different reasons, dedicated product flows are difficult to motivate and results in solutions where a large mix of low volume products have to share a limited amount of resources. This may create complex flows where the planning and control conditions are subjected to constant change [1].

This type of production logic therefore demands a more adaptive production control to reach high efficiency, something that previously has been hard to achieve due to the lack of the required data and computational methods. The use of modern industrial IT solutions enables real time access to large amounts of data, which creates new possibilities when these data are combined with modern data management and recent findings in optimization methodology. GKN already has experience from developing and using advanced optimization algorithms [2, 3] to schedule individual production cells, for example in a heat treatment facility which is a shared resource for many products. The results have shown considerably improved throughput and shorter lead times and the experiences, so far, have also recognized that this type of production control could be used much more frequently and in other workshop areas. However, to be more efficient and effective in creating and using those scheduling tools, the required input data should be made more easily available.

The Industry 4.0 concept provides a vision, platform and architecture [4-8] to lead the manufacturing sector towards the smart factories of the future. Parts of this address the requirements of flexible reaction of manufacturing systems to changes in terms of product variability, demand fluctuations and process disturbances etc. GKN is partner in an EU HORIZON 2020 project PERFoRM (Production harmonizEd Reconfiguration of Flexible Robots and Machinery). The project is aiming at concepts for agile, networked plug-and-produce production systems in order to achieve a flexible manufacturing environment, which includes being dynamically adaptable to changing production environments and conditions. PERFoRM intends to integrate and harmonize existing research and innovation results of the CPPS (Cyber-Physical Production Systems) paradigm and present a generic modular system architecture for open communication and standardized data exchange [8, 9, 10].

The purpose of this paper is to report, in an industrial context, the requirements for how to improve current scheduling tools, that is implemented at GKN today, and a concept for how to accomplish such a solution. The paper describes how the required information architecture can been designed and combined with the novel type of optimized adaptive scheduling, that can be more easily adapted and implemented in more production areas to achieve a significant improvement in production efficiency. The remaining part of the paper, which also constitutes the method for the paper, is organized in the following sections. Section 2 provides a description of the current scheduling logics, and IS/IT infrastructure. Section 3 is an analysis to identify improvement areas. Section 4 defines requirements and Section 5 proposes architecture to accomplish the goals. Section 6 discusses the conditions for implementation and the expected results. Section 7 sums up the paper and presents conclusions and future work.

2. Definition of current production planning and scheduling system

2.1. Several types of logic for production planning and control

The manufacturing resources within GKN are divided into several, more or less functional shops, which normally handle a number of products. The logic of each shop, or shop area, can differ significantly, and the logic of the production planning and control therefore must be derived from each shop's "structural properties", that determine how it can operate. Two types of logic that are of interest for GKN are:

- Adaptive production control for "open" shop areas, i.e. ordinary shop areas with many processes.
- Production control using advanced scheduling for delimited production cells/areas, i.e. areas with clear boundaries and limited number of resources.

2.2. Adaptive production control for "open" shop areas

The open areas generally have a large number of different products passing through; many of the resources are shared between these products. The situation in these areas is very stochastic, which requires an adaptive scheduling approach. GKN is currently looking at a control strategy where the demand situation downstream (defined as the ratio between actual work-in-progress and planned WIP) for the competing components in a resource are compared. The component with lowest ratio gets highest priority. The resource situation downstream is used as a secondary parameter for this comparison. This strategy tries to ensure that the overall flows are kept "on track" in a self-regulatory way. This approach, however, requires access to real time data about WIP along the production flow as well as workload at the resources. Studies at GKN have indicated that this type of production control has significant advantages over simpler methods such as static priority rules, e.g. FIFO (First In First Out).

2.3. Production control using advanced scheduling for delimited production cells/areas: The heat treatment facility and the scheduling process

GKN already uses advanced optimization algorithms to schedule individual production cells. In this paper, the implementation of the internally developed scheduling tool SOLV [11] at the heat treatment facility will be used as an example. The heat treatment facility is a highly utilized shared resource that is used for a number of products. The customers to the facility are the other shops in the factory, but also some external customers. The heat treatment process is regulated by a number of process related requirements that varies from product to product, for instance regarding processing times and temperatures. Additional characteristics as sequence dependent set-up times must also be considered within the scheduling process.

The facility has six furnaces with different characteristics, which means that different products fit the furnaces in different ways. Some of the components that arrive at the facility are late, some are ahead of the production plan and some are just in time. The furnaces are also heavily utilized, so it is important that they are used as efficiently as possible. Due to this very complex planning situation, it is very hard to efficiently schedule where and when to treat each component. The heat treatment has therefore historically been characterized by changes in priorities, re-scheduling and long queuing times. The customers to the heat treatment facility have therefore shown a great "interest" for the progress of their own components in the facility, which has complicated the everyday life for the facility's planner.

When a component arrives at the facility, it is the planner's task to schedule it in the best possible way. This is not a trivial task, as implied above; there are a number of matchings between product, furnaces and product recipes that need to be made. To these constraints are the priorities to meet customer demand added.

The current information flow that SOLV uses to calculate schedules for the heat treatment department is illustrated in Fig. 1. The information is preprocessed in the SOLV database, and the planner triggers the generation of an input data file for the mathematical optimization model (integer programming), which is then solved for the coming 24 hours. The resulting schedule is presented at a web site on the GKN intranet.

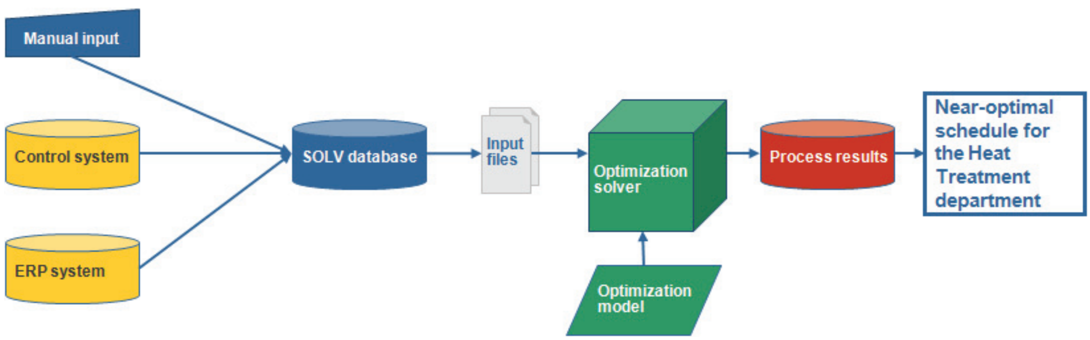

Fig. 1. The figure illustrates the current information flow used to calculate schedules for the heat treatment department.

From the description above, it is evident that production planning and control strategies as Lean or using fixed time slots etc. is not really appropriate due to the constantly shifting conditions, as these principles requires a low level of variation to be efficient. Instead, if the use of the furnaces is to be maximized, the planning and control data need to be up-to-date, so that the production schedules can be adapted and kept up-to-date.

3. Analysis of current system

3.1. Planning and scheduling

The current approach at the factory is mainly based on the use of human observations and information gathering and sharing. This can be supported by lean production methods and approaches for visual management. One disadvantage of the traditional lean shop floor management is that the data generated by the lean methods are seldom digitally acquired, and not seamlessly integrated in the shop floor data management systems [10]. Therefore this data is not available for agile processes linkage and applications for more advanced, mathematically based tools.

The access to real time planning data has facilitated the use of the optimization model, which has significantly increased the available capacity at the heat treatment facility. Up-to-date information about delivery times from the facility is now also readily available to its customers, which is much appreciated. Fig. 2 illustrates an example of the effects in increased utilization after 6 months of usage.

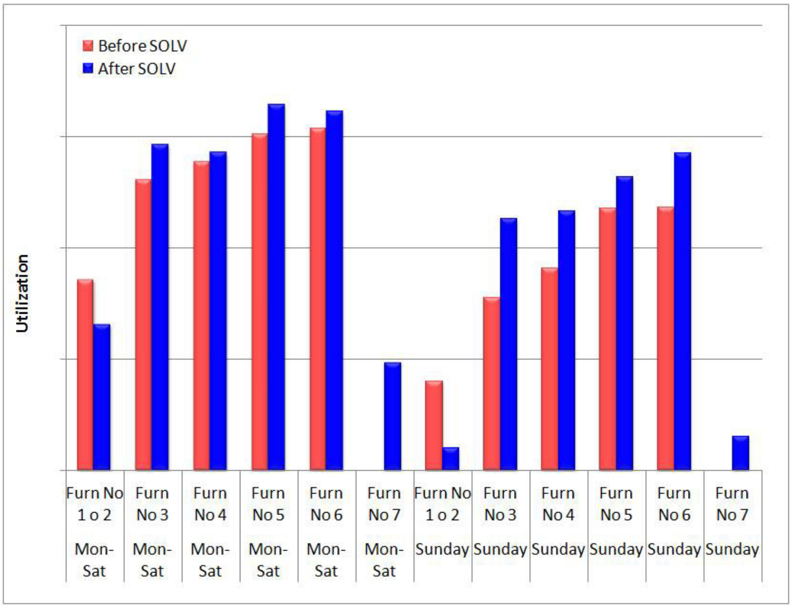

Fig. 2. *The average utilization of the heat treatment resources has been significantly increased by the usage of the optimal scheduling tool SOLV. The averages 'After SOLV' have been calculated for the first 6 months of usage of SOLV, and the averages 'Before SOLV' have been calculated for the corresponding months the previous year.*

The required information is data about which products that are in the furnaces, queuing at the furnaces or expected to arrive at the furnaces within the planning horizon. It is obvious that this information needs to be acquired in "real time". Demand data, as recorded in the current manufacturing plan is also required. Technical data that describe the heat treatment recipes, specific for each order, expected lead times for different recipes are obtained from statistical data, and regularly updated. The states of the furnaces (incl. maintenance requirements etc.) also need to be accessed.

Currently, the required information is obtained from several systems, as SAP and Microsoft Access, and put together in a database application which is used by the user to create the input to the optimizer. For this application the time delays, for data updates, are minor compared with the heat treatment lead times, which is important for the concept to work efficiently.

As indicated previously, the planning data is presently assembled from a number of different sources, where the majority of them was defined and developed prior to the optimized scheduling. The majority of these data sources is unique to the heat treatment facility, and not designed to accommodate the optimization models requirements. Some of the data also has to be entered manually. For this particular case, this is of limited consequence, as the comparatively long lead times within the heat treatment facility decreases the need for frequent updates of real time/on-line data. The heat treatment is, however, only one small part of the plant. Other production areas have other requirements and often need more continuous access to planning data. A general information structure is therefore required to facilitate a more general, and more efficient, implementation of this type of optimized scheduling.

3.2. The information infrastructure

In the current IS/IT system, all data (master data) is stored and managed through the SAP ERP system (Enterprise Resource Planning), which provides functions for production planning, scheduling and MRP (Materials Requirements Planning) and it also collects different kind of documentation from the processing and inspection in order to guarantee traceability.

The current shop floor IT systems and network are designed mainly for direct communication with CNC-machines (Computer Numerical Control), robots and other equipment as the information flow in the typical day-to-day process is to download programs to CNC machines, robots and other equipment that need specific control code, and to upload data such as measurement data from CMM (Coordinate Measure Machines) or CNC machines. Also some condition or process monitoring, as well as stops are logged in the OEE system (Overall Equipment Efficiency). There is no typical SCADA (Supervisory Control And Data Acquisition) or MES system (Manufacturing Execution System) and not much communication between different machines or cells, other than within well defined work centers or cells, typically robot to PLC (Programmable Logic Controller). There is mainly a vertical integration and very little of a horizontal integration and control.

PERFoRM intends to integrate and harmonize existing research and innovation results and prepare standards to facilitate industrialization and dissemination of distributed modular approaches, in accordance with the CPPS (Cyber-Physical Production Systems) paradigm. CPPS are characterized by collaboration and the capability to share information among production resources, robots and machines, which requires a solid manufacturing middleware able to ensure full interoperability via open communication and standardized data exchange [10, 13].

To summarize, the current IT infrastructure is principally based on ERP and MRP for the long term planning, scheduling and management of all data. Thus the production planning and scheduling is performed based on standard operation times as set by industrial engineers, rather than actual data acquired from the operations and its equipment. To make better use of the potential of advanced planning and scheduling tools, it is required to access data from the production execution level, using an architecture centered around a middleware that enables interfaces between the available systems.

4. Requirements for the design of future system

For industries with functional workshops and an increased degree of digitalization, there is a huge opportunity to use the data in control systems and ERP systems to optimally plan the workshops in order to increase production without investing in additional resources. Most workshops have special features in their planning situation, so the scheduling tool needs to be adapted to the current situation. Therefore, software that facilitates the necessary adaptations that is needed in each workshop should be developed. This should include: the user interface, the data interface with the workshop control system, and the building of the mathematical optimization model. The key functions and requirements for the next generation of planning and scheduling system are:

- Data such as order number, operation number, material number and due dates of the jobs in the queue to the workshop to be scheduled are needed to be retrieved from the ERP system. From the machines' control systems data on ongoing jobs and the machines' status need to be retrieved.
- Seamless and frequent updates of the data are needed. It is not "real time critical", but the frequency must be shorter than the cycle time of the production orders in the resource that is scheduled.
- The ability to apply the solution to various types of production systems, especially for shop areas with short cycle times, high mix of products, large volumes and automated systems. (A specific use case in the PERFoRM project is planned for GKN).
- The availability of equipment such as machines, tooling etc. needs to be known as input to the scheduling model. Information about planned maintenance or other down time must be available and gathered.
- Personnel resources also need to be included in the model and optimization, at least for some type of shop areas. Therefore, data about operators' availability, their skills, as well as production support (e.g. technicians) for the planning time frame is required.
- The scheduling system and its optimization will require objective functions, e.g., to minimize tardiness and/or earliness (JIT), the sum of the jobs' completion times, or to maximize energy savings etc. The optimal choice of objective function depends on the type of shop area and its logistic conditions.

To accomplish the need for transparent and seamless data acquisition, a Middleware will be needed. In the PERFoRM project a list of technical and functional requirements have been defined [13]. From an industrial perspective, it is expected that the migration of the technology will be done in different areas over a larger period of time. Besides basic requirements for data security, reliability and industrial standards, there are some other requirements of particular importance and interest:

- A Loosely coupled SOA (Service Oriented Architecture) using Web Services.
- Extendable and adaptable open architecture and/or plug-in support through a defined interface.
- Scalability of the system, to scale to the needs in terms of hardware requirements and distribution.
- Modularity of the system, i.e. that it is built with different modules to allow tailored functionality for each case.

5. Proposed information system architecture

The core ideas and principles for the architecture have been described in earlier publications from the PERFoRM project [10, 12, 13]. The architecture is based on definitions of functions and levels defined by the ISA95 standard (ISA 95.00.01 Enterprise-Control System Integration). The key element is a Middleware that act as a common interface between the diverse production resources' control systems, SW applications and databases. The solutions need to ensure a transparent secure and reliable data flow vertically and horisontally. An important architectural element is the interconnectivity of heterogeneous devices and applications, and the integration of legacy systems. The use of standard interfaces and technology adapters is needed to mask the legacy systems and expose their functionalities according to the PERFoRM standard interfaces. The standard interface is based on IEC 62714 AutomationML data models for the machinery environment, but further developed with a data structure and classes to meet the involved partners and use-cases. For the GKN case, it is implemented in OPC-UA (Open Platform Communications – Unified Architecture) as transport protocol.

The application and adaptation of the generic PERFoRM architecture have been further developed and adapted, to fulfill the requirements stated in section 4, for the purpose of optimized planning and scheduling. The principle model of the architecture is illustrated in Fig. 3. This will make it possible to feed the different systems with the relevant data, process and feed the SOLV database. R1 – RN are the number of production resources in the shop area for which the scheduling tool is used. Those are defined in the PERFoRM ML, as a standardized data model and structure. For the purpose of collecting data to feed the scheduling tool, primarily data to calculate actual process times (average/mean times) are needed. Also information about unplanned stops etc. is of interest. Signals that trigger events such as "start", "stop", "finished" etc. can usually be monitored or logged. However different adaptors or wrappers may be needed to collect and transmit signals in a desired format, especially for legacy equipment. However, there is a large variety of commercial solutions available that can be used to implement the solution using OPC-UA to provide a standard interface and data communication protocol from resource or sensor level to a database that can be accessed by or within the middleware. The solutions may differ depending on the installation of the OPC-UA interface. The Middleware will provide the data communication functions necessary to transfer the data between systems and the optimization tool database can be fed with the required data, and the result is sent to each of the production resources. For the Middleware, there are a number of different alternative solutions [13], still under investigation, to see how the requirements can be met and which the most cost effective solution is.

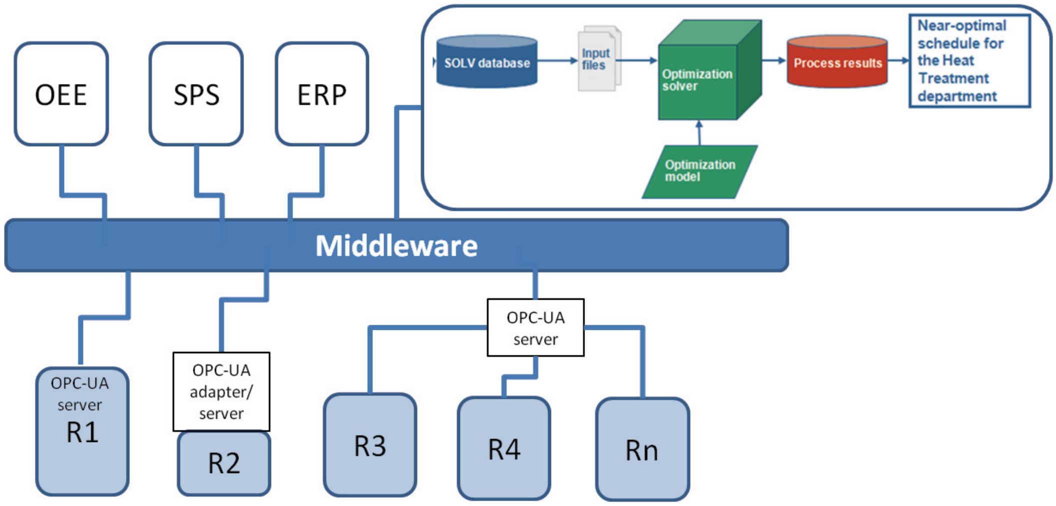

Fig. 3. The proposed architecture for the purpose of optimized planning and scheduling.

6. Discussion

Presently the data to feed the scheduling algorithm is obtained from a number of discrete sources. Some of the data (including statistical data) is compiled much less than frequently than the scheduling interval, due to practical reasons, some data need to be entered manually. It must be loaded separately into the scheduling tools, where it is compiled, inspected and supplemented before it is entered into the optimizer. In the future, the vision is that all the data should be seamlessly compiled and checked before it is inspected and released into the optimizer. A lower degree of manual input, and a higher degree of automatic examination of the data, will ensure more up-to-date data; and reduce the risk of entering erroneous data into to the optimizer – but also reduce the amount of work required by the planner. Each production area will need its customized optimization model as each area has different characteristics and thus are restricted by different set of constraints. With the current set-up, a specific model has to be designed for each area. A solution where these different models can be assembled from model modules will enable much more efficient exploitation of the methodology and also improve the efficiency of the further development as well as maintenance of these models. In the case of adaptive production control, there is much less room for manual inspection and verification of the production schedule. The data flow needs to be automatically transformed to a sorted list of products/orders that is presented each time a new order is to be submitted into the resource. This means that the data flow needs to be even more automated.

7. Conclusions

This paper has addressed the need for more advanced and mathematically based planning and scheduling tools. To develop and utilize such tools for different kinds of applications and type of conditions, better data acquisition and aggregation from the operational level on the shop floor are needed. The paper describes how the required information infrastructure can be designed and how it can be combined with this novel type of optimized adaptive scheduling to achieve a significant improvement in production efficiency. The solution is a based on a system architecture and information infrastructure with a middleware that provides a specific production cell with all the relevant scheduling data. These data include information about where the products are in the production cell as well as the rest of the flow; the status of these products, influence on the content and characteristics of the upcoming processes; and the condition of the production equipment.

Future work will be devoted to the implementation, testing and validation of the architecture, first as an application to a demonstrator cell for automated fabrication. This work also needs to be accomplished by the use of a common, cross-platform data model and through the use of adapters for legacy resources. The implementation of the new solution also requires that a migration strategy is developed to ensure the exploitation of the project results.

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