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Digital infrastructures as the basis for implementing digital twinning

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Abstract

Companies aim to spur quality, effectiveness, efficiency, and support growth. At the same time, however, conditions change significantly, imposing demands on companies to be flexible and agile with regard to their production environment. Changes involved are based on the business strategy, internal and external stressors, and impact operational and tactical level. The adaptability of the digital infrastructure determines the flexibility, control, and possibility of supporting decision-making in production processes. This paper specifies requirements and a blueprint for an adaptable digital infrastructure. Furthermore, components such as middleware are described that are needed to enable not only a flexible digital infrastructure, but to get the right information, at the right moment, to the right entity, system, person, and decision-maker.

Keywords: Digital Twinning; Decision Support; Digital Infrastructure; Middleware

1. Introduction

Companies often push digitalisation as the panacea to gain more insight, control, and grip on processes in their company. The underlying aim of the digitalisation push by companies is to increase the availability of data and information to facilitate effective decision-making. Whereas digitalisation might bring data into reach for stakeholders, it does not necessarily provide the stakeholders with more insight into the context, predictability, and verifiability of the awaiting decisions. Decision-making is strongly influenced by the complexity of the data, the context, the information, and the wide variety of stakeholders involved. The challenges related to this are so significant that a broad, structured, and robust foundation for data/information provision is required before individual stakeholders can be facilitated in their decision processes. Because the information and processes in organisations are strongly connected and volatile, structuring all the data, information and processes will be an unattainable task. Moreover, the ability to structure information and to employ those structures depends on the maturity of an organisation. The effectiveness and efficiency of an organisation's foundation to provide data/information for decision processes within the organisation depends on the aptitude to balance process descriptions and information structures with the information content. This publication focuses on that data provision foundation to determine the minimal viable that is required to support the processes, and structure the data, as the imperative for decision support.

For decision support, it is essential to have the data/information available in a contextualised, meaningful manner [1]. The notion data refers to stand-alone facts,

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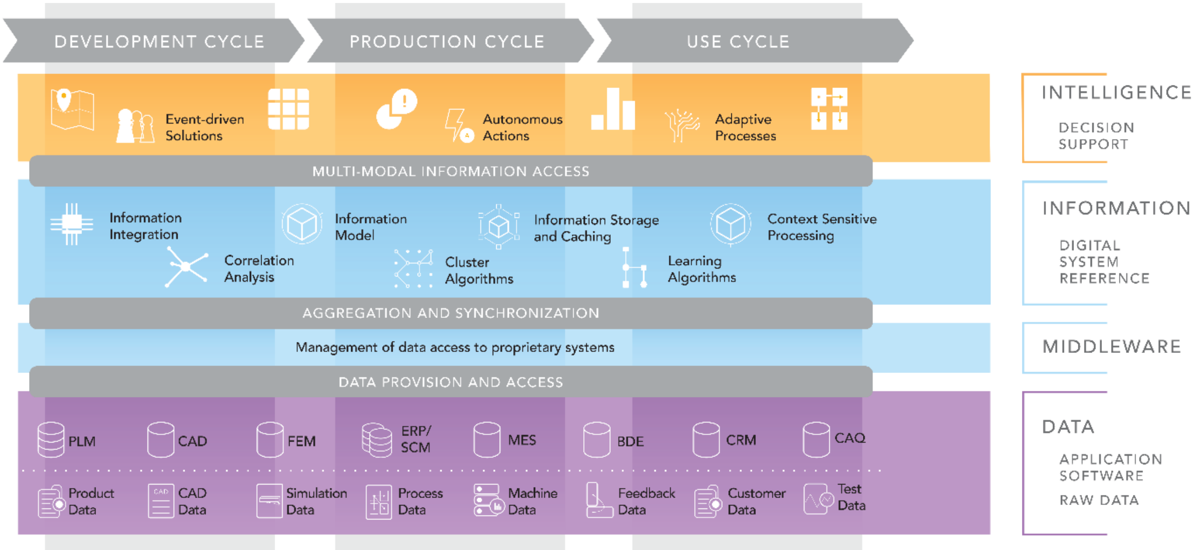

Fig. 1: Advanced Manufacturing Landscape (adapted from [4])

concepts, or instructions independent of them; suitable for communication, interpretation, or processing by humans or automated systems. Contextualisation and interpretation of the data allow it to become meaningful information for a particular perspective [2], thereby facilitating decision-making. For this purpose, a sheer digital twin that represents the as-is situation is inadequate since it is unable to simulate different decision scenarios on different levels of aggregation. Therefore, a digital twinning approach is induced that extends on the notion of the digital twin. Digital twinning entails not only the actual and real-time state of a physical asset (digital twin), but also the intended state as designed (digital master) and the potential state as simulated (digital prototype). Digital twinning is referred to as the activity of a person or asset to use the feed-forward and feedback loop between the digital twin, digital master, and digital prototype. This allows for learning, validation, and optimisation of the production environment, as well as decision support for stakeholders [3]. Conjointly, the digital twin, master and prototype are referred to as the Digital System Reference (DSR) [3–6].

Before a DSR can be used effectively, companies must first identify the appropriate set of problems and opportunities in their production environment. If an adequate articulation of the incentive for digital twinning is available, the selection of tools and approaches will be based on a technology pull instead of a push. The articulation allows for a purpose-oriented alignment, provided that companies have a foundation of data to establish a proficient starting point for digital twinning in their company. Without a proficient foundation of data, a company will not be effective in facilitating the information that is required for the incentive of the DSR. A description of such a foundation of data for decision support can be found in the advanced manufacturing landscape [4], depicted in Fig. 1. The landscape is an organisational representation of a production environment. The data layer consists of the software/information systems that are embedded in a production environment. Such systems (e.g., PLM, ERP, or MES), hereafter referred to as data provision components, capture data in environments and may initiate and steer activities based on predefined workflows or process descriptions.

In theory, the data provision components in the data layer of the landscape should be able to facilitate decision-making. However, data provision components often provide decision support based on one perspective and a limited set of data. Therefore, the data provision components cannot optimally facilitate decision-making, as they lack the ability to provide perspective-dependent and real-time information at all required levels of aggregation. The DSR can facilitate perspective-dependent decision support based on the contextualised combination of data and information from the foundation of the landscape described in Fig. 1. The data layer and middleware layer in the landscape can be referred to as the digital infrastructure of a company, as it comprises the entirety of instantiated software/information systems and datasets embedded in a production environment [1].

The digital infrastructure plays an essential role in enabling digital twinning as it can function as the data foundation. Fig. 1 shows the structure of the landscape and its constituents. Yet, it does not show how (by what method/means) the data should be provided by the digital infrastructure to enable digital twinning and, therefore, support in rationalising decisions. In order to enable purpose-oriented digital twinning, an overview is required of which life cycle phases use which data provision components, the type of data available and where it is located in the digital infrastructure.

1.1. Research aim, scope, and application

This paper focuses on the challenges of production companies regarding the ability to use the digital infrastructure effectively and efficiently as the basis for purposeful decision support with the use of digital twinning. The basis for this research is the digital infrastructure that exists in every company and the digital twinning approach that allows for purposeful simulations, what-if analyses, and scenario analyses. Prevalent application areas relate to discrete manufacturing in companies that combine research & development with production.

Two case studies form the basis for the research depicted in this publication. The first case study involves an SME that designs and produces bikes for the elderly and people with a physical or mental challenge. The digital infrastructure will be re-aligned with and redesigned for the identified problems and opportunities in the production environment. A research-by-design approach is applied, implying that this case study will be used to simultaneously study, develop, implement, and verify solution directions in an ongoing sequence of iterations.

The second case study involves a greenfields shopfloor development project called the AMC (Advanced Manufacturing Centre). The AMC grows into a research and development facility that is characterised by a continuously altering organisation and composition of the physical shopfloor infrastructure. For this case study, the digital infrastructure needs to facilitate decision-making under circumstances, that are for now mostly unknown, but also will be subject to change in the future. The AMC case study will be used to validate the developed solution directions.

2. Adaptability in digital infrastructures

Digitalisation seems to be pushed forward in industry as the apparent solution to challenges such as high customisation needs, fluctuating demand, intricate planning caused by supply chain issues, and many more. However, digitalisation efforts commonly act on visible, explicit problems. However, such problems are often mere symptoms of the implicit need to obtain more grip and control on processes and information in the company. It is the wide range of aspects, viewpoints, stakeholders, and levels of planning and control that, together with the volatility of production environments, renders establishing an absolute and encompassing model of the environment cumbersome. In the absence of such a model, it is well-nigh impossible to root the rationale and foundation for decisions in the available data and information.

In many companies, data provision components (see section 1) evidently limit the flexibility and the adroitness of data provision within the company and the production environment. Often, data provision components have been implemented by companies with certain circumstances and workflows in mind that are largely uncertain, even uncertain or that might deviate from what is required today, in order to facilitate for the requirements of tomorrow. This makes the current processes (and control thereof) more prescriptive than necessary, effective, or efficient. Hence, most components fail to support the current, as well as the future ideal way of working. Despite this, data provision components are often (implicitly) allowed to enforce the structure and accessibility of the data involved. In contrast, the data content in itself would be a much more objective and unequivocal driver for decision-making. For example, in one of the case studies, it was observed that (legacy) components did factually force the company to prescribe certain workflows as the designated way to access specific data.

Data provision components are often incapable of mutual, equivalent communication, and therefore limit the interoperability of the digital infrastructure. It is exceedingly difficult for companies to facilitate decision-making based on joint and interrelated data if there is no lenient, bi-directional communication between data provision components. The data provision components often only allow for a limited set of predetermined, process-oriented interfaces to the data. Not to mention that the offered middleware functionality (as shown in Fig. 1) by vendors is not always focused on interoperability and communication with all available data provision components in the company. It, therefore, limits the adaptability of the digital infrastructure towards other data provision components in the company. This limitation often forces employees to simultaneously work in multiple systems per activity, resulting in a significant risk of, e.g., inconsistencies, ambiguity, and incongruencies, next to elementary interpretation errors. Given the observation that any decision can be just as good as the data/information it is based on, companies should focus on getting the appropriate information, to the right person, at the right moment, to the right entity, system, person, and decision-maker.

2.1. Requirements for an adaptable digital infrastructure

Interoperability and adaptability of the digital infrastructure is determinative of the flexibility of a production environment, the degree of production control, and effectiveness of decision support. Because adaptability and interoperability of the digital infrastructure are such significant determinants for future flexibility, it is advisable for companies to have deliberate control over the digital infrastructure. In many cases, this will imply that companies need to define criteria for data provision components and the bi-directional communication between them. Often adjustments on the existing digital infrastructure are needed, which can range from removing, adding, or changing data provision components, to facilitating communication between them. Companies need to evaluate, specify, and improve the format, location, context, and accessibility of the data to enable the possibility to use, filter and process the data that is required for digital twinning and decision support.

Taking control over the development of a digital infrastructure while avoiding the inefficiencies of the data provision components and ensuring its adaptability can be an intricate undertaking for companies. A specification of requirements for an adaptable digital infrastructure can support companies to select their data provision components in a more purposeful way. Experience gained in the case studies and the analysis of the inefficiencies described in the previous section resulted in formulating requirements that offer companies criteria for establishing an adaptable digital infrastructure. The requirements encompass:

- The digital infrastructure shall allow for changes in processes, process steps, business strategy, and business logic.
- Processes and business logic, as well as information structures, shall be captured separately from the data provision components.
- The digital infrastructure shall facilitate data from different data provision components to be combined as the basis of effective and efficient decision support.

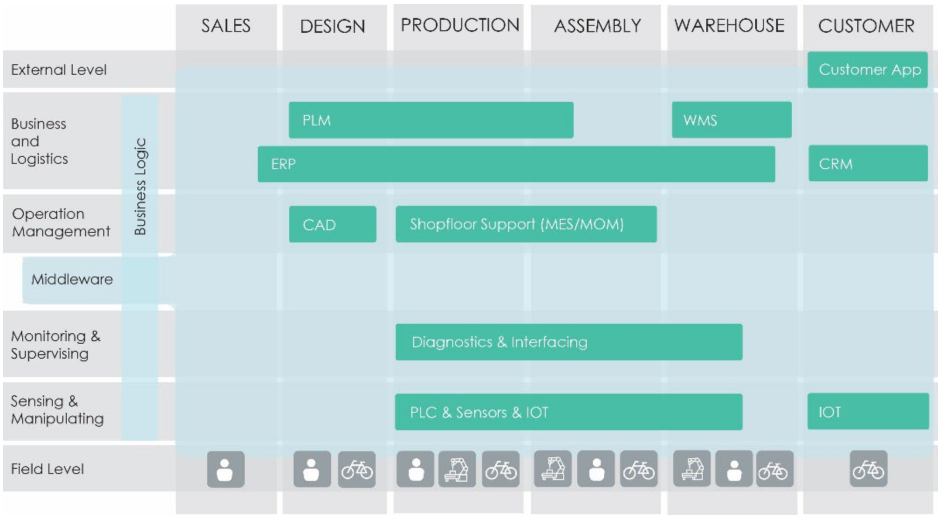

Fig. 2: Blueprint for digital infrastructures

- Bidirectional communication flows in all relevant formats shall be facilitated.
- Data provision components shall have versatile ways to connect to other components.
- Data and information shall be accessible for relevant data provision components within the digital infrastructure.
- The digital infrastructure shall allow for filtering of data to facilitate stakeholder-dependent perspectives.

The landscape in Fig. 1 shows a list of data provision components and raw data. It does not specify which data components are required for which level of aggregation, nor does it show the functionality of the data provision components and middleware. For companies to increase the control over their digital infrastructure, an overview of how and in which phase data and data provision components can function can be useful. Moreover, a further specification of what the middleware entails and what its functionalities are, is required for companies to improve the interoperability of their digital infrastructure to allow for digital twinning. This, together with the formulation of the requirements for the digital infrastructure, allows for the development of a so-called blueprint for digital infrastructures. This blueprint aims to provide an integrated representation of the digital infrastructure, its middleware, and data provision components. The blueprint can be used for a new design of a digital infrastructure or as a starting point to evaluate and map the current digital infrastructure. The blueprint aims to make the development of the digital infrastructure in companies unequivocal, transparent, and well-defined to accomplish the sought-after adaptability.

2.2. The blueprint for a digital infrastructure

The blueprint builds on the advanced manufacturing landscape as it interprets the data provision components and their application in the different stages of the product life cycle. As stated before, the digital infrastructure comprises of data, data provision components and the middleware. Even though the middleware plays an essential role in this, the definition of the middleware layer in Fig. 1 is limited. It describes the middleware as the manager of data access to data provision components. The middleware should enable, conjointly with the data provision components, the digital infrastructure to become the main, integrated data provider that is required to meet the requirements described in section 2.1. The functionalities of the middleware are further elaborated on in section 2.4. The blueprint for digital infrastructures is depicted in Fig. 2; it shows how the data, data provision components and middleware are positioned over the different product life cycle phases.

Whereas the individual data provision components specified in Fig. 2 are representative of the bike manufacturer case study, the specific data provision components will be different for each company. Companies can delineate the existing and required data provision components to align with the purpose of their digital infrastructure. The approach towards purpose-driven development of the digital infrastructure can be based on the 3P (purpose, perspective, priority) approach [3], which ensures that the selection of the data provision components is based on companies goals and needs rather than on a mere technology push.

2.3. Levels in a digital infrastructure

The blueprint has rows that distinguish functionalities and columns to indicate the applicability of a data provisioning component for a product life cycle phase. This grouping also makes transparent what type of data is located in which data provision component, and in which product life cycle phase the data in the data provision component is acquired, to facilitate for filtering of stakeholder dependent information. The grouping is based on a combination of RAMI4.0 [7], ISA95 [8], and the Advanced Manufacturing Landscape [4]. Where, e.g., ISA95 uses the notion levels, this naming convention is also adopted in the blueprint; however, it does not imply any hierarchical control principle is also adopted. The lowest level represents the *Field Level*. It addresses the physical production environment and includes stakeholders, products and production equipment, and other assets in the production environment. The *Sensing and Manipulating* level captures the status of assets, products, and processes. This includes data acquisition and the analysis of data in the correct format. Data can be gathered by means of, e.g., sensors connected to an asset's PLC, and standardised with the use of the Asset Administration Shell (AAS) and OPC UA [9]. The next level is *Monitoring and Supervising*. It allows for diagnostics and interfacing in the production environment and thus allows for analyses, representation, and visualisation for the stakeholder. It can show information about the effectiveness and efficiency of assets and resources on the production floor. Therefore, it can increase the insight into the current and previous statuses of the production environment. Above the middleware, the *Operation Management* level is located. It processes data related to planning, capacity, and order specifications. The functionality ranges from the product design to the communication in the production environment, such as visualising order-specific instructions. The next level is *Business and Logistics*. This level includes the infrastructure components required for business such as financial information, warehouse management, stock information, portfolio management and version control of products. The top level is the *External* level, which includes the system relations for the product in the field. This can be, for example, a customer app.

2.4. Middleware & business logic

As stated in section 2.2, the middleware should, conjointly with the data provision components, enable the digital infrastructure to become the main, integrated data provider. The middleware is a part of the solution to meet the requirements stated in section 2.1, that are aimed at the communication between data provision components, accessibility of data, and alteration and processing of data into information. The middleware facilitates the communication and connection between data provision components and therefore, makes the data in these components available for usage outside of the data provision components. Fig. 2 shows the position of the middleware in the digital infrastructure. The middleware is related to all the levels in the blueprint; its goal is to facilitate bi-directional communication between the data provision components - independent of business strategy and business logic. This allows for changes in processes, process steps, and business strategy without influencing the facilitation of communication. In other words, it separates the content of the communication from its structure. With that, the middleware acts as a broker in the digital infrastructure to facilitate data access based on the needs/requests. The DSR is, therefore, the shell that allows for access to the data in the digital infrastructure. Concepts such as OPC UA and AAS can be used as carriers within the middleware to exchange data and information in meaningful ways [9]. The data provision in the digital infrastructure, facilitated by the middleware, is essential in order to provide the data/information foundation for digital twinning. Without this foundation the DSR is not able to provide perspective-dependent and real-time information to support rationalising decisions.

The communication between data provision components should be facilitated without prescribing any structure because data should be available and useable independent of the process, activity, and perspective. Moreover, the structure of the data should be independent of individual users, as individuals cannot anticipate the consequences of changes in the information structure for other users. Therefore, the organisation of the communication should be independent of the bearing of the communicated data. With that, the *Business Logic* is connected to, yet distinct from, the middleware. Therefore, the connection between the digital infrastructure and the DSR is twofold: content-based (middleware) and organisation-based (business logic). Both connections can be used mutually independent. Business logic aims to interrelate the rationale and context of the information in the digital infrastructure, such as process definitions, activities, and process steps, as well as business strategies. Therefore, middleware and business logic together provide companies with more flexibility, interoperability, and control to allow for evolvement with the production environment in reciprocal dependency. Business logic can target each level of aggregation in a production environment; therefore, the business logic ranges over all levels. If a company is in control of its digital infrastructure and can also purposefully define, establish, and use its middleware, the comprehensive data repository can become an essential information base and contributor to decision-making in the production environment.

3. Case studies

The case study at the bike manufacturing company highlights the process of renewing and further developing its digital infrastructure. The case study is based on a 3-year project and is currently in its second year. The purpose of digital twinning in this case study is to increase the reliance on data-driven decisions to improve and optimise production, to improve control over the production processes and reduce dependency on suppliers. The current digital infrastructure and its data provision components was mapped with the use of the blueprint to determine how and in what direction the digital infrastructure should be developed to facilitate digital twinning. The digital infrastructure turned out to consist of many small data provision components, with a significant dependency on one component: the ERP system. Moreover, it was observed that the communication between the data provision components was not always facilitated, which caused the same data to be stored in/by multiple components. Currently, the ERP enforces the structure and accessibility of the data and limits the company from easily changing its business logic.

The lack of communication possibilities caused a significant risk at data inconsistency and instability of the data provision components in the digital infrastructure. This was visible in the blueprint because there were many data provision components with a similar purpose. Consequently, the current digital infrastructure led to high maintenance and problem-solving efforts. The bike manufacturer decided to re-establish its digital infrastructure by taking ownership of the development of the middleware. Here, a specific task of the middleware is to provide control over the communication between data provision components, the data structures and reduce the dependency on the ERP system. Even though investment of effort and time has been required from the bike manufacturer to change the digital infrastructure and mitigate dependencies on individual data provision components, a clear return of investment is already visible. Implementing the first functioning version of the middleware has already reduced the efforts to provide data to the diagnostic and interfacing component in Fig. 2. With the further development and implementation of the middleware and business logic, the digital infrastructure at the bike manufacturing company will be capable of facilitating information for the envisaged DSR.

The AMC case study is used as a final validation of the blueprint. The blueprint acts as the basis for determining the additionally required data provision components of the digital infrastructure at the AMC, while the business logic and infrastructure of the AMC is still under development. Because of the greenfield approach, the AMC case study provides much more freedom and flexibility for research by design than the bike manufacture case study. Therefore, the AMC will be used as a learning environment. The middleware will connect the data provision components and facilitate communication between new and existing data provision components. The aim is to interchange different data provision components with the same functionality to validate, test and further develop (as part of the research-by-design approach) the flexibility of the blueprint and the requirements for the middleware.

4. Conclusion

At any level in the organisation, processes, and information (structures) are mutually dependent. Therefore, any digital twinning approach needs to take the information content into account along with the processes and workflows involved. This does not imply that the one drives the other, rather in any decision-making process, the interdependency between content, context, and activities needs to be assessed. With the large number of decisions that are made, trust in if and how data and information is available is vital to prevent a repetitive search for the right information and data. The blueprint is a valuable starting point to clarify where given information is available. Risk and time can be reduced by putting the information in the right format and location. Furthermore, the lesser time is lost on finding the right information, fewer risks are built in, and less unnecessary uncertainties will be included in the decisions. With that, decision processes can focus on the actual added value of decisions instead of the involved preconditions.

The adaptability of the digital infrastructure provided by the middleware is key to facilitating the data and information foundation for the DSR, in order to enable rationalising decisions in production environments. If a company takes control of its own middleware, it can prevent uncontrollable and expensive situations caused by a vendor lock-in or dependency on software suppliers. Therefore, companies should invest into developing and maintaining the middleware to be independent of software suppliers, hence, creating more adaptability in their digital infrastructure. The adaptability of a digital infrastructure can be further increased by only committing to suppliers that offer a powerful, stable, and open platform that allows for connection to the middleware and communication with data provision components from other suppliers. With this, it is advised to test and develop the digital infrastructure and the middleware using the blueprint and verify it based on the defined requirements in section 2.1. The blueprint representation stems from a combination of literature research and experience gained in the bike manufacturer case study; the blueprint is subsequently validated in the AMC case study. With that, learnings from the brownfields approach at the bike manufacturer are transferred to the significantly contrasting greenfields approach in the AMC case study. Given the applicability in both cases, it seems defensible to claim that the blueprint is applicable for other discrete production environments as well. The blueprint has proven to be useful as the first step for companies to understand the need to develop their digital infrastructure consciously and effectively. Moreover, the blueprint illustrates that with the use of middleware, the digital infrastructure can be made adaptable and flexible enough to serve as the data foundation for digital twinning and, thus, decision-making in the production environment. With the data/information foundation of de digital infrastructure in place, the DSR will become the powerful tool for the contextualisation of information for decision-making and the simulation of decision scenarios.

5. Future Work

With a DSR in place, still, not all components that are required for stakeholder-dependent decision support are available. A coherent set of functionalities to cooperate with stakeholders to process requests and coordinate the data, context, information, and perspectives is still required. In the context of the digital infrastructure, the functionalities should coordinate the right data provision components while using the middleware to bring the required data, context, and information together for decision support. Further research is required to establish and facilitate the orchestration in digital twinning to align requirements and functionalities to the digital infrastructure and the DSR. Further development of the proposed blueprint will be focused on specifying and further validating the blueprint with the use of case studies.

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