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Closed Loop Cycle Time Feedback to Optimize High-Mix / Low-Volume Production Planning

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Abstract

High-mix / low-volume production environments require advanced planning systems to optimize their outputs along conflicting targets such as cost, time and quality. However, given the constant change in those environments, it is becoming increasingly complex to provide a planning system with accurate input information. This work presents an approach to create a closed-loop information system to automatically update selected planning parameters based on historical product and process information. By using available shop-floor data directly from the machines, the information quality level in high-mix / low-volume production environments can be significantly increased.

Keywords: production planning, closed-loop information system, centurio.work

1. Introduction

Today's high-mix or job-shop manufacturers push their traditional manufacturing systems towards more complex "mass customization" strategies to fulfill increasing customer demands in regards to delivery times, quality and costs. Mass customization strategies focus on providing individualized products at cost of mass production, while acting in a volatile and uncertain market environment and therefore will further increase complexity in the manufacturing environment [1], [2].

A successful implementation of a mass customization strategy requires a strong focus on differentiated planning approaches and fast shop-floor-control mechanisms that provide most accurate information about current state as well as are capable of adapting quickly to changes in the manufacturing environment [3].

As a solution, manufacturers traditionally implemented different production planning and control software systems along the automation pyramid such as Enterprise-Resource-Planning (ERP) systems, Manufacturing-Execution-System (MES) or a combination of such.

However, manufacturers often struggle to provide the required master data quality as input for such ERP / MES systems, hence, limit systems capabilities to execute the planning and control tasks accordingly. Studies in the machining industry highlight that many reasons for unsatisfying master data quality can be linked to the following two aspects [4]:

- Human-centered planning approaches leaving opportunity for organizational / human error (e.g. undefined responsibilities for data maintenance, insufficient frequency of updating procedures, dependency on best-guess estimates from experienced personnel).

- Lack of vertical system integration supporting personnel to manage their planning and control data in increasingly complex manufacturing environments (e.g. lack of proper software systems in general, large effort to realize data exchange interfaces between ERP and MES, missing link to real shop-floor data from machines and other equipment).

To reduce the impact of the challenges described above, the authors suggest that alternative approaches shall target closed loop system architectures that (a) limit the human interaction with the data as much as possible and rather use experienced personnel in an advisory role within the process as well as (b) fully close the integration gap between the entities that create data and the systems that use the data for planning and control purposes e.g. ERP or MES systems.

In this paper an approach to close the loop between shop floor and ERP focused on cycle times is presented. This approach uses features of the *centurio.work* software platform. *centurio.work* is based on Business Process Model and Notation (BPMN) workflows and allows connecting different systems, machines and employees. With this solution it is possible to gather contextualized data from different sources, interpret them and make a suggestion as realization of a closed loop.

The paper is structured as follows. In Section 2 master data management and its influence on production is discussed. Section 3 outlines related scientific approaches and follows by the theoretical outline of a closed loop in master data update. Section 4 introduces the idea of an closed-loop architecture and defines most important process steps needed. In Section 5 a proof of concept based on *centurio.work*, a modular platform is shown. As example the demo production of a part in the Pilot Factory 4.0 of the Technical University of Vienna was used. On this part the benefits of the closed loop are presented.

2. Master Data Management and its Influence on Production

The availability of correct information at the right time has become key for today’s businesses success and the success of production planning as the interface of business and production. As the efficiency and functionality of software systems and infrastructure improves, an organisation gains advantage of the availability of more and more data and connections. Along with that it is seen that different areas of an enterprise have created islands of information coherence, in particular among business processes and production processes. To exploit that, both areas are widely operating with the same information basis also known as master data. Master data is defined as data that usually is not being changed over a longer period of time, hence, is often referred to be static. Examples in the production area are supplier information, work stations, bills of materials or production routings [5], [6].

Today, static master data builds the backbone of every operating software system. In regards to production planning and shop floor control, high-mix manufacturers widely use an ERP system and its respective master data as the leading system to run their manufacturing systems effectively and efficient. Trends towards a more flexible manufacturing setup, such as mass customization, Industry 4.0 or digitalization, force companies to keep their ERP system, its functionalities and therefore its related master data highly adaptable[1], rather than static.

A good example for required master data adaptability in today’s ERP systems is the cycle time per production working step, functioning as an important connection of shop floor and business world. All planning and control modules of an ERP system in regards to resource, lead time and cost planning are based on cycle times, documented in the production routers for a certain product. The better the quality of those cycle times, the better the overall performance of the planning and control modules in the ERP system. However, ever changing product specifications, new machine equipment, new production personnel and other production related changes, challenge high-mix manufacturers and their complex systems to continuously update related cycle time master data in the ERP system to correct its impact on production planning and shop floor control. This means the ERP system must be as agile as the overall production itself.

This need introduces an opportunity for enterprises to establish a higher information integration. An approach to understand the essence of master data and the opportunities created by an organized view on business information, is Master Data Management (MDM). MDM focuses on data management procedures that support the acquisition, integration and resulting distribution of consistent, timely, consistent and accurate master data. In order to establish a well working production planning process the availability of correct data is crucial. In a high mix low volume product range MDM might not be an efficient and sustainable approach without software support.

3. Related Work

Along with data management there has a large amount of literature and scientific research been done. For this paper to position it in a research context, there are several perspectives solving part of the problem listed. However, in most cases the practical approach and industrialization aspect have not been considered.

Enhancing ERP system's functionality with discrete event simulation [7]. This paper gives an example to use simulations to keep master data up to date. Thereby the authors focus on a more generalistic business view, rather then related master data in production. The context in this research is targeting functionalities in ERP systems and automated material requirement planning, that is equally dependent on correct master data.

A holistic approach to diagnose uncertainty in ERP-controlled manufacturing shop floor [8]. A similar has been chosen in this paper, however the focus is related to a statistical approach rather than simulation. Moreover, uncertainty is in this case named as the cause for misleading performances in production, such as late delivery.

RFID-based wireless manufacturing for real-time management of job shop WIP inventories [9]. The core of this paper is to equip the shopfloor with RFID technology to gather data that will also be feedback to an ERP system, how this can be done is not described.

[1] https://www.it-production.com/allgemein/datenpflege keine-industrie-4-0-ohne-saubere-stammdaten/

Benefit oriented production data acquisition for the production planning and control [10], this research realized master data as a potential root cause for production planning shortcomings. Nevertheless a consistent loop from data collection to correct master data in an ERP system is missing.

Data-driven production control for complex and dynamic manufacturing systems [11]. In this paper the authors focus on production control and the best feedback of the current state of production that allows best decision making.

Increasing data integrity for improving decision making in production planning and control [9]. The approach in this research shows a highly technical algorithm that aims for highly correct data. The practical approach has seen that there is also a high need and benefit for adaption on a higher level.

A dissertation submitted at the TU Munich with the title “knowledge based system for product specific order data machine occupation” aims for a highly complex data collection and the subsequent processing with algorithms to improve planning quality. Interestingly enough, master data was outlined as a core success factor [12].

4. A Closed Loop to align Shopfloor and ERP

Manual timing all different material types, work centers and variants of products is very complex and costly. As a result, different mathematical methods that only require snapshots of operations were developed. However, maintaining these models and updating their input data still is a time-consuming task. So why not use the existing data from shop floor systems and retrieve the cycle times in a standardized approach? In particular with a fully digitized shop floor, the necessary mechanisms could be implemented in a data platform, a digital core to continuously process data.

Fig. 1 describes the process how the actual update of master data regarding standard cycle times looks like. The core component is a continuous loop of updated information The necessary steps are discussed in the following.

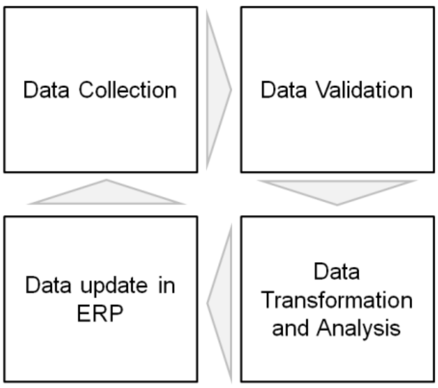

Fig. 1. Closed loop process steps

4.1. Data Collection

For data collection several technologies exist. The most important thing is to use an interface which provide semantically rich data. In the manufacturing domain currently two technologies fulfill this requirement. On the one hand there is MTConnect[2], a read-only interface based on HTTP using an eXtensible Markup Language (XML)-based information model. On the other hand there is OPC UA [13], the so called enabling technology for Industry 4.0. OPC UA provides an object-oriented meta model which can be used to describe complex data structures [5].

The major problem of data collection is the contextualization of the data; time series data of sensors are typically not enough. These data have some correlations to more abstract information e.g. the workpiece information or the work order. The effort of collecting data and preparing them for the data analysis is still very high.

Currently there is a trend for creating platforms which gather information from different systems. A good example in the manufacturing domain is Siemens Mindsphere[3]. They all have different connectors for data collection but they still save the data as time series and not in the context of their generation. A platform which is capable saving the information in a contextualized way would significantly simplify the data collection process.

4.2. Data Validation

Extracting information from time series data in an automated process may be subject to errors. Individual datasets possibly deviate from what they actually should be representing, e.g. because a process has been interrupted, some trigger condition has been missed due to a communication problem, etc. Such invalid data sets have to be identified to be able to exclude them when calculating new values for master data. Thus, the data first have to undergo a plausibility check. Depending on the master data to be updated, this may also include identifying outliers, i.e. data sets that are in principle valid but do not represent normal or average operating conditions. AI techniques such as classification can be used to automatically detect invalid data sets and outliers during the data validation phase.

4.3. Data Transformation and Analysis

The further processing with trustworthy data is performed within a platform approach that takes over the task of data processing procedure from the shopfloor to ERP level. The core of this step is to bring the data in a context, enrich the data with process information retrieved from machine, operator and material. Thereby the time measurement can be enriched with attributes that allow further differentiation and more trustworthy associations can be made. Once this data transformation has been done and the data is available in a structured way, additional analysis can be performed. To aim for a industrial practicability, simple but efficient statistical methods must be selected. One approach could be using a boxplot [14]. This setup

[2] https://www.mtconnect.org/

[3] https://siemens.mindsphere.io/en

provides information about median or average, upper and lower quartile, the whisker and most importantly outside values in both directions. Hence this method relates to basic standard deviation the limit values can be set according to the production paradigms. At this stage, data can be collected and aggregated based on equal attributes, e.g. type or product specification.

4.4. Data Update in ERP

Once the data platform collected enough values, the aggregation an update procedure can be established. The initial step to do so would be to set up an interface from the platform to the ERP system. Typically this can be done with web-services. One way along the automatization pyramid is to provide actual cycle times from the ERP material master. The other way provides the measurements done on shop floor level. If the gap between those times is within a given timeframe, there is no update required. To reduce manual input among a large product range with a multitude of machinery, small changes within predefined boundaries can be done automatically. However, if these boundaries are exceeded, a new cycle time will be proposed to an operator for validation and justification by experts.

5. Proof of Concept

To demonstrate the feasibility of a closed-loop cycle time update, a proof of concept prototype has been implemented at Pilot Factory 4.0, a test lab ran by Technical University of Vienna.. By this, improvements of master data quality in regards to part cycle time on machining equipment were determined.

To generate real production data, a sample part called “Lower Housing” has been chosen. The part is a standard aluminium part and requires several turning and milling operations for finishing, using different machining technologies (cf. Fig. 2). All operations have been performed on turning and milling machines available at the Pilot Factory 4.0.

Fig. 2. Sample part “Lower Housing”

The prototype for the closed-loop system itself, has been fully implemented within the framework of an software platform called centurio.work. centurio.work provides modules to execute all process steps described in Section 4 and will be explained in detail in the following subsections.

5.1. *centurio.work* - Architecture

centurio.work [15] is a modular framework based on processes which allows data collection, data storage, data analysis using apps and a feedback to other systems, in this case an ERP. The architecture depicted in Fig. 3 shows this. *centurio.work* follows a true service-oriented approach and has advances like the BPMN [16] modelling language, and flexible execution [17], [18].

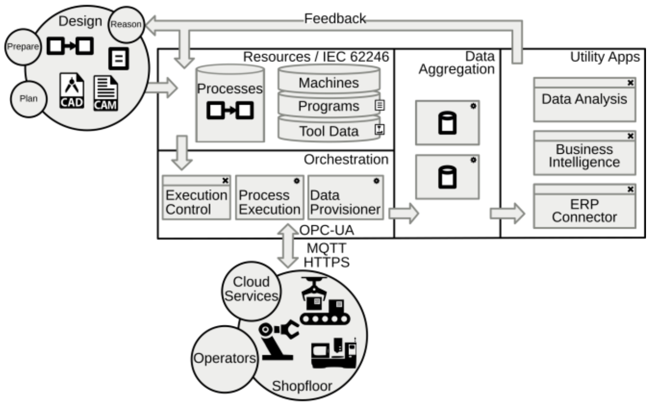

Fig. 3. Centurio.work architecture

The architecture is strictly separated in contextes with a well defined communication flow. The production planning and control systems as well as the Production Lifecycle Management (PLM) systems are allocated in the Design bubble on the top left. All necessary data for production, e.g. the processes and resources, are transferred during design-time to the resource context in *centurio.work*. During run-time *centurio.work* communicates with other systems using the data provisioner service. The Orchestration context is based on processes which are executed using a process engine. All data collected during run-time are pushed to the Data Aggregation context, where different Utility Apps can access the data.

5.2. Closed Loop Cycle Time Feedback implemented using *centurio.work*

For the presented approach using centurio.work for data collection, analysis and feedback to an ERP, a demo production run in the Pilot Factory 4.0 of the Technical University of Vienna was done.

During this, the process models for data collection based on generic models described in [19] depicted in Fig. 4 have been adapted and used. In total the amount of 2 GiB of data for the creation of a Lower Housing on an EMCO MaxxTurn 45 lathe machine and an ECMO MaxxMill 500 milling machine and has been collected.

The data collection is realized by some processes depicted in Fig. 4. The process on level 1 is permanently listening to the start of a certain NC program from one of the two machines. Level 2 shows the process for monitoring a machine during production. The processes are modelled in the same way as described in [20]. For the scenario used in this paper relevant parameters for the ERP have been monitored, e.g. minimum- maximum-, average-production time, and work order. Level 3 is necessary to check if the production is finished. During processing, the machine operator stops the machine for measuring some parameters. Afterwards he either starts the NC program again or jumps to the NC line where he has stopped before. The other option is, that he can mark the part as "good" or "bad", bad meaning that the part is waste. The process on level 4 gathers data. The values during processing have been collected using an OPC UA interface of the machine at a rate of about 50 Hz.

5.3. Result of Lower Housing Production

The lower housing production is split in several lots. The data analysis is done with a ruby script[4] which is public available and is part of the Utility Apps in *centurio.work*. The first batch consisting of five parts were the prototype parts, where the machine operator checked and adapted the NC programs. The data of these lots gave us a starting point. The result of this batch is displayed in table 1. It shows the five parts and its gross and net time. The difference between is caused by manual adaptations of the machine operator e.g. stop the program an measure some features. After these adaptations he steps forward in the nc program. The net time is the time which the program runs without any overlap.

Table 1. Production time of Lower Housing batch 1

Part	Turn 1		Turn 2		Mill 1		Mill 2	
	Gross [s]	Net [s]	Gross [s]	Net [s]	Gross [s]	Net [s]	Gross [s]	Net [s]
1	90.4	90.4	1229	1229	9030	4357	4048	4048
2	90.2	90.2	1154.0	1154.1	7420	7420	3932	3932
3	94.8	94.8	1149.9	1149.9	7717	7717	3958	3958
4	92.6	92.6	1172.3	1172.3	6776	6776	6815	3984
5	92.2	92.2	1153.1	1153.1	7456	7456	3940	3940
Avg.	**92.1**	**92.1**	**1171.8**	**1171.8**	**7680**	**6745**	**4539**	**3973**

The second batch consisted of two parts. Here no adaptation of the program and tools was necessary and therefore, the production time was shorter than the planned value of the previous lot. The results of this batch are shown in Table 2.

Table 2. Production time of Lower Housing batch 2

Part	Turn 1		Turn 2		Mill 1		Mill 2	
	Gross [s]	Net [s]	Gross [s]	Net [s]	Gross [s]	Net [s]	Gross [s]	Net [s]
1	93.5	93.5	1196.7	1196.7	6262.9	6262.9	3929.7	3929.7
2	96.9	96.9	1157.5	1157.5	5905.6	5905.6	4011.4	3905.5
Avg.	**95.2**	**95.2**	**1177.1**	**1177.1**	**6084.3**	**6084.3**	**3970.5**	**3917.6**

As shown in the two tables the production time of the second batch is shorter than of the first. Only the Turn 1 Operation is a bit longer, because an additional operation was added to the turning process. The average values of the second batch were the basis for the new planning values in the ERP system. As this information is stored in a context, including material and routing information, the microservice can crosscheck the cycle times. As there is an update suggested, the previously established web service allows a direct override of the cycle times in the ERP system. This information conduces as the new reference for planning, calculation and future updates .

6. Conclusion and Future Work

Current trends in manufacturing such as mass customization will further increase the complexity in industrial planning and control systems and require improved master data quality. Today, human interaction as well as missing system integration limit data quality levels that can not cope with these future demands. This paper presented an approach to solve this situation by establishing a closed-loop data update process for ERP systems using a software platform called *centurio.work*. The approach was applied in a demonstration scenario at Pilot Factory 4.0 in Vienna, producing a sample part called "lower housing". Firstly, the results show that the contextualized data collection using the process engine integrated in *centurio.work* significantly supports the data transformation process in generating meaningful update values for the ERP system in an automated and error-proof manner. Secondly, the results of the sample part production indicate the value of updating ERP planning parameters for a complex manufacturing system, consisting of several machining technologies and a variety of parts with different process steps. Further research is needed to apply more sophisticated methods of statistics and data analytics in the data transformation process step. In the future this approach can also be used to adapt the processes dynamically based on the collected data.

[4] https://centurio.work/lowerhousing_logextract.rb

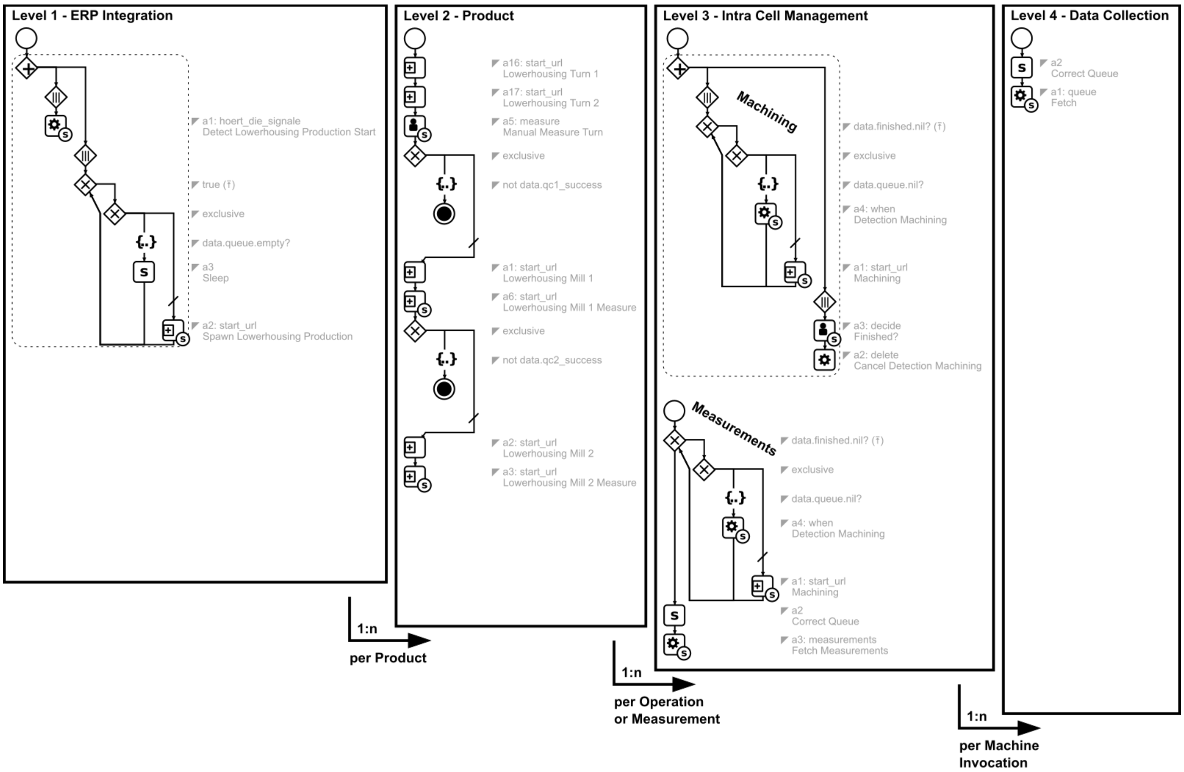

Fig. 4. Processes for Lower Housing production

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