Managing Production Complexity with Intelligent Work Orders

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Keywords: Intelligent Work Order, Decentralised Production Systems, Process Configuration, Information Management.

Abstract: Progress of Industrial Internet of Things is rapidly increasing the amount of data collected from manufacturing operations. This data can be utilized to control and improve production systems in various ways. Production control systems play a key role in realizing the potential cost savings and productivity increase. Companies are required to manage increasing complexity while shortening response times to changes. A concept of Intelligent Work Order (IWO) is proposed to assist in these challenges. It supports local or distributed decision-making, and decreases integration complexity between different factory IT-systems. IWOs also increase information visibility at the shop floor. The IWO structure and functionality are described with a discussion of the benefits of the approach.

1 INTRODUCTION

Production processes are facing increasingly higher demands for planning and control that start to resemble one-off production. The Web-based consumer trade is pushing the requirement of minimal lot-size down as the customers want and are capable for selecting or even configuring digital product orders at the level of detail that so far has been viable for large companies placing orders for big production lots or for skilled sales personnel specifying high-cost products, such as cars or kitchen furniture, for and according to the customer.

Allowing the increase in the product configuration variability also increases the need for more integrated IT and manufacturing systems along the ordering-production planning-manufacturing chain. Likewise, more flexible and accurate monitoring and control systems on the factory floor are then needed for maintaining the product quality and efficiency, ensuring the human-machine safety under the increased variability in the production process, and managing the significantly more complex logistics associating each individual product to its components, production schedule and the customer data.

The industrial recognition of the need to increase digitalization and to introduce novel control systems has led to German Industry 4.0 initiative (Brettel et al., 2014) and other similar approaches. A survey conducted in Finnish manufacturing industry (Järvenpää et al., 2015) showed similar interest from the companies but also a large gap between the academic concepts and the status of the control system implementations. In this paper a concept of Intelligent Work Order (IWO) is presented, which is an effort to bridge that gap and show how existing Manufacturing Execution Systems (MES) can be extended to meet the future requirements of production control systems. In Section 2, decentralized production control systems are discussed in general and in relation to IWO. Section 3 presents the structure and functionality of IWO, while Section 4 is dedicated for information systems integration. Benefits of IWO are summarized in Section 5, before closing remarks of Section 6.

2 DECENTRALIZED PRODUCTION CONTROL

Commonly stated reasons for distributing production control are managing complexity and gaining the ability to react quickly to production changes or disruptions in the system. Decentralized control systems are built on local decision making and lack a holistic view over the whole system. In agent based control systems, such as in (Caridi and Cavalieri, 2004), a coordination process is designed to diminish

Toivonen V., JÃďrvenpÃďÃď E. and Lanz M.
Managing Production Complexity with Intelligent Work Orders.
DOI: 10.5220/0006507801890196
In *Proceedings of the 9th International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management (KMIS 2017)*, pages 189-196
ISBN: 978-989-758-273-8

the negative effects of having a narrow view of the whole system, while in holonic manufacturing systems (HMS) the decision makers are only connected to higher level controllers (McFarlane and Bussmann, 2000). This means HMS are always hierarchical, while the form of agent based systems can vary more freely. These approaches are applicable both in a single manufacturing site or a supply chain (Saharidis et al., 2006). Some often noted benefits and hindrances of centralized and distributed control policies are listed in Table 1 (Zannetos, 1965) and (Toivonen et al., 2011).

Decentralised control systems are sometimes viewed to contradict any kind of forward planning of production. More practical view is to plan on aggregate level and allow a decentralised control system enough decision making power to take care of execution. Another integrating approach between planning and control is to have the decentralized control system forecasting future events (Valckenaers and Brussel, 2005).

3 INTELLIGENT WORK ORDER

Intelligent work order provides one possible infrastructure for realising an agent based production control system in real environments. In this case IWO can be an information agent or sometimes both an information agent and a controller. Control decisions (such as resource allocation and job dispatching) are done based on the information gathered by the intelligent work order. In order to fully realise a decentralised control system, IWO needs to fulfil the following set of minimum requirements:

- Ability to recognize and communicate with resources
- Ability to create work orders for subtasks
- Ability to communicate with a higher level controller
- Inclusion of a decision making control logic

Intelligent work order collects information from several corporate IT-systems and can also be used to collect and communicate process information for various purposes.

Table 1: Comparison of decentralized and centralized control hierarchies.

Decentralized	Centralized
Benefits	Benefits
• Increased flexibility due to self-configuration that also enables efficient response to changes. • Provides decision-making power to lower level managers or workers with better experience on local processes. • Efficient development of the local operations and processes. • Detailed and up-to-date information. • Clearness of goals and responsibilities. • Expanded responsibility and decision-making authority which often result in increased work satisfaction, motivation and efficiency.	• Lower costs for organizational and transaction management. • Fast dissemination of information. • Fast decision-making due to one author controller. • Consistent processes and practices. • Combined control system that enables fast review of resource allocation.
Disadvantages	Disadvantages
• Higher costs for organizational and transaction management. • Possible lack of coordination among autonomous managers. • Lower level managers' decisions could be damaging, because they do not necessarily have full understanding of the wider perspective. • Lower level managers may have goals that are different from the goals of the entire supply chain. • Lower level managers may make decisions that are not in the organization's best interests.	• Inflexibility that is caused by the complexity of information systems and organization structure. • Weak ability to respond to changes that is caused by the complexity of organizations. • Challenges that result from information validity and integrity • In a strongly centralized organization process optimization is difficult due to the complexity of the organization's structure. • Lack of collaboration that is caused by a centralized control system which is managed by a dominant authority.

3.1 IWO Functionality

Traditionally a work order describes either the process or the end result of the required task. These work orders are commonly delivered to the factory floor in paper format (Järvenpää et al., 2015), which means they have limited information content and are difficult to maintain. Intelligent work order is digital and contains up-to-date information of both process (e.g. instructions, NC-programs) and output (e.g. specifications, quality control guidance) in a machine and human readable format, as shown in Figure 1. IWO is role- and context dependent. It can be configured based on the operators' personal characteristics, preferences and experience. For instance, the way to present the work instructions may be modified based on the operator's native language and experience.

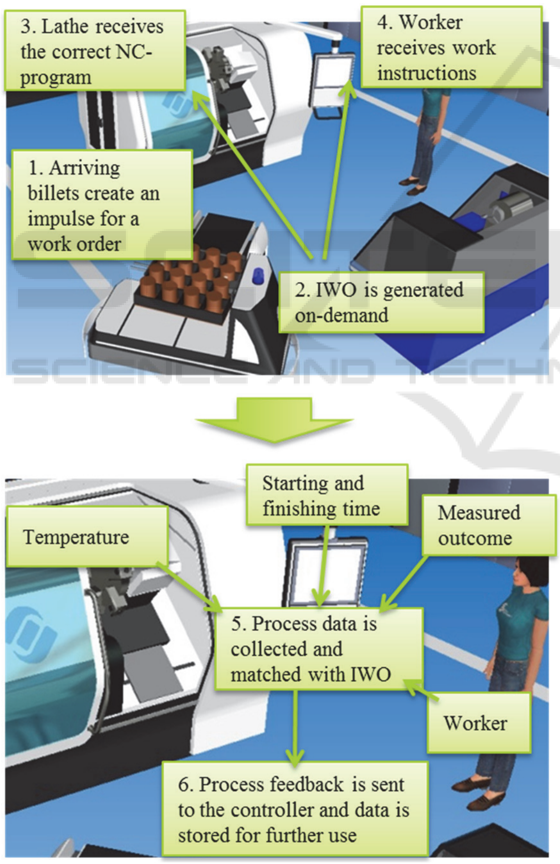


Figure 1: Principle of Intelligent Work Order.

IWO is created only at the time it is needed, after which it calls for resources required in the process. This approach is intended to ensure that changes made in ISA-95 level 3 and 4 planning systems (ANSI/ISA-95.00.03-2005) are automatically considered in the process level. After completion of the task, process data is aggregated to a desired level of detail and stored into the memory of IWO. Without aggregation a lot of the data acquired from the process might not be directly very useful (e.g. signal values) to a higher level planning system. The collected process information can later on be viewed from resource, time, customer or product point-of-view. This allows managers to link process information with businesses processes in a meaningful way.

3.2 IWO Structure

IWO is an information element that has a clearly defined lifespan from start to the completion of a specific task. Figure 2 shows a generic IWO structure and information content that has been deducted from the requirements. A digital work order is essentially an information distribution agent that contains all relevant process information. The additional features of IWO require a more diverse structure. Communication interface allows user specific views to information and the realisation of online negotiation or alarm systems. Data collection interface tries to standardise some of the factory floor data exchange and decrease the related integration effort. Processing unit contains the local controller in distributed systems and can be utilised to perform some operations and reduce complexity of centralised control systems. Data storage is a short term storage location for work order data and feedback from the manufacturing process.

The information content of IWO is closely related to the element structure. In addition to the process data, IWO contains metadata defining how information is shown, collected and distributed:

Parent – Defines the process structure

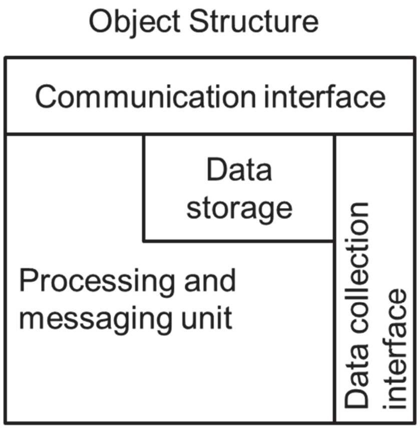
Process Information – Task specific information e.g. work instructions and NC-programs

Information Distribution – Defines connections and integration to other IT-systems

Information Collection – Defines reporting activities and connections and integration to the control logics

Processing and Acting – Decision making and communication block that allows raising alarms, calling other services etc. This part defines the low level controlling logic.

The information content should be fairly similar for any digital work order. The main difference in IWO is the processing block that allows it to be used for decision making.



Information Content

Class	Description
Parent	• *Connection to the process that the task is part of*
Process information	• *Machine readable part, NC-programs etc* • *Order details* • *Work instructions* • *Quality control instructions* • *Picking lists* • *Customer and other additional information*
Information distribution	• *Integration to higher level IT-systems* • *User role definitions* • *UI management* • *Status reporting*
Information collection	• *Factory floor integration* • *Timestamping and reporting*
Processing and acting	• *Calling other services* • *Status monitoring and automated alarms* • *Production control*

Figure 2: IWO Structure.

3.3 IWO Creation and Storing

IWO constructor is responsible for creating and configuring work orders. The main information content of work orders exists in MES and other higher level information systems but the configuration can also be based on the status of the production system. As an example, a work order could be configured to always link with a machine that has the shortest setup time.

IWO constructor needs integration to systems that maintain the work order related information. While system integration is not discussed in detail in this Section, differences of the two main approaches should be noted. Integrating the constructor solely with MES is cheaper and easier than creating connections to several higher level systems. However, it is important to understand the depth of the existing MES integration. Alarming systems and other real-time control methods require a deep integration to ensure up to date information and rapid response capability. If the existing MES implementation contains mainly historical data for aggregate planning or the information content is otherwise limited, the constructor might require additional integration effort to shorten the time delay of information updates.

Table 2 summarises the elements required for creating IWOs.

Table 2: Key elements for creating IWOs.

Constructor	Contains a tool for defining IWO content, see IWO structure for details
	Data storage for created IWO models
	Integration to valid IT-systems for collecting information
Information element (IWO)	A digital work order for production tasks
	Short-term storage for documenting the process
	Communication ability to real-time applications
Distribution center	A database or a server
	Long or mid-term data storage for process information
	An interface for information systems to access process information

After a task has been completed, results are collected and stored for later use. The proposed concept does not describe what should be done with the process data after it has been stored. However, the information should be made available for different IT-systems in a way that does not depend of the MES integration.

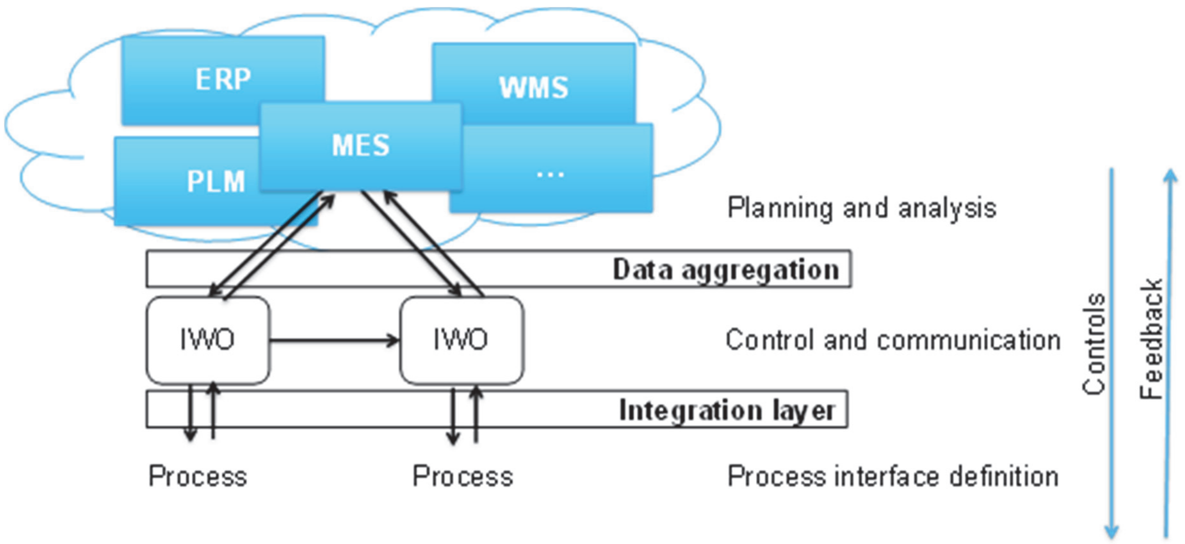


Figure 3: Control hierarchy.

4 SYSTEM INTEGRATION

The approach presented here is meant to reduce integration complexity and improve system connectivity while the related industrial standards are still being under discussion and development. In order to achieve this, the factory floor integration has been reversed to a bottom-up process as shown in Figure 3. This means that production process defines how work orders are brought to and how information is collected from the process. In addition to the lower level integration layer, IWOs form a layer of abstraction between the higher level information systems and the process data. System complexity increases in the lower levels of control hierarchy while the higher level system interfaces stay usually fairly constant. One important aspect of IWO is to provide accurate process level information for later analysis and development purposes. Mapping the feedback information and sensor data against IWO combines process plan, end result and resource, environment and customer data into a single information object.

The link between two work orders describes a process chain where a result from a prior task affects the configuration of the IWO in a later task. The direct communication between work orders is more relevant when one is functioning as the controller of subtasks. The implementation of the system defines how much of the controlling power is given to IWOs and which decisions are made by a higher level controller. The higher level systems are used for planning ahead, which means that the utilized data is always somewhat aggregated and delayed.

4.1 Data Collection

In manual reporting the data must often be written down first and later entered into the system - sometimes by a different person than the one who recorded it in the first place. Typographical and transcription errors are common. Once these errors become part of the data set, they become difficult to detect and eradicate, making all the resulting reports less reliable. At the shop floor of manufacturing companies, there are thousands of operations without any link with the current Enterprise Resource Planning (ERP) and MES solutions. In addition to that, the relationship between shop floor actions and data input into MES is in majority of cases off-line. This means that workers are feeding information of processed jobs manually and often with a time lag to the actual events. That is why, traditionally ERP and MES solutions cannot be used to process real time information from shop floor or to compare real actions with planning. The lack of real time information into the MES and ERP systems are leading to a very low rate of response from the management team, which is leading to a high percentage of scrap, useless consumption of raw materials and energy, increase of waste in process, and nevertheless losses for SME's.

The long and continuing effort of removing waste from manufacturing systems should be directed to information management as well. This does not only involve the system side but even more importantly the practices of producing and consuming information in the factory floor. In this approach a large portion of the information management procedures are defined in the process, allowing similar streamlining and continuous process development as has been executed with Lean methods in manufacturing. This is different from the typical approach where the IT-systems are defined top down and users are constricted to those definitions.

4.2 Integration of Individual Controllers

The trend of digitalization is rapidly increasing the amount of available data from the factory floor. At the same time, the complexity and cost of MES integration are also increasing in the same fashion. This means many companies create subsystems or ‘digital islands’ in domains where the direct benefits of digitalization are greatest. In manufacturing industry this can be seen for example in supplier specific automated solutions that can offer great flexibility but are difficult to integrate under a single controller. IWOs can be used in two different ways to improve the situation:

1. IWO can assist in connecting these islands by providing a common communication interface. In this case defined information can be exchanged between individual systems, but there is no controller linking them as an integrated system.
2. Both systems provide an integration to allow IWO to function as a controller. This takes more effort but allows extended automation and process control. In such an approach IWO can be seen as an integration platform to reduce the complexity and costs of integration.

In a similar fashion, IWOs can be utilized in human-machine interfaces to reduce human input to the machine controller and to communicate the current status and future actions of the machine to the worker. Flexible integration is especially important for increasing the level of automation in industries where it has been difficult.

5 IWO VALUE PROPOSITION

Some of the main benefits and potential applications of IWO are listed here as a summary of the concept. The list is categorised to follow timeline of a process; planning, execution and reporting. MES implementations are always company or manufacturing site specific, which means that the following list is suggestive at best:

Quality of Information

Several practices have been considered to improve the information quality of IWOs. IWO creator is integrated to the original source of information as closely as possible. This is meant to enforce ‘one owner policy’ and reduce harmful data replication to several systems. From the process side the aim is to reduce manual input by increasing automated data collection and also to give control over reporting to the process where information is created.

Targeted Quality Control

One benefit of the Intelligent Work Order is the ability to reconfigure work process in real-time. This can be utilised for example in quality control practices. In case of deviations, such as appearance of a defected part, an additional inspection can be assigned for each task that involves a part from the same batch. IWO allows to focus corrective measures quickly and precisely to the orders that might be affected.

Real-Time Process Control

All information needed to accomplish tasks in the workstation is delivered automatically to the workstations without the need of worker involvement. The information of task status and realized production is always available for production planning and control, which enables fast reaction to possible variations and disturbances. The application of rapid response in quality control can also be extended to increase system responsiveness in general. IWO allows order and task specific process configuration, which means even individual production orders can be controlled in real-time.

Worker Specific Work Instructions

IWO allows user based configuration of the process information. In practice this can mean, for example, choosing the language of work instructions based on the recognised worker. Similarly new and less experienced employees might get more detailed instructions and be required to sign more additional verifications during the process. Context aware applications can also involve physically readjusting the work place to assist in the operation.

Improved Traceability

Mechanical engineering industry has lagged many other industries in building traceability chains through their supply chains. IWOs provide a systematic approach for recording in-house actions in detail and as such improve product traceability.

Automated data collection

One key driver of digitalization is to reduce manual handling of information. This is essential for reducing mistakes and shortening the time delays between events and information availability. IWO supports introduction of novel reporting and sensor technologies by simplifying their integration to the MES.

Development and Analytics

The information generated during the production processes, e.g. recordings, task duration, measurement and quality data, and other data collected by various sensors, are linked to the intelligent work order. Analysing existing products and processes is facilitated by linking the product, resource and operational process data. The generated expressive information object can later be used for different analytics and for increasing the accuracy and quality of planning and control.

6 DISCUSSION

We have proposed a concept of intelligent work order (IWO) to tackle increasing complexity, to improve real-time control and to allow a better integration between different factory IT-systems. The trend of digitalization has increased the interest of manufacturing industry in similar approaches and industrial implementations do exist. We believe the additional effort required for MES development and integration has a very short payback time in most manufacturing environments that have a dedicated production control system in place. The concept should be applicable to different control hierarchies and MES implementations, and allow cherry picking the benefits that are chosen as key drivers for the investment.

The concept is providing tools for closing the gap between current MES implementations and the future needs from the control systems. There is a recognized need for convergence of factory IT and operational technology. Tools and methods are required especially to facilitate integration of legacy hardware in factories. These should allow both collecting real-time information of production processes and moving decision making power closer to the process while maintaining a holistic view of the production.

This research has started from interests of our industrial partners and we are hoping for this work to contribute to industrial adaptation of the presented ideas and digitalization of manufacturing industry in general. At the moment, industrial demonstrations are being planned in order to further advance this development. Interesting applications could also be found in rapidly developing fields such as collaborative robotics.

ACKNOWLEDGEMENTS

This research was carried out as part of the Finnish Metals and Engineering Competence Cluster (FIMECC)'s MANU programme in the LeanMES project.

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