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Versatile information provisioning in a configure-to-order production environment; a case study

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Abstract

Problems or challenges at operational/tactical levels in configure-to-order production environments are more often than not caused by inadequate information provisioning. Additionally, incomplete, uncertain, and ambiguous information hampers adequate decision making and control. This is especially the case in configure-to-order environments, where there is a high variability in processes. Consequently, standard software solutions often fail to allow for the required flexibility, adaptability, and agility. Moreover, in industry, software solutions (be it PLM, ERP, IoT, …, MES or CAQ solutions), oftentimes tend to become dominant factors in primary processes, thus further stifling the anticipated flexibility. If, however, these software solutions – here conjointly referred to as Digital Infrastructure – are regarded as subcontractors in a digital twinning approach, the primary targets in production/assembly can remain the driver in the overall process. This paper depicts how this digital twinning approach can be used to establish versatile and adaptive information provisioning. To ensure that the approach is not merely a theoretical discourse, the approach is depicted based on a case study. This case study, embedded in a Dutch manufacturing company for special needs bicycles, is rooted in e.g., the seasonal fluctuation in the market, on the broad product portfolio, but foremost on the ability to strengthen customisation as the unique selling point in that portfolio. For this reason, a use case focuses especially on one of the most demanding parts of the production/assembly-line: the welding robot digital twin for frame welding. On the one hand, this twin encounters all product variants and exceptions; moreover, this twinning approach will aim to provide decision support for upscaling of the production facilities. Next to this specific application, the paper also addresses the middleware solution that is under development to integrate individual applications in the bigger company context and strategy.

Keywords: Digital twinning; Configure-to-order; Information provisioning; Case study;

1. Introduction

Manufacturing companies have the goal to make their production environments as effective and efficient as possible. For this, adequate decision making is a prerequisite, as is the availability of appropriate information, with sufficient completeness, certainty, and unambiguousness. The importance of informed decision-making increases with increasing variability in a production environment. This is particularly acute in configure-to-order (CTO) environments, given its fluctuations in products, processes and process configurations. In such environments, the information provisioning in the company is one of the main facilitators of variability. The information provisioning allows for assessing

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multiple scenarios, which aim to explore potential future circumstances of the production environment and can be rooted in data and information from current, past and (simulated) foreseen situations. Bringing together such as-is, as-was, to-be, and could-be situations is referred to as digital twinning (see section 1.2).

CTO production strategies are often applied to production environments with highly customisable products, where the product aims to fulfil the exact customer needs [1]. A CTO production environment often consists of build-to-plan, assemble-to-order, and make-to-order operations. Consequently, products are mostly produced and assembled from several modular components based on the customers' orders, under the influence of high demand variability and order uncertainty [2,3]. The variability of the order stream requires constantly changing processes, process configurations, resource, and production planning, as well as extensive communication/alignment about all individual orders and their associated arrangements and exceptions. CTO environments are therefore characterised by high demands for adaptability and flexibility of products, processes, and systems [4,5], leading to extremely complex decision-making and information provisioning. Therefore, a CTO company and its shop floor could benefit greatly from being able to access, capture and manage the data and information associated with the order, the product, and its production process. This research focuses on how companies can improve their information provisioning to support and improve decision-making within the CTO production environment. The hypothesis of this research is that effective and efficient information provisioning in CTO production environments is a purposeful basis for improved decision making in operating and managing such environments. In this, information provisioning refers to a systematic, structured way of making information accessible and available.

2. Information provisioning

Decision support relies on the availability of contextualised data, as the basis for interpretation by all stakeholders and perspectives involved. Hence, effective decision support is based on providing the appropriate information, at the appropriate moment, to the appropriate perspective – as the basis for adequate information provisioning. Especially in CTO production environments, problems, or challenges at operational or tactical level often originate from inadequate information provisioning facilitated by the data systems and repositories in a company. These data systems and repositories include Enterprise Resource Planning (ERP), Manufacturing Executing System (MES), Warehouse Management System (WMS), and data providers such as machines and sensors. Where such systems certainly provide specific solutions for production challenges, such as planning and resource management, they can also add complexity to the production environment [3,5,6]. The entirety of these data systems and repositories within a production environment is referred to as a company's digital infrastructure [7], providing the basis for a company's information provisioning.

Where the 'ideal' digital infrastructure would be a sound foundation for decision support, in reality the conglomeration of systems and repositories may offer incomplete, ambiguous, and sometimes redundant representations. Common issues stem from the lack of connectivity between data systems and repositories. As a result, data sometimes needs to be recreated or duplicated in multiple systems by the user, hence creating multiple 'sources of truth' in the production environment [7]. Furthermore, the impact of issues with the digital infrastructure (uncertainty, inaccuracy, incompleteness, redundancy, etc.) are well-nigh impossible to assess, yet the consequences can be significant. In addition, companies lack the ability to extract meaningful data and information from data systems and repositories to make it available for decision support [8].

Besides evaluating the data, also data management can be quite challenging for companies. Most systems that underly digital infrastructures are acquired from external software vendors. The resulting vendor lock-in limits the adaptability of the data systems and repositories. Additionally, it limits the adaptability of information provisioning with respect to current and future processes. As a result, data systems and repositories tend to ordain the primary process instead of supporting it. As these data systems and repositories often fail to deliver the required flexibility, adaptability, and agility, CTO companies often require more versatile information provisioning than the digital infrastructure currently provides.

2.1. Digital Twinning Approach

Whereas the components of the information provisioning system can adequately meet the requirements of individual perspectives and fields of expertise, there is a clear need to mutually align such components in an overall approach to facilitate decision making by multiple stakeholders conjointly. Moreover, such an approach should enable and strengthen scalability, collaboration, and communication between stakeholders. Digital twinning has been identified as an effective tool that can support decision making by representing and contextualising the appropriate data and information in an interpretable and understandable way for the appropriate perspective [9,10]. Digital twinning can therefore be used to provide decision support for optimising production environments [9,11,12]. Moreover, it allows for simulation of what-if scenarios based on potential solution spaces [8,13]. Digital twinning entails the usage of a feedforward and feedback loop between the real-time state of an asset (digital twin), the intended state as-designed (digital master) and the potential state as-simulated (digital prototype) [13].

The digital twinning approach (DTA) is introduced to provide stability to the information provisioning. The DTA aims to facilitate decision making, while ensuring sufficient flexibility and adaptability in the uncertain context of product development [7]. The DTA is instrumental in achieving a company's goals and purpose by focusing on the (contextualized) information content, rather than focusing on the process descriptions [9]. Therefore, the DTA constitutes an information-driven approach, which can be instrumental in supporting the facilitation of contextualized and unambiguous information in different perspectives [7]. This research aims to establish how a digital twinning approach, based on the underlying information provisioning, can provide a versatile, flexible, adaptable, and agile decision making for all perspectives involved under continuously changing circumstances. In a research-by-design approach, this research applies the DTA in a case study to verify the hypothesis (effective and efficient information provisioning as a purposeful basis for improved decision making) and to assess the effects of the DTA on the flexibility, adaptability, and agility of information provisioning.

3. Context of the case study

Assessing the relation between information provisioning and digital twinning in a sheer theoretical way is impossible. Understanding this relation needs to be infused by a realistic environment and representative circumstances. Where several industrial case studies are part of this research project, this publication highlights the case study at the Van Raam bicycle factory. Van Raam produces bicycles for people with disabilities. Since their customers all have different needs, the unique selling point of Van Raam bicycles is the high degree of customisation of their products. The customisation of the products leads to a high level of complexity in managing the production environment. In addition, the company is growing rapidly and has high fluctuations due to seasonal demand. To cope with this, Van Raam applies a CTO production strategy in a production environment that aims to be flexible and scalable. The high variability does not only require scalability of the production environment, but also scalability in the information provisioning. Especially the alignment of the volatile production environment with the evolving information provisioning presents significant challenges.

Until recently, traceability of products and production process at Van Raam was ambiguous, indefinite, and error-prone and the exchange of information between departments was complex and cumbersome. As a start of introducing the digital twinning approach, a blueprint for digital infrastructures [7] was used to analyse the existing data systems and repositories at Van Raam. The use of this blueprint highlighted the high dependency on one software system and the limited connections between the different data systems and repositories. This presented difficulties in maintaining the digital infrastructure and to being resilient to problems and downtime. Additionally, data was not always available or complete, nor was there a structured way to capture data from orders, resources, and processes. Various analyses of the digital infrastructure at Van Raam showed that the current structure of information provisioning is not able to provide the required flexibility and scalability. As a result of the findings, the analyses, limitations on scalability and dissatisfaction with the existing digital infrastructure, Van Raam has decided to develop a new information provisioning structure.

4. Requirements for information provisioning structure

The challenges with the digital infrastructure are certainly not unique to Van Raam. Companies with a CTO production strategy often lack an adequate digital infrastructure to provide information for decision making. The required digital infrastructure needs to inherently change with future changes in the company processes, products and needs. In addition, the information provisioning structure needs to be the intermediary between the different systems and repositories; it will have to act as a middleware for information. Based on the problems described with the current information provisioning in CTO production environments, the requirements for a versatile information provisioning structure can be established. In summary, the information provisioning structure shall:

- Ensure the provisioning of the appropriate information at the appropriate time for the appropriate perspective;
- Have access and provide access to the data and information when needed;
- Be adaptable to current and future processes and data systems and repositories;
- Be able to contextualise and process data into meaningful information to support decision making;
- Unequivocally provide the DTA with perspective dependent information;
- Be scalable to different production environments and requirements of the production environment;
- Provide a single source of truth;
- Deploy existing systems and repositories of the digital infrastructure;
- Consist of reusable components to ensure flexibility and adaptability.

As the concept of versatile information provisioning is impossible to address for an entire company at once, without severely disturbing primary processes, a case study has been defined to act as a proof-of-concept. This case study describes the initial development of the information provisioning structure at Van Raam and shows how the DTA is used to establish versatile information provisioning within the production environment.

4.1. Requirements for the case study

The new information provisioning structure to be developed at Van Raam is the Van Raam Information System (VRIS); it will be developed using the DTA. Next to the general requirements mentioned in section 4, additional requirements for VRIS are formulated based on the needs specified by Van Raam. Firstly, standardised ways of transferring data between their information infrastructure and their machines/equipment need to reduce development time and vendor dependency. Also, components for the new structure should be built in such a way that they are reusable for similar applications. Given the changes and growth of the company, Van Raam aims to simulate a variety of scenarios based on historic, current, and simulated data, in order to anticipate potential futures. This requires the extension of the digital twin (as-is representation of an asset) with a digital prototype. The digital prototype allows for the simulation of what-if scenarios based on historical and simulated data. Finally, since Van Raam is a 'live' production environment, a step-by-step implementation of the information provisioning structure is required. This allows for the development of the digital infrastructure and the digital twin while the systems and processes are running. At the same time, the current data systems, and repositories can be integrated, adapted, or phased out. Therefore, a modular approach and structure is required to ensure adaptability, flexibility, and scalability.

Based on these requirements, the case study aims to further develop VRIS, while and by establishing a digital twin of a welding robot. This simultaneity allows for an iterative approach in which development steps and verification alternate. In this, the welding robot is representative of the many individual components, systems and repositories that will interact with VRIS. The use case is described to illustrate how effective decision support can be provided with the use of a versatile information provisioning structure.

5. Developed information provisioning structure

As Van Raam has a running production, VRIS will be set up based on the currently available data systems and repositories. This structure will be implemented in small steps and any existing interfaces are refactored for the new system. Based on the requirements, VRIS will be developed according to a loosely coupled, high cohesion principle [14]. This allows components, systems, and repositories to be connected and disconnected without affecting or influencing the structure. The main objective of VRIS is to be able to combine different data sources to provide the appropriate information and insights. This implies that VRIS will facilitate the connection of, and communication among, systems and repositories, rather than confiding in the systems themselves. This implies that VRIS reasons from the functionality of system components; consequently, the DTA instigates a critical evaluation of which functionalities are indispensable in the existing data systems and repositories.

VRIS is based on the principle of event logging and streaming [15,16] This implies that all events within the company are captured in a stream, here based on Apache Kafka [17]. Data systems and repositories are connected as subcontractors (producers and/or consumers) of events in a specific log (called a topic). The structure and connection of these topics are based on a domain model that establishes how information types are related and what context is associated with the information. VRIS acts as a middleware between all the data systems and repositories in the digital infrastructure. In addition to event logging, VRIS also consists of microservices, which are processing units running in a Kubernetes environment [18]. The microservices each handle events and process them into information for external data systems and repositories. For example, one microservice handles the events from the ERP system. Since the defined requirements aim at reusing the components within the information provisioning structure, the microservices are developed as reusable software components/ building blocks.

The microservices provide information to users based on a trigger when a particular event occurs within a topic. For example, when an order is entered into the ERP system, an event is created; this event is registered and processed by VRIS that logs the order information from ERP into a topic. The event triggers VRIS to send the Bill of Materials based on the configuration number to the WMS, so that the materials can be reserved for the order. To show the role of VRIS at a specific level of aggregation, a digital twin of a welding robot at Van Raam is developed. The use case shows the welding robot and the digital twin as connected components in terms of the information provisioning structure.

6. Use case welding robot

Welding is one of the most important steps in the production of the bicycles. Van Raam has nine welding robots that can produce twenty-six different frame types plus additional custom frames on request. The production of custom frames adds additional complexity during the production process since it requires the combination of a make-to-order and configure-to-order strategy. Currently, there is insufficient insight in lead times of the welding process and in the effectiveness and efficiency of the welding robots. In addition, there is no means to predict or see the effects of adjusting fixtures or welding programmes on welding efficiency. This information could support decision making to improve the flow and optimise the planning of the welding robots. Additionally, one of the welding robots will soon be moved to a second, remote factory. Van Raam therefore wants to have an overview of the robots and their performance in their own factory, as well as in the remote factory. For this, a digital twin of the welding robot is realised.

The DTA ensures that the twin is based on the requirements of the stakeholders within the company. The DTA helps to determine what data needs to be captured and what information needs to be provided based on the required perspectives. This approach ensures that users are not bothered by redundant or irrelevant information but can make informed decisions, based on the appropriate information. The first step is to define the needs of the stakeholders in order to select the data to be collected. Based on the activities and needs of the employees at Van Raam, three perspectives for the welding robot were defined. These three perspectives are based on the operational, tactical, and strategic view of the welding robots. The operational perspective provides the machine operator with real-time information on takt time, machine cycle times and the number of products produced. The tactical perspective requires information on the cycle time of the frames per robot and the total number of frames produced in the production environment. This helps to plan and monitor production planning and scheduling. The strategic perspective focuses on the operational efficiency of the robots, the uptime of specific robots and the total number of frames produced in a given period.

These perspectives require information from the welding equipment. The communication and acquisition of this information is based on OPC UA [19], providing direct access to robot data. The required welding robot data is collected in a topic and contextualised within VRIS, so that whenever a status in the robot changes, it is captured and becomes accessible in VRIS. The event stream allows for a timeline that shows current and past status overviews. Since the information provisioning structure is information driven, VRIS allows for versatile tailoring of the information for the required

Figure 1: Dashboards of welding robots perspectives.

perspective. Using the data from the welding robots, the three perspectives as illustrated in Figure 1 have been realised. The perspectives make it possible to analyse and reduce the number of common errors based on uptime and error registration Furthermore, the dashboards provide quick reporting capabilities and allow operators to identify errors and anomalies more effectively. The early detection of anomalies in the dashboard provides the opportunity to prevent costly breakdowns or downtime. Moreover, the information provided by the dashboards provides insights that enable better-informed decisions. For example, insights in takt-time (historical and averaged) help the planning department to be more resilient and accurate in its planning. Moreover, to validate and visualise the data, VRIS was subsequently employed to drive an additional fourth perspective, in which a 3D representation of the robot allows for context-dependent evaluation of the data availability and quality. This virtual representation of the welding robot is visualised in Figure 2.

As mentioned, one of the welding robots will be moved to a remote location. The modular approach of the information provisioning structure, the standardised data exchange protocol and the microservices will allow for the extensibility and scalability of the structure to the remote location. The approach and structure will remain the same, only the company-specific details such as processes and perspectives will change. Therefore, additional dashboards can be created, and existing dashboards can be adapted to meet the needs of the stakeholders in the remote factory. Moreover, the current proof-of-concept does not yet allow for simulation or what-if analysis. Further development of the information provisioning and the digital twinning solution using the DTA will focus on incorporating these simulation possibilities.

7. Validation of the approach

In the research-by-design approach used in the welding robot case study, the development steps were continuously and iteratively checked against the requirements specification. Some requirements have been addressed only rudimentary and require more attention in future research, for example with respect to adaptability for future processes. However, generally, all requirements have been met in the welding robot prototype, thus providing an adequate alignment between the theoretical approach and the industrial case study.

In assessing the added value of the approach, it is clear that Van Raam has already identified many benefits in the initial implementation of the approach and the structure. One of these benefits is that VRIS has made it easier to provide insights and reports across the company. In addition, the increased availability of information has allowed the company to create new insights that have already demonstrably increased the efficiency of resources in the factory. It can therefore be verified that the new structure increases the availability of the information from existing systems and repositories for perspective-dependent information provisioning.

Although the DTA is still under development, the advantages of the approach in the company are already becoming visible. VRIS has become the middleware layer to provide information for various need-driven perspectives in the company. Moreover, the company has started to critically assess the development of each component and how it relates to the structure as a result of the information- and need-driven approach of the DTA. This development also considers the modularity and reusability of components. The modularity provided by the structure has increased the resilience of the digital infrastructure, as problems can be traced back to one single microservice – thus significantly reducing the time to find and solve issues. In addition, the approach of making data systems and repositories subcontractors in the structure avoids vendor lock-in, which caters for additional adaptability and flexibility of the digital infrastructure. The modularity, flexibility and adaptability of the structure and the need-driven approach provided by the DTA make it possible to keep the same core structure for information provisioning and to build a flexible shell that can be adapted to the required perspectives, user needs, and company-specific processes. It can, therefore, be verified that the DTA has a positive effect on the flexibility, adaptability, and resilience of the information provisioning. Moreover, it can also be demonstrated that the structure developed using the DTA can meet the requirements for a versatile information provisioning structure.

The application of the approach and the structure in the use case help to validate the effectiveness and efficiency of versatile information provisioning as a purposeful basis for

Figure 2: The welding robot and representations of its digital twin

improved decision making. The use case showed that the information provisioning structure is currently able to contextualise and process data into meaningful information to support decision making for various perspectives. This has resulted in improved insight and control of the production environment through improved efficiency of the welding robots, better planning of the robots, improved communication with and among multiple stakeholders and an improved process flow. Therefore, in the use case, mutually alignment of the components of information provisioning has been accomplished, in an overall approach that facilitate conjoint decision making by multiple stakeholders.

Whereas these findings stem from a single use case, the outcomes, and evaluations of the welding robot use case show that the DTA could be used in a way that is fully independent of the (specifics of) the welding robots themselves. With that, the goal to gain more insight and control over the environment based on improved information provisioning has been reached in a generic manner, thus legitimating the assertion that the DTA can equally attend to different resources, cells, and department on a factory floor. Moreover, the extension of the solution from one to nine welding robots, and soon to another production environment, indicates how scalability is embedded in the approach. The ongoing and evolving implementation of VRIS in the, eventually, entire factory will further validate the flexibility, scalability, and adaptability of the information provisioning structure. Moreover, it will further demonstrate the effectiveness and efficiency of the approach as a purposeful basis for decision support and improved management of the entire CTO production environment.

8. Concluding Remarks

Versatile information provisioning is essential to provide decision support to improve the management of a CTO production environment. A CTO production environment requires a flexible and adaptable information provisioning to cope with the complexity of constantly varying and changing processes and products. The focus of the DTA on user needs ensures that the information is adaptable to the perspectives that are required by the users. In addition, the flexible information provisioning structure makes the components, used to provide perspectives and information, reusable in addressing additional perspectives and other situations.

The information provisioning structure that underlies the use case challenges the data systems and repositories to be subcontractors rather than leading systems. In this way, the need for information drives the demeanour of the systems; consequently, the flexibility of the production environment is not stifled by the data systems, repositories, or (predefined) workflows incorporated in them. The information needs of the company, and the information provisioning structure will lead to more transparent requirements for current and future data systems and repositories that will be (and are) incorporated. The case study shows that it is valuable to employ the DTA and the requirements on the information provisioning structure as backbones for the development or revision of data systems and repositories. The use of the requirements as a driver will further increase the flexibility and adaptability of the information provisioning structure. As a result, companies can provide perspective-dependent information for decision support more effectively and efficiently.

In extending the research project, the case study in this paper is currently restated as the basis for implementing similar information provisioning structures in three other companies. Future research focuses on the adaptability of information provisioning for these companies, based on the DTA. Van Raam will further implement VRIS in the production environment and the company as a whole. In addition, the possibilities of simulating potential and future scenarios based on the DTA in the production environment will be explored.

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