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A structured digital twinning approach to improve decision-making in manufacturing SMEs

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ABSTRACT

Companies aim to adapt their shopfloors to increase the efficiency and effectiveness of their production activities, adding value to their shopfloor. However, it has become increasingly challenging to obtain an accurate and comprehensive overview of the shop floor and organisation, leading to difficulties in making operational, tactical, and strategic decisions. Existing methods to support such companies either restrict access to information or pre-determine the perspectives on the information for decision-making. This research employs a research-by-design approach to develop the digital twinning approach that can facilitate companies to develop a solution that can provide the appropriate information at the right moment and in the right perspective. To structure the digital twinning approach, key functions in the approach are outlined in a functional architecture. Two case studies demonstrate and verify the applicability and added value of the architecture in developing an information provisioning solution. The positive outcomes and experiences from these case studies highlight the potential of the digital twinning approach to facilitate companies in developing adaptable and company-specific solutions to enhance decision-making processes.

1. Introduction

Companies strive to improve shopfloors by improving their effectiveness and efficiency of their production environment. This involves producing products of envisaged quality effectively and efficiently and delivering them to the right customer in a timely fashion. This is particularly important for manufacturers of discrete products, who operate in a volatile environment that is subject to uncustomary orders, fluctuating batch sizes, increasing product variety, evolving customer demands and requirements, and unpredictable events [4–7]. In the context of this research, an environment is defined as the definable sphere of influence including the known external stressors [8]. Companies that manufacture high variety discrete products often have the strategy to make their shopfloor as flexible, adaptable, and agile as possible to handle the volatility of the environment. The volatility of the environment makes it complicated for companies to provide an adequate overview of the shopfloor and the decision-making processes in and around it [5,9–12]. This is further complicated due to real-time changes on the shopfloor that invalidate or outdate such an overview. A company's inability to provide an adequate and accurate overview stresses the impact of uncertainties in describing the current state and envisaged future states of the shopfloor. This makes it difficult for companies to support, argue, design, instigate, select, plan, and decide on the actions and activities that are required to implement a strategy to increase the effectiveness and efficiency of the shopfloor.

Companies must be capable of informed decision-making over various levels of aggregation (e.g.: operational, tactical, strategical) in their organisation to implement their strategy such as having an adaptable and flexible shopfloor to handle volatility, or to increase the effectiveness and efficiency of the production activities. However, these decision-making processes are often hindered by the unavailability or inaccessibility of the relevant information [9,13].

Each level of aggregation has its own recursive environment and context. In this, the context is described as the undefinable setting in which something exists and where external stressors origin from that are not yet known or relevant [8]. Companies face challenges in overseeing the outcomes of decisions beyond the level of aggregation in which the decision-making process occurs due to a lack of insight in the environment and context. The combination of unavailable or inaccessible information and the lack of insight in the environment and context make it

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difficult to evaluate outcomes of decisions [11]. This implies that decisions are often made without considering all relevant information and without having a clear understanding of the implications a decision will or might have on the shopfloor and the organisation. The provisioning of the appropriate information for decision-making can increase the insight in the shopfloor, increase predictability of the outcomes and implications of decisions, and reduce the uncertainty involved in these decisions.

Industry has had a focus on optimising process control and decision-making workflows, rather than on the information that underpins these decisions. This process-oriented emphasis has led to information being dispersed throughout the organisation in sectional or topical solutions for specific processes, process activities, or departments. This often results in inadequately linked solutions that do not consider the complete shopfloor, the organisation, and the external influences on the environment. In addition, these solutions often restrict the availability of information to a specific process or department, rendering it unavailable for decision-making, and for addressing multiple perspectives. In this research a perspective is defined as the way in which (a group of) stakeholders interpret information and reach decisions given their field of expertise, experience, the domain in which they work, and their role in the decision-making process [8]. Dispersed information throughout the information fundament of a company can lead to incomplete, uncertain, and ambiguous information that can hamper decision-making and the predictability and verifiability of their outcomes.

To enhance decision-making at all levels of aggregation in the organisation, it is essential to provide stakeholders with the appropriate information through interfaces that are tailored to their needs and perspectives [4,9,14,15]. In addition, appropriate information provisioning can allow for more apt overviews which can improve the company's ability to evaluate decision outcomes at different levels of aggregation. The aim of this research is to facilitate companies in establishing a solution that can provide information for decision-making in a perspective-dependent and timely manner to all levels of aggregation in a company.

1.1. Scope and methodology

This research addresses small to medium-sized enterprises (SME) that produce discrete products. These SMEs aim to be adaptable, flexible, and agile to handle the volatility within their environment. They can benefit from having an information provisioning solution that makes the information available and accessible to supports the decision-making processes. Making changes to the way information is provided in a company has a relatively similar impact on SMEs and multinationals, however, the financial resources required for SMEs compared to multinationals is relatively much higher. Multinationals are more likely to have the financial resources to invest in changing their information infrastructure or developing customised software to provide information throughout the organisation. SMEs often struggle to develop a solution that improves their information provisioning throughout the organisation. This research focuses on defining a solution that can improve the provisioning of information for decision-making with a focus on manufacturing SMEs.

This research applies a research-by-design approach embedded in two industrial case studies. The first case study is based on the engine shop of an airline, where airplane engines are inspected, maintained, and repaired. Although the airline company is large, the engine shop itself functions as a SME with its own management. The management of the engine shop has expressed their need to increase the insight in the engine shop and its processes. An airplane engine consists out of many parts which each can have a different route through the engine shop depending on the required maintenance. This high variation in routing through the engine shop makes it difficult to plan the production activities. Delays often occur, due to a lack of insight, the variation in routing and the difficulties to plan the production activities. These delays are heavily fined. Therefore, the company aims to improve the flow of the orders through the engine shop to minimize delays. In this, the engine shop aims to address challenges arising from the high variability in the repair and maintenance routes of engine parts by improving the information provisioning throughout the engine shop.

The second case study is based on a bicycle manufacturer which produces bicycle for people with a disability. The company can be characterized as a SME manufacturing company, that produces bicycles based on a configure to order (CTO) strategy. The company faces complexity in its shopfloor and organisation due to a high volatile market that is highly influenced by seasonal demand. The company has the ambition to grow and scale in the coming years, which includes upscaling to other locations in the world. However, the current information provisioning makes it difficult to provide the required insights and information that is required to make decisions throughout the organisation. The company aims to develop a scalable solution that can provide the appropriate information, in the right perspective, at the right moment. In addition, the company is part of a consortia of three manufacturing SMEs that face similar challenges regarding information provisioning and decision-making throughout their company. The aim is to apply the learnings from this research and the two case studies in the companies of the consortia and use these companies to further validate the outcomes of this research.

The research-by-design approach is guided by the following research question:

How can companies be enabled to make informed decisions while gaining insight in uncertainties, predictability and verifiability of decision-making processes and their outcomes?

This research proposes an approach that facilitates companies in maximising added value by improving the effectiveness and efficiency of the shopfloor over all levels off aggregation, rooted in well-informed decision-making. The design and development of the approach will be elaborated on within this paper. To do so, first, the current decision-making in manufacturing and its challenges are elaborated on. Based on the current state of decision-making and input from the case studies, requirements for the approach will be defined. Subsequently, requirements are defined for the information provisioning solution emerging from this approach. In addition, the research will elaborate on digital twinning as solution direction. To develop the approach, the functions within the approach are specified and structured in a functional architecture. The proposed approach will be verified through the application in two use cases, which will serve to demonstrate its alignment with the specified requirements. Furthermore, the approach will be fully implemented within the bicycle manufacturer case study to validate its efficacy and efficiency in improving decision-making based on improved information provisioning.

2. Decision-making in manufacturing

Prior to the emergence of IoT and Industry 4.0, shopfloors were managed by operators and fore(wo)men who were very experienced and possessed implicit knowledge about the shopfloor. These employees acted as linking pins, by being the go-to person that could interrelate the information in the environment in an understandable and contextualised manner, based on their implicit knowledge and experience, to underpin decisions [10]. However, the growing complexities, including intricate designs, the impact of globalisation, and increasing volatility have substantially challenged the employee's abilities to maintain an adequate overview of the shopfloor and oversee the outcomes of decisions [4,5,10–12,16]. Therefore, the knowledge and expertise of these employees is no longer sufficient to provide the adequate information and overview for decision-making processes throughout the organisation. The growing complexities and globalisation has increased the amount of stakeholders and the multi-departmental responsibilities involved in decision-making processes [11]. The involved stakeholders each have a subset of the complete overview of the shopfloor. The required coordination between all these stakeholders and departments has made creating an overview for decision-making more cumbersome.

To solve the lack of adequate information provisioning, companies try to improve their control and insight of their environment by formalising processes and improving process control. Process definitions can structure production activities and the information that is related to these activities. However, it provides companies with a false sense of control and appearance of insight in the shopfloor. Process definitions and control frequently prescribe a certain set of information for a given production activity, process, or perspective, which can restrict the information accessibility to all relevant stakeholders. Therefore, process-oriented solutions such as formalisation of processes limit the possibility to provide perspective-dependent information and insights. In addition, the more standardisation and formalisation of processes, the more unlikely it becomes to maintain adaptable and scalable of these processes to handle the volatility of the environment. This inflexibility can have a negative impact on the effectiveness and efficiency of the entire shopfloor and organisation. Therefore, a process-oriented solution in a company is unlikely to significantly improve the information provisioning and thus allow for more informed decision-making.

Information-driven technologies, which include sensor technology and the Internet of Things (IoT), have been introduced as an alternative to process-oriented solutions. These technologies facilitate the acquisition, storage, analysis, and representation of data and information to support decision-making. However, the implementation of these technologies without a structured approach have resulted in a continuous source of data and information that is acquired. The implementation of these technologies has resulted in an unorganised data explosion in many companies, rendering them data-rich and insight poor [17]. To make use of this vast data volume, technologies, and tools such as analysis and simulation tooling, machine learning and AI. However, the effectiveness and efficiency of these analysis, forecasting and simulation tools rely on the availability, accessibility and reliability of the data and information. Moreover, these solutions do not allow for filtering of the relevant information and representing it in a perspective-dependent manner to facilitate for decision-making.

A range of data systems has been introduced to address this need, including Enterprise Resource Planning (ERP), Product Lifecycle Management (PLM), and Manufacturing Execution System (MES) software. These systems aim to increase the accessibility and availability of the data and information, by managing the data and contextualising the data as meaningful information that is provided to stakeholders in user-interfaces. In this, the notion data refers to stand-alone, unprocessed facts, whereas information represents the meaning that is assigned to data by utilising known conventions in relation to, and specific for the perspectives involved [3,8,12,18,19]. The Advanced Manufacturing Landscape [3] (represented in Fig. 1) illustrates the digital landscape of a company, and describes the different data systems often found in a company. The entirety of instantiated software, data systems and repositories that are embedded in a company are referred to as a company's digital infrastructure [10,13].

Data systems are often implemented using predefined workflows, processes and perspectives that describe the ingrained way of working. As a result, most data systems, after implementation, do not fully support the current and envisaged way of working. Instead, data systems enforce the way of working according to predefined processes and environment and don't allow for adjustments easily. In addition, when data is structured using processes definitions, it predefined the perspectives on the data and the access of stakeholders to the information [13]. This can negatively affect the ability and flexibility to provide the appropriate information to all levels of aggregation [20,21]. Moreover, the different data systems each have different user-interfaces. Dealing with diverse user-interfaces and dispersed data and information in different solutions throughout the digital infrastructure introduces risks of miscommunication, missing or duplicated data, and ambiguity, which can lead to ill-informed decision-making.

The data and its interpretations, which are used to inform decision-making, are currently often stored in different data systems and repositories. This separation of data sources causes unnecessary complexity in providing information to support decision-making processes at all levels of aggregation. While the data systems can adequately meet the requirements of individual perspectives and fields of expertise, they often do not allow for communication of information between the solutions. Consequently, companies have a clear need to align such solutions in an overall approach to facilitate decision-making processes, by means of information provisioning, throughout the organisation [2].

3. A generic approach for the development of an information provisioning solution

Every manufacturing company is unique in their own way. Companies can be characterised by their context, environment, and shopfloor, as well as their own unique set of goals, stakeholders, and information needs. An information provisioning solution needs to be tailored to these company specific characteristics and needs. Due to the wide variety of company specific characteristics and needs, it is impossible to provide a comprehensive guideline with a specific step-by-step instruction to develop a solution that would fit every company. However, companies do need guidance and support to develop and

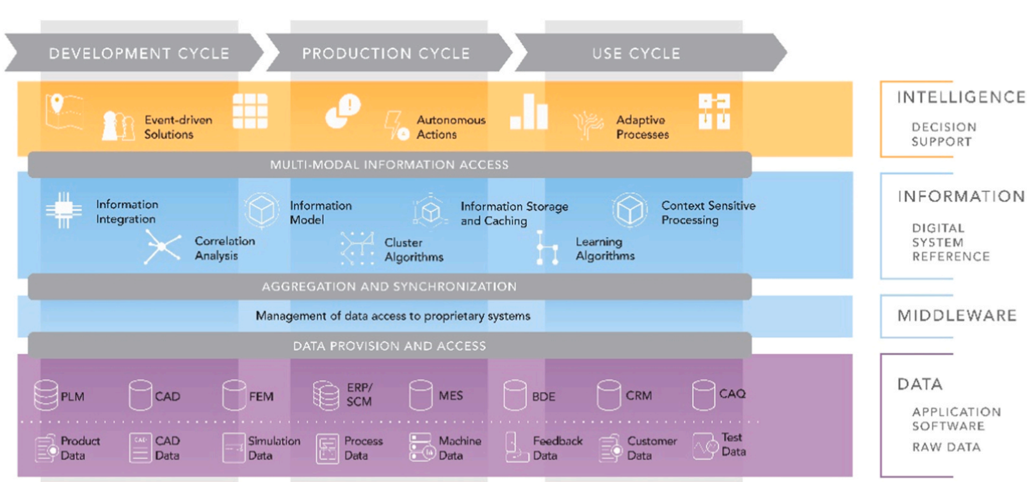

Fig. 1. Advanced Manufacturing Landscape [3].

implement such solutions. This research aims to develop, implement, and evaluate a generic approach that can facilitate SME manufacturing companies to develop a holistic solution that can adequately provide information for decision-making processes throughout the organisation. This section elaborates on the requirements for a generic approach.

3.1. Requirements for generic approach

To be of value for SMEs the approach needs to enable companies to develop a holistic information provisioning solution that supports decision-making throughout the organisation. This solution needs to act as an information fundament that provides the appropriate information from the information source to the stakeholder. The solution should be able to provide information in a perspective-dependent and timely manner based on the needs of the company. The information provisioning solution should be adaptable and scalable to the volatility of the environment and context, since the information, context, environment, company characteristics, stakeholders and information sources vary per company and over time. A more detailed explanation of this holistic information provisioning solution will be covered in Section 4. In addition to the development of a solution, several other requirements have been formulated:

- The approach should assist companies to define their company vision, underlying problem, goals, and purpose to ensure the solution can meet the current and future requirements and purpose.
- The approach needs to be generic enough to implement it in different context and environments at any SME manufacturing company.
- The approach needs to allow for the integration of company specific needs and requirements in the development process of an information provisioning solution.
- The approach needs to be information-driven rather than process-driven, i.e. it needs to focus on how the information can be used to support production activities and decision-making processes in the company.
- The approach needs to facilitate companies to develop a holistic solution that is applicable to all stakeholders if required. The approach should assist companies in identifying the stakeholders involved, their needs, and requirements.
- The approach should facilitate companies in mapping their current data systems and understanding where the information is stored and how the solution can utilise the data systems in the digital infrastructure.
- To handle the volatility of their environment, companies are continuously adjusting their logistics, planning, shopfloor, and organisation. The approach needs to be able to cope with the volatility and any changes to the environment as a result thereof.
- The approach should allow for continuous evaluation and improvement of the solution to adapt to changes in the environment, future requirements, and stakeholder needs.

The initial set of general requirements is specified for the approach. Further development, application, and evaluation of the approach might lead to the identification of additional requirements for the approach. The next section will further elaborate on what the information provisioning solution should do and specify the requirements for the information provisioning solution.

4. Information provisioning solution

The digital infrastructure of a company should form the information fundament of a company. This information fundament needs to allow for the provisioning and accessibility of the data and information. In addition, the information fundament must allow for the combination of information from various sources in the digital infrastructure in a single source of truth that can be used for decision-making.

To facilitate for decision-making in a perspective-dependent and timely manner, the data must be managed, aggregated, synchronized, filtered, contextualised as information, and represented for the required perspective. These functionalities cannot be provided by the information fundament. Therefore, a holistic information provisioning solution is required that allows for these functionalities and can function as the bridge between the data layer and the intelligence layer illustrated in the Advanced Manufacturing Landscape (Fig. 1).

The aim of the information provisioning solution is to provide the information from the data layer to the decision-maker, to support decision support across the entire company. The solution must enable the provision of information in a perspective-dependent and timely manner.

4.1. Requirements for information provisioning solution

This section outlines a set of initial requirements for the information provisioning solution. It is important to note that, inherent to the research-by-design approach, this list of requirements is inherently incomplete and requires adjustments to accommodate company specific and future requirements and needs.

As stated in the introduction, companies have a dispersed information fundament that limits the accessibility and provisioning of the information to specific data systems or perspectives. *Therefore, the information provisioning solution should function as a middleware and interface that allows for the provisioning of information between the information fundament and the decision-maker.*

Each stakeholder that is involved in a decision-making process represents specific perspectives, expertise and intents and will thus interpret data differently [8,11]. An underlying cause for this is the fact that the interpretation of data by a stakeholder is environment sensitive [22]. The difference in interpretation introduces ambiguity in the decision-making process, that complicates the decision-making process. Contextualisation of the data as meaningful information will help to reduce the ambiguity in the decision-making process and ensure the information can be represented to the stakeholders in a meaningful manner [8,10,23]. *Therefore, the information provisioning solution should allow for contextualisation of the data as meaningful information tailored to the involved perspectives.*

Information provisioning needs to allow for the provisioning of information throughout the organisation irrespective of the perspective or meaning of the information. *Therefore, the information provisioning should allow for the structuring of the relationship between the information entities and their meanings without prescribing the meaning of the information.*

Additionally, stakeholders have varying information needs based on their perspective, tasks, and responsibilities. To avoid overwhelming them with irrelevant information, the stakeholders should only be presented with the information that is pertinent to their needs. *Hence, the information provisioning solution should allow for the filtering of the appropriate information based on the information needs and perspective of the stakeholders.*

It is important to consider factors such as privacy regulations, company critical information, and decision-making rights when determining access of stakeholders to the information. Whether a stakeholder should have access to the information depends on its tasks, responsibilities, perspective, and level of aggregation. For example, one operator should not have access to the performance information of another operator or have access to all strategic financial information. *The information provisioning solution should allow for the filtering of the information within perspectives and based on the information type.*

Manufacturing environments are volatile, and subject to technical, logistic, and organisational adaptations. *The information provisioning solution should not limit stakeholders in making such adaptations and exploiting the consequences thereof. In addition, the information provisioning solution needs to be adaptable and scalable towards changes in the environment.*

Each decision encompasses information on the historic, current, possible, or envisaged future states, of the shopfloor and its environment. Decision-making usually involves information from a combination of (all) these states [9]. The more distant the time horizon or state is from the current state and the measured data, the greater the uncertainty involved in the decision-making process. To avoid speculation in the decision-making process, it is important to acknowledge the uncertainty involved in determining possible outcomes. Decisions that involve high uncertainty, risk or investment may benefit from simulating and evaluating different scenarios and their outcomes. Furthermore, these scenarios and their outcomes can serve as learnings for future decision-making. Thus, *the information provisioning solution should allow for the simulation of scenario's and allow for the storage of predicted and simulated data, along with scenario and decision outcomes to enable learning for future decision-making.*

As predicted and simulated data involves more uncertainty than measured data, it is important to store the data clearly and concisely to identify the level of uncertainty involved. *To achieve this, the information provisioning solution should allow for the structuring of the data between different time horizons and states, including the historical, current, potential, and envisaged states.*

The formulated requirements are generic requirements for an information provisioning solution. Since each company has its own unique environment, strategy, stakeholders and thus information provisioning needs, company specific requirements will need to be defined per company. Now that the generic requirements for the information provisioning solution are defined, the next step is exploring how the information provisioning solution can be realised.

4.2. Digital twins

As described in Section 2, process-oriented solution are not sufficient to provide for perspective-dependent information provisioning throughout the shopfloor and organisation. In addition, it is not desirable to implement a sectional or topical solution that restricts and predetermines the information, context, perspective, and meaning of the represented information. Therefore, an adaptable solution is necessary that allows for the structuring of the relationship between information entities and their meaning in a holistic and integrated way. The introduction of information-driven solutions enables a different approach to structure, store and provide information. The concept of digital twin has been introduced as a solution for information provisioning and decision support [24–28]. A digital twin can relate captured data to its meaning and context, with that, it allows for perspective-dependent information provisioning. Therefore, the concept digital twin is further explored as information provisioning solution.

The concept of digital twin has received a lot of attention from academia, moreover, there has been a growing number of promising examples of digital twin implementations. These implementations of digital twins demonstrate their added value in the manufacturing industry [29–39]. Digital twins have been used for decision-making to enhance the effectiveness and efficiency of the shopfloor and its organisation [40–49]. For example, digital twin have been employed to; improve the assembly process for satellites [50], optimise planning and scheduling [43,51,52], improve the design and performance of production lines and environments [30,53,54], and predict maintenance to reduce downtime [25,27,34,35,37,55].

There are many different definitions of the notion digital twin [15,27,54,56–61]. Many definitions align with the definition stated in [27,61–63], and used in this research, in which a digital twin is described as "a conglomerate of data, information, models, methods, tools and techniques to represent current and previous states of an instantiated system coherently and consistently". A digital twin can integrate and represent information from various sources for the required perspective, as a basis for purposeful and underpinned decision-making [8,10]. As stated in [10], digital twins are recursive, which implies that a digital twin can consist of digital twins. The recursion of digital twins enables various levels of aggregation and granularity to be achieved through the interconnectedness of individual digital twins [10]. In this, digital twins are modular, which allows for adaptability and scalability of the digital twin to the needs of its environment [10,46,54].

To fulfil the functionalities of simulation and integration of information from different time horizons, and to manage the complexity associated with these different perspectives, information sources, and time horizons the so-called Digital System Reference (DSR) is proposed (illustrated in Fig. 2) [1,8]. The DSR can help to structure the data and information as well as establish correlations between the different time horizons involved. The DSR makes a distinction between the digital twin, digital master, and digital prototype. The digital twin captures the current and previous conditions of an entity, the digital master captures the definitions of the envisaged future states, and the digital prototype allows to test what-if scenarios by the evaluation of the simulations based on the design intent and the measured and predicted data of an entity [1,8,23,24,42,64,65]. The DSR is a conceptual model, and referred to in a limited number of publications [1,3,8–10,66,67], of which none elaborates on how to specifically implement it in practice. However, the publications do suggest that it is a valuable reference model to enhance the information provisioning and structuring the information fundament. The combination of digital twin and the DSR can theoretically fulfil the requirements stated in Section 4.1.

4.3. Digital Twinning

The DSR is represented in the DSR Reference Model and in the Advanced Manufacturing Landscape. In the landscape the DSR is placed in the information layer, where solutions such as information models and context-sensitive processing are situated. However, the Advanced Manufacturing Landscape does not provide a clear description of the DSR. The DSR reference model presents a distinct perspective and places particular emphasis on elucidating the DSR. The emphasis of the reference model is on the learning and feedback loop associated with the digital twin, the digital prototype and the digital master. Neither of the literature describing the DSR provides a uniform explanation of how the DSR can be applied in practice. Existing literature does not elaborate on the realisation and implementation of the DSR, nor how to develop the solution that is necessary between the data and intelligence layer of the Advanced Manufacturing Landscape. Even though, the DSR provides guidance on a structure for the information between different time horizons and states. Companies require more guidance on how to develop and implement such structure and information provisioning solutions.

The definition of the digital twin and the DSR are accompanied by the introduction of the notion digital twinning. Digital twinning is described in [8] as the approach that leads to the purposeful development, implementation, and usage of information backbones, such as digital twins. The implementation of digital twinning can facilitate companies to establish information provisioning solution that allows for the structuring and filtering of information from various sources and representing information in the right perspective for decision-making.

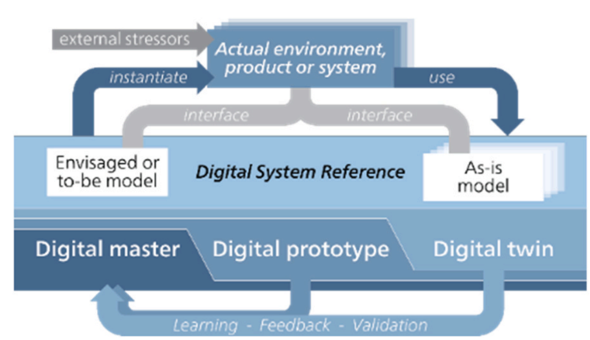

Fig. 2. Digital System Reference [1].

Moreover, digital twinning encompasses the usage of interrelation and the feedback loop between the different states of the DSR as the basis for purposeful and underpinned decision-making [9]. The use of digital twinning to simulate scenarios and evaluate potential outcomes can be particularly advantageous for SMEs that are hesitant to invest in new equipment or want to reduce the risk of downtime and uncertainty associated with adapting their shop floor.

Digital twinning can meet the requirements for the generic approach formulated in Section 3.1. Digital twinning currently cannot be considered as an off-the-shelf approach and needs further specification and elaboration to facilitate solution in the develop of an information provisioning solution. In addition, companies may find it challenging to assess the extent of the required investment in terms of time, resources, finances, and risk. SMEs are hesitant when it comes to uncertainty in these factors to develop and implement such solutions[7]. To address this, companies need a structured approach that offers guidance and tools to facilitate the development and implementation of an information provisioning solution. This research will further explore how companies can be facilitated using the digital twinning approach to develop a holistic information provisioning solution that can provide timely and perspective-dependent information.

5. Digital twinning approach

As stated, the development of an information provisioning solution varies for each company and depends on factors such as, context, environment, company requirements, stakeholder, and perspectives required. These factors make it impossible to prescribe a guideline with specific steps for the development of an information provisioning solution that fits all companies' specific needs. However, experience from (academic) projects demonstrated that there are similarities in the activities, duties, and influences in the development of information provisioning solutions such as digital twins.

6. Functions of the digital twinning approach

The activities, duties and influences in the development of information provisioning solutions are generalised in common functions in the digital twinning approach. The collection of the identified functions will outline the digital twinning approach and facilitate the development of information provisioning solutions that can enhance decision-making while meeting the requirements described in Section 3.1. The following functions are described in this section: purpose and environment, stakeholder and perspective manager, requirement manager, configuration and modularity, information fundament, information provisioning, environment characteriser, simulation of scenarios, and evaluation and learning ability. The functions described in this section will be structured as a functional architecture in Section 6. The objective of the functional architecture is to facilitate the comprehension of the functions and their interrelationships in the digital twinning approach, thereby enabling companies to apply it effectively.

6.1. Purpose and environment

The configuration of the information provisioning solution depends on company-specific details and the environment in which it will be developed. Determining the solution's purpose and underlying goal will support the development of an optimal solution that can positively impact the entire shopfloor and its organisation, rather than creating a sectional, topical, or single-issue solution [9]. The purpose of the solution is influenced by the environment in which the solution will be developed and implemented. The environment helps to define the scope of the solution and describes the level of freedom granted to the solution. The environment in which the digital twinning approach is applied can be specified by describing the companies' vision and goals and by determine the strategy to achieve them. A company's strategy outlines the actions and decisions needed to achieve the vision and goals of the company, which can guide decision-making. The strategy of a company is influenced by a company's capabilities, maturity, and capacity. It is essential to specify the environment at the beginning of the approach to ensure that the solution's purpose and requirements are fitting to the environment it is develop for. Additionally, it is crucial to regularly review the information provisioning solution to ensure that it remains aligned with its purpose and environment.

6.1.1. Stakeholder and perspective manager

Companies have many and various stakeholders, each with their own intentions, goals, and requirements [8]. Information needs to be represented in the right perspective and time horizon to ensure that each stakeholder can use and interpret the information for decision-making. Stakeholders and their perspectives can be identified at various levels of aggregation in the company. Therefore, the digital twinning approach should incorporate a stakeholder analysis that allows companies to map which stakeholders are involved, what their needs are, and which perspectives are required. The output of this analysis can be used as input for the specification of the requirements and the development of the information provisioning solution. Hence, one of the functions in the digital twinning approach is the stakeholder and perspective manager, which involves the analysis and management of stakeholders, their perspectives, and needs.

The decision-making processes in organisations frequently involve multiple stakeholders. Consequently, the functions in the digital twinning approach must ensure that the information provisioning solution allows for simultaneous access and changes to data and information by these stakeholders in the same information source. This stakeholder and perspective manager function should help companies to determine the stakeholder's access to information and decision rights.

In addition, to ensure that the solution can accommodate for all relevant stakeholders and their needs over time, continuous improvement and evaluation of the stakeholder and their requirements are necessary. Therefore, the stakeholder and perspective management function should ensure companies continuously evaluate and improve the stakeholder specification. These improvements include enhancing, reducing, or expanding the stakeholders, perspectives, and information provided in the solution.

6.1.2. Requirements manager

The development of the information provisioning solution should be based on the various requirements that follow out of the purpose and environment of the solution and the stakeholder and perspective needs. These requirements include technical, functional and scenario requirements [12]. The technical requirements focus on filtering, representing, and analysing the information, while the functional requirement focus on the configuration of the solution. The scenario requirements determine the extent of freedom for the simulation and determine the level of aggregation and granularity of the simulated environment. These requirements must be specified, stored, and managed to facilitate the development, implementation, and improvement of the information provisioning solution. Therefore, the digital twinning approach should incorporate a requirements manager function that stores and manages the requirements. Based on the changing environment, stakeholder needs and feedback, the solution requirements need to be frequently updated and evaluated. The digital twinning approach should allow for the evaluation and adaptations of the requirements.

6.1.3. Configuration and modularity

To ensure the approach can be implemented in different companies, shopfloors, contexts, and environments, the information provisioning solutions resulting from the digital twinning approach should be similar in their core but configured and adapted to meet company specific needs. By using a modular structure, the information provisioning solution can be configured to meet company specific needs and adapted to future needs and changes. The benefit of the modular structure is that the developed modules, such as representation and interpretation modules, can be stored in a repository for reuse for further development of solutions. Therefore, the digital twinning approach must include a configuration function that can configure these modules in a company specific information provisioning solution. The solution can be configured based on the definition of the environment and context, requirements, and stakeholder's needs. With this, the configuration function can orchestrate the relevant modules for a functioning information provisioning solution that behaves according to the company's wishes.

6.1.4. Information fundament

The information provisioning solution should be able to make use of the existing information fundament of a company. The information fundament spans the entire organisation and often facilitates the communication between companies. The digital twinning approach should incorporate a function that facilitates the provisioning of the necessary information based on the requirements, the perspectives, and the stakeholder's needs. For this, the DSR was presented as a reference model to help structure the data and information from the different information sources and different time horizons in the organisation. Therefore, the DSR will be a function in the approach that represents the information fundament. The DSR function in the approach should ensure that companies develop and structure their information fundament.

Since the data and information used for decision-making changes and evolves constantly and can be used by multiple stakeholders simultaneously. The information fundament should be developed to be dynamic so that it allows for real-time updates and access to the latest and relevant information. The approach needs to facilitate companies in the further development of their information fundament to make the relevant information available and accessible.

6.1.5. Information provisioning

Each perspective requires a different variety of information and representation, therefore, in the digital twinning approach, it can be beneficial to implement multiple information provisioning solutions that are part of the larger information provisioning solution. The approach requires a function that can instantiate the information provisioning solutions according to stakeholders need, the defined requirements and the configured modules. The result of the instantiation can be for example a digital twin, or dashboard that is tailored to a set of stakeholders and perspectives, as a basis for decision-making.

6.1.6. Environment characteriser

To present the data to stakeholders in a meaningful way, it is important to identify and describe the characteristics of the company's environment. The functions in the digital twinning approach should ensure that companies store the data separately from their meaning, to allow for perspective-dependent information provisioning. The characteristics of the environment can help to interrelate the rationale and meaning of the information for decision-making, independent of individual stakeholders, as they cannot anticipate and oversee the consequences of decision on the entire organisation and shopfloor [13]. In addition, the characteristics of an environment can be crucial input for the simulation of scenarios. The environment characteristic can include parameters that describe the environment, its influencing factors, and the envisaged state of the shopfloor, which can be used for the simulation and evaluation of scenario and their outcomes. Therefore, the digital twinning approach should have a function that contains the description of the environment. The environment description should include company-specific information, such as business logic, a description of the current state of the company (including manufacturing processes, layout, and equipment), and a description of the envisaged states. This characterisation of the environment helps to determine and describe the scope, and therefore the solution space, between the current state (as-is) and the future state (to-be). Moreover, it should include a roadmap outlining the changes required to achieve the company's vision and envisaged future state. This function is described as the environment characteriser function in the digital twinning approach. This function contains a figurative library of the environment characteristics and provides the necessary context for the interpretation and contextualisation of data.

6.1.7. Simulation of scenarios

To make decisions with longer time horizons and greater uncertainty, it may be valuable to evaluate the outcomes of various scenarios before deciding. This can be facilitated by simulating the possible scenarios. By simulating multiple scenarios, insights can be gathered from the potential outcomes [65]. The simulation should be developed based on the requirements, environment, and defined scenarios. In addition, the simulation requires information on the various states, models of system behaviour, and the characteristics and influences of the environment. To accurately represent the environment, it is necessary to understand its rules, logic, and behaviour. Engineering principles can describe the rules, logic, and behaviour of the environment, using engineering models, such as laws of physics, planning principles, and business rules. The approach requires a function to develop, maintain and store engineering models. Therefore, an engineering model repository function needs to be incorporated in the digital twinning approach, as well as a model developer function that is responsible for developing and updating these models. Additionally, the digital twinning approach should allow for the simulation of different scenarios using these engineering models. Therefore, a scenario simulator function must be included. The scenario simulator utilises information from the information fundament, engineering models, and environmental characteristics to conduct simulations. The simulator's outcomes can be presented to the stakeholder in a configured and instantiated representation.

6.1.8. Evaluation and learning ability

Evaluation is crucial in the digital twinning approach as it allows for improvement of the developed information provisioning solution based on learnings during the development, implementation, and usage of the solution. During the development and usage of the information provisioning solution issues can occur such as an incorrect definition of the environment, inadequate requirements definitions, and incorrect outcomes of the engineering models that do not fully align with the current situation. These issues often lead to information provisioning solutions that do not fulfil their purpose fully. Moreover, during the development and usage of the information provisioning solution, new insight might have occurred that require adjustment of requirement, environment, and the solution. By incorporating a learning and feedback and improvement mechanism in the approach, the solution can be continuously improved and adapted to changes in the environment. The evaluation of the solution is based on the requirements and the ability to meet its purpose. In addition, feedback from the evaluation on the implemented solution regarding information provisioning, configuration and simulation can be used to improve the solution by further specifying or adjusting the requirements and environment. Moreover, stakeholder feedback can also be utilised to improve the information provisioning and the module configuration. With this, the evaluation function can ensure that the develop solution can be continuously improved.

The evaluation and user feedback of the implemented solution can be used to identify interrelations between the stakeholder information needs, perspectives and requirements and the environment, information source, and configuration of the solutions. By increasing and decreasing these interrelations the solution can learn from the usage and feedback of the information provisioning solution. These learnings can be used to provide the appropriate information for the right perspective at the right moment more effectively and efficiently in the future.

The combination of the identified functions provides an outline of the activities, duties and influences involved in the development of an information provisioning solution. Collectively, these functions constitute the digital twinning approach. The functions indicate the blocks that should be realised to develop an information provisioning solution, without prescribing the specific form that the solution should take. To facilitate companies in the development of information provisioning solutions, the digital twinning approach should be made as tangible and structured as possible. To provide structure to the functions in the digital twinning approach a functional architecture has been developed and will be discussed in the next section.

6.1.9. *Functional architecture for digital twinning*

A functional architecture has been developed based on the functions described in section 5.1, and depicted in Fig. 3. The objective of the functional architecture is to clarify what functions relate to each other in what way. Moreover, it facilitates implementation trajectories by allowing companies to better understand and better structure their goals, activities, and efforts.

To allow for a comprehensive explanation of the architecture, the functions in the architecture are clustered by means of colour. The functions depicted in grey and dark blue together represent the digital twinning approach. The functions shown in light blue and green together depict the activities that are required for the development and configuration of an information provisioning solution.

The functions related to the digital twinning (grey and dark blue) concern the analysis and definition of the environment, the needs of the stakeholders, and the purpose and requirements of the solution (grey). The objective of these functions is to determine the requirements and configuration for the information provisioning solution that will be managed in the requirement manager (dark blue).

The environment, stakeholder and perspective manager, and evaluator functions are depicted in grey, as these functions are influenced by the physical environment and, accordingly, influence the requirements and configuration of the solution. The grey functions establish a feedback loop between the stakeholders and the solution specifically for the definition of requirements, the instantiated information provisioning, and the configuration of the solution. The evaluator function ensures that there is an additional feedback loop to evaluate the requirements, environment, and models used for scenario simulations.

The functions related to the information provisioning (light blue and green) are concerned with the activities that are required for the development and configuration of such an information provisioning solution. In this, the light blue functions represent the repositories that are required for the information provisioning solution and consist of the information foundation, which is structured by the DSR, the module repository, and the engineering models. The light green functions consist of a module configurator and module generator, which ensure the development and configuration of modules for the information provisioning solution. The developed modules are stored and are accessible in the module repository for the configuration of the solution. The environment characteriser and model developer allow for the contextualisation, representation, and simulation of the environment and the data and information available in the information fundament that is structured by the DSR.

The combination of the dark blue, light blue, and light green functions can be described as the orchestrator of the digital twinning approach. The functions in the orchestrator facilitate the configuration of the information provisioning solution. The configuration realised by the orchestrator is based on the requirements specified in the requirements manager, the needs of the stakeholders defined in the stakeholder and perspective manager, and the feedback from the evaluator.

The dark green functions ensure the instantiation of an information provisioning solution and the simulation of scenarios to facilitate for decision-making. If a scenario simulation is required for decision support, the orchestrator utilises engineering models to simulate a scenario, along with using the model developer and environment characteriser to develop and refine the models to accurately represent the environment. The engineering models and information from the information fundament are utilised by the scenario simulator to provide simulation outcomes. These outcomes are then provided to the information provisioning instantiator to represent them in the appropriate perspective.

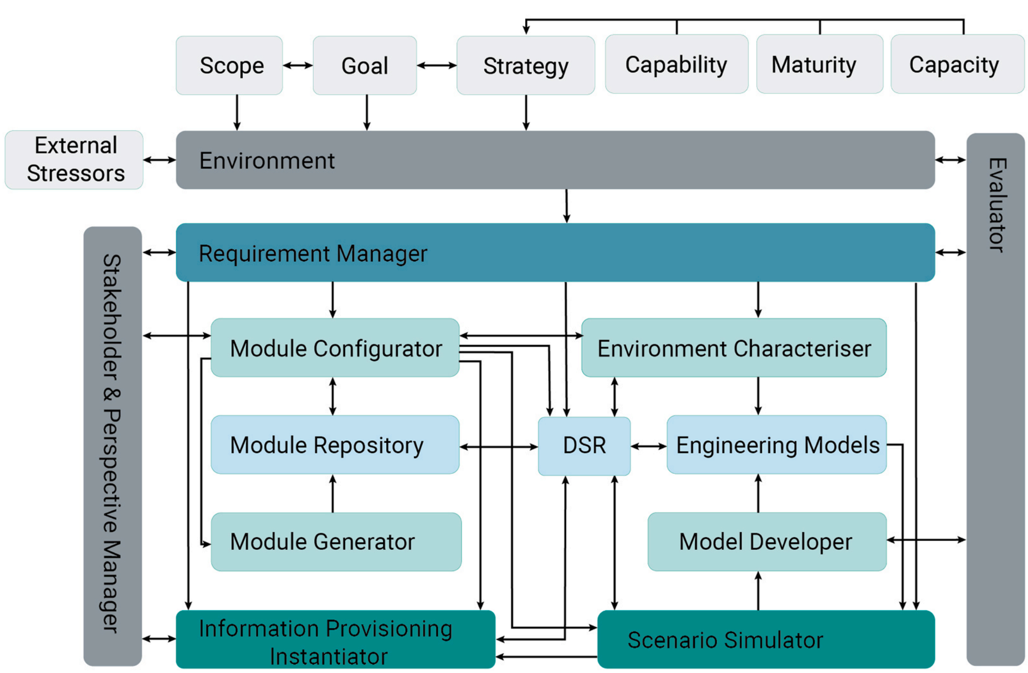

Fig. 3. Functional Architecture for Digital Twinning approach.

The combination of functions in the functional architecture facilitate the definition, configuration, and development of an information provisioning solution, while illustrating how the functions are interrelated. The functional architecture helps to structure the digital twinning approach and provides support in formulating tangible activities, duties and influences that are required to develop an information provisioning solution. The functions in the architecture can be performed by either a human or a system. It is assumed that a human will initially perform these functions, and some functions can be automated in the future. The next section will illustrate the application of the functional architecture in two use cases. These two case studies will be used to demonstrate its application and verify its ability to support companies in the development of an information provisioning solution.

6.1.10. Use cases functional architecture

This section will elaborate on two use cases in a manufacturing setting to evaluate and verify if the architecture of the digital twinning approach can be used to develop a solution that provides the appropriate information, in the right perspective, for decision-making. The verification of the digital twinning approach and the functional architecture will be done based on the requirements for the generic approach and the outcomes of the use cases.

6.1.11. Engine shop use case

The journey of the engine through the engine shop ranges from disassembly to cleaning of the countless individual components. Based on the quality inspection and the required maintenance the components then follow various technical and logistical routes before undergoing the final quality checks of the re-assembled engine. The components of the engine can't be interchanged, and thus, one delayed part will cause an overall delay in the re-assembly process. There is a strict deadline and throughput time for each engine, any delay to this can result in a large fine. Currently, delays are often caused by local prioritization decisions at workstations in the engine shop. These priority decisions are often made based on employee preference rather than priority of deadlines for each engine.

The airline aims to improve the efficiency of the engine shop by improving the coordination between, employees, resources, planning, and order flow. This includes improving the information availability to support the activities and decision-making in the engine shop. The purpose of the information provisioning solution is to improve the insight and control to make well-informed decisions that help to increase the reliability in the overall throughput times and minimising delays. A further analysis of the environment is done through interviews with employees and observations in the engine shop. The scope of the solution is set on the cleaning department since most delays are caused in this department.

The stakeholders are interviewed to gain insight in their information needs and requirements, to determine the required perspectives, and to determine how the stakeholders can be enabled to make more informed decisions. In this context, there are several stakeholders identified, which are the employees of the cleaning department and the department heads. The cleaning department's employees require more insight in which parts are in the process, their location, and their priority. To improve the priority decisions, the stakeholders request an overview of the upcoming components. The department heads are responsible for the planning and currently have limited insight in progress of components in the process, making it difficult for them to identify potential delays. They require an overview of the progress of the components and their delays in the department.

Based on the environment, the stakeholder, and perspectives, the solution's requirements can be determined and specified by the requirement manager. These requirements include the needs for an interface that is specific for each buffer in the cleaning department which shows the components in the buffer in relation to their priority. In addition, an interface is required for the department heads that allows for the representation of the location of all components in the department and if they have a delay. An analysis is done to identify and specify the environmental characteristics such as the process activities, flows, business logic, and the layout of the engine shop. These characteristics are all described by the environmental characteriser and will be used for the contextualisation and representation of the information in the solution. During the analysis of the cleaning process, it became apparent that monitoring the components during the initial cleaning steps was nearly impossible due to the substantial number of parts that were cleaned together and the sensitivity of the location sensors to the cleaning process. As a result, the environment and scope were shifted to monitor the buffers between the cleaning process steps instead of the entire process.

To configure an information provisioning solution for the employees and the department heads, several modules need to be developed by the module generator. These modules are for example the representation of the order information for each buffer in the cleaning department, the representation of the part location in the engine shop, and an analysis module to calculate the priority of the parts based on the deadline and current progress. Once the modules are developed the module configurator can configure the information provisioning solution for the required perspectives. Two visualisation modules were developed and evaluated with the stakeholder to fit the required perspectives and to further specify the requirements for the solution. Next to the development of the visualisation modules, the solution requires the availability of data and information. Currently a minimal set of information is available in the ERP system. Moreover, the information required for the solution is scattered throughout the information fundament. Next to the acquisition of additional data, the information needs to be made available in the information fundament. Therefore, a solution needs to be implemented first that can monitor the location of the components in the engine shop. Moreover, the required data needs to be made accessible in the information fundament. Based on a proof of concept of a monitoring solution, the visualisation modules, the analysis module, and a dataset exported from the information fundament, two dashboards were instantiated by the information provisioning instantiator, which are shown in Fig. 4.

6.1.12. Bicycle manufacturer use case

The second use case is based on a bicycle manufacturer that manufactures bicycles for people with a disability. The manufacturing process involves producing the bicycle frames, gritting, and painting them, and then assembling them into finished products based on customer orders. The high-level of customisation of the products results in an enormous number of different product configurations, this leads to a high level of

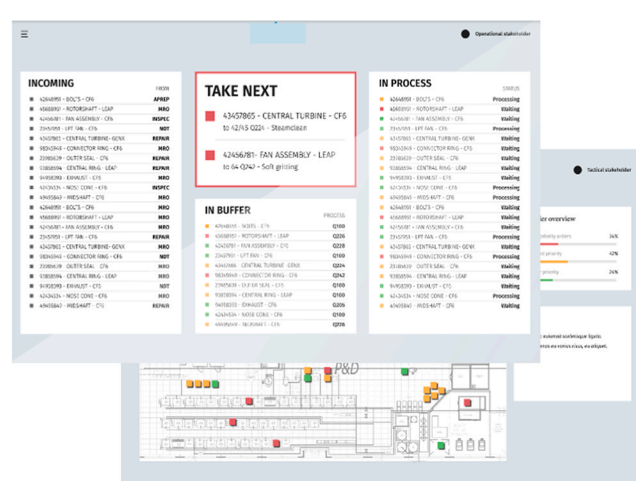

Fig. 4. Representations developed for engine shop use case.

complexity in managing the shopfloor. Additionally, the company is experiencing rapid growth and high fluctuations in the order intake due to seasonal demand.

The company states that the current information provisioning in the company is inadequate to support decision-making at operational, tactical, and strategical level. This due to the information being either not accessible, available, or paper-based. The company aims to develop a solution that improves the information availability and accessibility throughout the organisation to improve decision-making. The environment, strategy and company vision are identified and specified by organising several workshops and developing a visual representation of the company vision in the form of a vision map. This vision map is shared throughout the organisation to ensure the involvement of the entire organisation in achieving this vision. The scope of the use case focuses on the production department, specifically the work preparation of the production department.

Currently, the laser cutting process is the critical bottleneck in the production department. The organisation has limited insight in the processing times and performance of the machine. Moreover, the company is considering buying an additional laser cutting machine. In this environment, the stakeholder needs, and the required perspectives can be identified by the stakeholder and perspective manager. The identified stakeholders are initially limited to the operators of the laser cutting machine and the department head of the production department who oversee the planning around the laser cutting. The department head requires operational information to be available in an interface, including throughput times, machine efficiency, and an overall overview of active orders. This information can assist the department head in optimising the department's planning and the process flow. The operators require an interface that displays machine health and status, as well as order information such as drawings and instructions for the current production order.

The requirements for the solution can be determined based on the stakeholders' needs and environment. The company's goal is to develop a scalable solution. Therefore, this use case defines generic requirements for the information provisioning solution for the entire organisation and specific requirements for the information provisioning solution for the operators and the department head of production. The requirement manager manages the combination of these requirements. The requirements for this solution include standardised methods of transferring data between the information foundation and resources. Additionally, the solution must allow for the simulation of various scenarios based on historical, current, and simulated data to anticipate potential futures. As the company operates in a "live" shopfloor, the aim is to minimise downtime during the development and implementation of a solution, therefore, a step-by-step implementation is required. Workshops are organised to determine the characteristics of the environment, such as the process definitions, resources, and business logic and roadmap of the company.

To develop the required information provisioning solution, the module generator created a representation module for the interfaces. The company aims to provide consistent interfaces with a standardised look and feel across the organisation. To achieve this, the interface was developed using a standardised template and smaller functional modules. For example, a functional module was developed to scan, start, and stop an order and to search for an order in the ERP, and represent the drawings from the PLM system in the interface. In addition, an analysis module needs to be developed that calculates the average processing times, based on the start, and stop registrations of the operator.

The development of the solution relies on the availability and accessibility of the information. Therefore, the current digital infrastructure is mapped to identify where the information is stored and how the data systems are connected. The digital infrastructure is mapped in the blueprint for digital infrastructures [13]. The analysis of the blueprint showed that the current digital infrastructure was limiting the information provisioning in the company, and adjustments to the current implemented data systems required considerable time investments. The current information fundament did not allow for the provisioning of the drawings. Based on this limitation, an information provisioning solution was instantiated based on the representation module and the functional modules. An example of the operator user-interface is presented below in Fig. 5. In addition to the operator user-interface, a dashboard was developed for the department head that shows the average processing times. As the current digital infrastructure was limiting the flexibility to make information available and accessible, the company determined that developments should first focus on improving the information fundament.

7. Verification functional architecture

This section will verify if the digital twinning approach by means of the functional architecture can facilitate companies in developing an information provisioning solution and whether it can meet the requirements for the generic approach.

The two use cases demonstrate that the functional architecture can facilitate companies in the development of an information provisioning solution. The application of the functional architecture in both use cases illustrated part of the functions the digital twinning approach entails, how these functions relate to each other and how they can support in realising an information provisioning solution. Due to the limited availability of data, the scenario simulation function has not been elaborated on in the use cases.

The functional architecture is applied in two use cases that both have a varying context, environment, and requirements. The functional architecture is generic but allows for a company specific solution in the environment, requirements, stakeholder and perspective manager and environment characteriser, which results in a company specific configuration of an information provisioning solution. The application of the functional architecture in the varying environments of the use cases and the resulting information provisioning solutions give a first positive indication of the applicability of the functional architecture in different manufacturing environments.

The functional architecture includes the environment function, which include the vision, goals, capacity, maturity, and capability of a company. This function allows companies to specify the purpose of the information provisioning solution to formulate requirements and ensures that the company define a vision for their company. By consciously considering the environment and purpose of the information provisioning solution, the solution can be configured to meet its intended purpose and to ensure it aligns with the vision of the company.

In addition, the function of the stakeholder and perspective manager in the approach and architecture ensures companies identify and manage the relevant stakeholders and their perspectives. This enables the integration of various perspectives and levels of aggregation in the development of the solution. In addition, the module configurator in collaboration with the other functions facilitate for the configuration of a solution and ensure that the developed solutions meet its purpose, and the company's needs. The solution's modularity and alignment with the

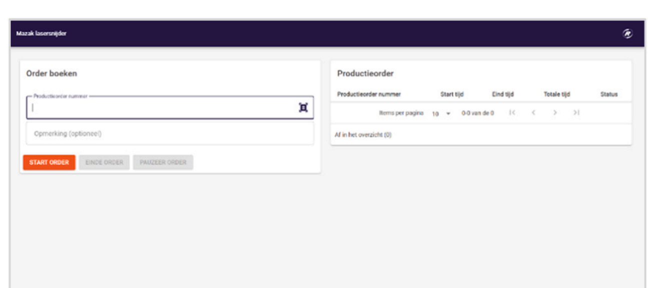

Fig. 5. Representation for workstation laser cutter.

environment enable further scaling and incremental implementation in the organisation.

In both case studies, the implementation of the digital twinning approach has sparked discussions in both companies about the limited availability and accessibility of information in their information fundament, as well as the need to reduce the limitations of existing solutions in terms of information accessibility and perspectives. The digital twinning approach has helped both companies to identify what developments are required to develop an information provisioning solution. The blueprint for digital infrastructures in the digital twinning approach facilitates companies to map the current state of the digital infrastructure of the company and to identify how the information fundament can be used in the information provisioning solution. The combination of the information fundament (DSR) and the environment characteriser allows for the development of an information driven solution that interrelates the information and its meaning, outside of the information fundament and implemented solutions.

Furthermore, by integrating the evaluation function in the architecture, the information provisioning solution can be continuously improved to handle the volatility in the environment and adapt towards stakeholder needs and changes in the environment.

The digital twinning approach and its functions structured by the functional architecture can meet the requirements for the generic approach. To assess the validity of the digital twinning approach, it needs to be further applied in a real-time environment. Currently, the engine shop project is still running, and the solution is still under development. Therefore, it cannot be used to demonstrate the full implementation of the digital twinning approach. The bicycle manufacturer has committed to improve their information fundament and develop the digital twinning approach in a 3-year project. Therefore, this case study will be used to fully implement and validate the digital twinning approach.

8. Versatile information provisioning case study

The bicycle manufacturer has decided to focus on the development of a holistic information provisioning solution using the digital twinning approach. This decision was supported by the analysis of the existing digital infrastructure, that indicated that the current communication between the data systems, and the availability of the data was insufficient to support decision-making throughout the organisation. Before developing an information provisioning solution, the information fundament needs to be improved to reduce the limitations of the current digital infrastructure. This section will elaborate on the development of the information fundament and an information provisioning solution that is based on the improved information fundament and the digital twinning approach. In this case study several information provisioning solutions will be developed as part of an integral whole. This includes several user-interfaces for decision support and digital twins of the welding robots and the production order flow. The implementation in the case study will be used to validate the digital twinning approach in the next section.

8.1. Information fundament

To identify how the information fundament needs to be improved, an analysis was conducted using the blueprint for digital infrastructure [13] to map the current digital infrastructure. The analysis of the digital infrastructure showed that the company had a high dependency on the ERP system. The company assigned many functionalities to the ERP system, from order planning to Bill of Materials (BOM) and process (BOP) which caused improper use of the ERP system and caused the ERP to become slow and inefficient. Additional issues were caused by various smaller software packages, that would allow for the data to be communicated towards the shopfloor. The current information provisioning solution was not developed in-house and was causing errors throughout digital infrastructure, making it difficult to maintain, adapt or scale this existing solution. In addition to the limitations of the current digital infrastructure, the majority of the shopfloor information is paper based, leading to significant time loss in sorting and linking paper orders to physical sub-assemblies/products. Moreover, there is no digital feedback on the order process and paper instructions are not always complete or clear.

Maintaining the current digital infrastructure has become increasingly challenging due to difficulties in overseeing the impact of changes and resolving software issues. To address the limitation of the current information fundament, a middleware solution based on the DSR will be designed and developed to serve as the information fundament that makes use of the digital infrastructure. The solution needs to facilitate communication and data accessibility between systems and stakeholders. The purpose of the middleware solution is to combine data from various sources to provide filtered data that can be contextualised to meaningful information and insights in the information provisioning solution.

The middleware solution will be developed incrementally using microservices and following the loosely coupled, high cohesion principle [68]. This principle enables the connection and disconnection of components without affecting the function of the middleware. It allows the middleware to request information from the digital infrastructure and provide the information when necessary. The middleware will not replace the functionalities of the data systems, it be merely connected to all the data systems and will be responsible for the communication between them. Consequently, this enables a critical evaluation of the functionalities provided by each data system, determining which are essential and which can be phased out.

The middleware solution includes microservices, which are processing units in a Kubernetes environment. Each microservice manages and captures events and transforms them into data for other systems and repositories. Microservices are designed as reusable software components or building blocks, enabling their reuse in the middleware solution. The middleware solution is based on the principles of event logging and streaming [2,69,70]. Event streaming means that all events in the company are recorded in a stream, which is based on Apache Kafka [2,71]. Data systems and repositories work together as subcontractors (producers and/or consumers) of events in a given log (known as a topic). The middleware comprises various topics, each allowing for the addition of events as a producer or subscribe as a consumer to receive events. A domain model developed by the company guides the structure and linkage of these topics, which describe the relationship between information types and their meaning and environment. Structuring the middleware in this way has the benefit of creating a self-developed and self-owned domain model that contains the company's business logic.

The middleware increases adaptability and scalability in the information fundament to handle the volatility of the environment and increases the availability and accessibility for information provisioning. Moreover, the domain model in the middleware allows for the structuring of information in the information fundament and enable for example, customers to be informed about their orders based on real-time data from different information sources. In addition, the event streaming in the middleware will allow for the structuring of the data over different time horizons. With that the information fundament can facilitate for the provisioning of information throughout the organisation. The developed middleware will be implemented initially in the welding department, along with the development of an information provisioning solution for this department.

8.2. Welding robot digital twin

Welding is a crucial process in the manufacturing of the bicycle frames. The company has nine welding robots capable of producing 26 different frame types, including custom frames upon request. The manufacturing of the bicycles requires both make-to-order and configure-to-order strategies, which increase manufacturing complexity. Currently, there is a lack of understanding about welding process lead times and robot performance. It is not possible to predict or observe the effect of modifying welding fixtures or programs on welding efficiency. This information can aid in decision-making to optimise the flow and planning of the welding department. The stakeholders are the welding robot operators, the engineers, and the person responsible for the planning. The perspective required for the solution can be defined with three level of aggregation, operational, tactical, and strategic. For the operational perspective, information is required to show how well the welding robot is functioning as well as show the progress of the order. The tactical level requires information about the number of welded frames and the number of products welded per product type per robot. The strategical perspective is required by the planning department that needs to know more about the machine efficiency and availability to plan toward future operations.

Next to the generic requirements for an information provisioning solution, the bicycle manufacturer specified additional requirements. Upon analysing the data acquired from the robots, it became apparent that there were instances of missing and incorrect information, which compromised the reliability of the dataset. The analysis resulted in a more detailed plan for implementing machine connectivity, data storage and analysis of the data in the information fundament. This resulted in the requirement to have a standardised manner of transferring data between machines/equipment and the information fundament. In this the welding robots will be an example of the various components that will be connected to the information fundament through the middleware solution. An additional requirement of the company is that all the modules that are being developed for the information provisioning solution need to be reusable. In addition, they require the information provisioning solution to allow them to perform simulations of scenarios. Furthermore, since the company is a 'live' environment, a step-by-step implementation of the information provisioning solution is required.

Workshops with the production department were conducted to describe the current activities and order flow through the welding robot department. The activity description along with other characteristics of the environment were described and specified. With the environment, stakeholders and perspectives, and requirements and characteristics determined, the modules can be generated, and the information provisioning solution can be configured. The data is stored by the middleware in a topic for raw data and a topic for interpreted data. The event stream of the topic for interpreted data allows for a timeline that shows current and past status overviews. In addition, the middleware solution provides the data from the welding robot and the related order information from the ERP system. Three dashboards are instantiated for each required perspective. This is elaborated on in [2] and shown in Fig. 6. The three perspectives allow to analyse and reduce the number of common errors based on uptime and error registration. Furthermore, the interfaces provide quick reporting capabilities for the department head 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 represented in the interfaces provide insights that enable better-informed decisions. For example, insights in takt-time (historical and averaged) have helped the planning department to be more resilient and accurate in its planning.

It is significant to ensure the reliability of the data, as the information provided by the welding robot will be utilised for decision-making processes, including those related to planning. It became evident that the data obtained from the datalogger was not consistently accurate or reliable. On occasion, the datalogger failed to register a signal or event, resulting in incomplete or inaccurate data. A collaborative effort with the machine supplier has been ongoing to address these issues. To gain a comprehensive understanding of the reliability and accuracy of the data, a fourth perspective was introduced. The fourth perspective was designed to facilitate the representation of the data in a manner that

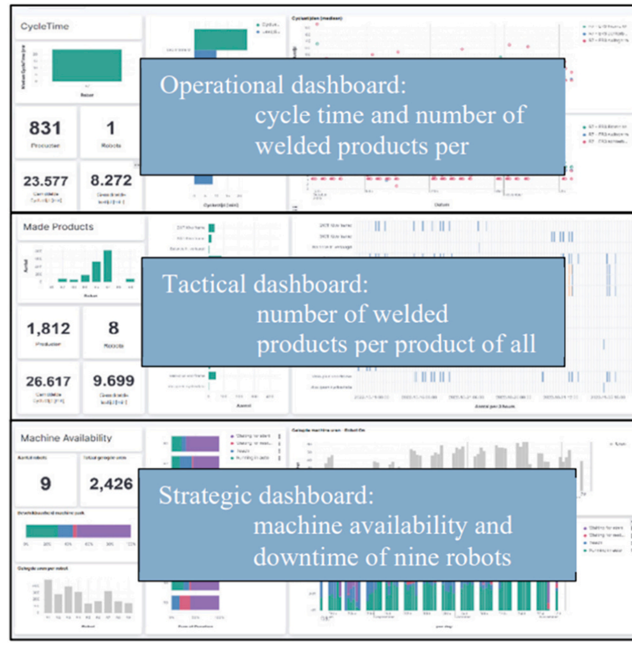

Fig. 6. Dashboard for welding department in three different levels of aggregation [2].

would enable the operators to validate its accuracy and reliability. The fourth information provisioning solution, therefore, employed a three-dimensional representation of the welding robots instead of using graphs and raw datasets. The configuration for this fourth perspective made use of the same core modules and information fundament as the first three perspectives, with the addition of a three-dimensional representation module for the welding robots, as illustrated in Fig. 7 and detailed in Fig. 8.

Fig. 8 shows the information provisioning solution that was developed for the evaluation of the real-time welding robot data. The bulb displayed above each welding robot employs a colour-coded system to indicate the operational status of the robot. The states indicated are as follows: error/standstill (red), running (green), waiting (orange), and turned off (black). Furthermore, the representation also displays the duration of the status. The interface allows the user to switch between specific views of the nine robots and a total overview of all robots. The illustration at the bottom of Fig. 8 shows the additional information provided for each robot in the robot specific views. The information shown in the 'virtual dashboard' are based the request from the operator. The operators stated they required this information to evaluate if the data that is acquired from the welding robot is in line and accurate with the real-time physical activity of the welding robot. The operators stated that they were able to determine that the acquired data was sufficiently reliable to analyse often occurring errors and downtime.

The information provisioning solutions for the welding robots

Fig. 7. The welding robot and representations of its digital twin [2].

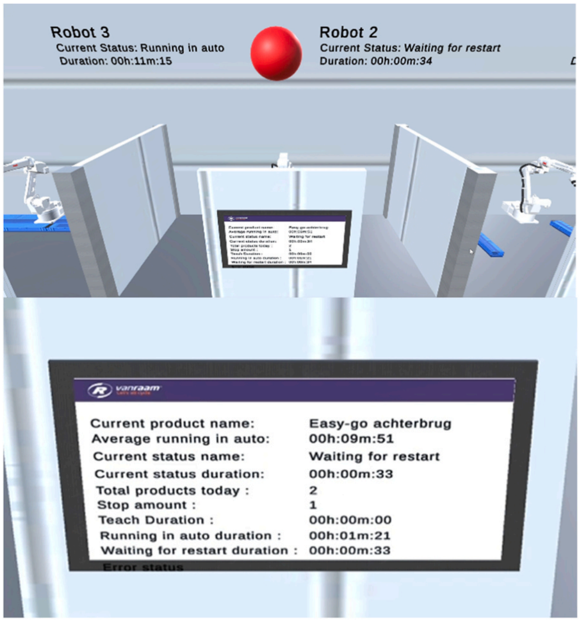

Fig. 8. Digital twin of welding robot.

allowed for analysis of the uptime and downtime of the welding robots. For one welding robot, it was calculated that 7 % of the production capacity of the welding robot was lost due to downtime caused by errors. The information provisioning solution provided the opportunity to analyse the often-occurring errors. Following the analysis, modifications were implemented in the welding robot programming, resulting in a reduction in the frequency of errors. The alterations to the welding robot program led to a decrease in the number of errors from one occurrence per three and a half welding cycles to seven cycles. The information provisioning solutions will be employed in the future for the analysis of individual and overall downtime of the welding robots, with the objective of reducing waiting times and optimising the scheduling of all welding robots.

To conclude, the implementation of the digital twinning approach allowed for the development of four interconnected information provisioning solutions that were able to support the stakeholders in their decision-making effectively. Further development is focused on an additional interface for the operators to view current orders and the corresponding instructions and drawings. This will be done based on the existing template and modules that were developed for the laser cutting interface.

The company planned to move one of the welding robots to another remote shopfloor of the company. With the moving of one of the robots to a remote shopfloor, the modularity of the solution was tested. The approach and structure of the solution remained the same for the development of the information provisioning solutions in the remote shopfloor, only the company-specific details such as processes and perspectives changed. With this, the use case showed that the modular approach can facilitate for adaptability and flexibility at the shopfloor and moreover, in facilitating for additional perspectives and needs of stakeholders.

8.3. Small assembly use case

During the implementation of the middleware solution and the development of the information provisioning solutions in the production department, a warehouse management system (WMS) was implemented in the entire organisation. The implementation of this data system was necessary due to significant issues with the supply chain and inadequate control over stock levels and parts in storage. The communication between the WMS and the other data systems is provided by the middleware solution. This communication is based on events in the WMS which are stored in topics in the middleware solution. The data systems are updated, when necessary, based on the events and triggers in the topics. These triggers are based on business logic that is managed in the domain model. In this way, the business logic is not predefined in the WMS.

The WMS is implemented with the aim to track the stock levels throughout the factory and to digitise the logistics process. The WMS requires employees to log their production activity, which automatically, when ending the production activity subtracts the used components or parts from the stock. The implementation of the WMS accelerated the development and implementation of the middleware solution and the user-interfaces to log the production activities and logistic movements throughout the entire organisation. These interfaces were configured using the digital twinning approach and the lessons learned from the application of the approach in the production department.

The focus was first put on the small assembly department. In the small assembly department, sub-assemblies are built up so that they are ready for the assembly line. This includes the assembly of for example electro engines for bicycles. Small assembly employees can benefit from having the order information, required parts and assembly drawings available. In addition, the department head has requested for insight in the assembly times and order flow through the assembly department. Currently, the department works paper-based and only has paper instructions and order instructions available.

A user-interface needed to be developed that can provide and combine the information from three different sources in the digital infrastructure: the order information from the ERP software, drawings and bills of materials from the PLM software, and a link to the WMS software to request additional part, subtract the used components and book the finished parts as stock. The representation and functional modules of the previously developed interfaces were used to configure the information provisioning solution for the small assembly department. A user-interface was instantiated for each of the four workstations in the small-assembly department. These user-interfaces are all instantiated information provisioning solutions that are part of a larger information provisioning. The user-interface developed for the small assembly is shown in Fig. 9.

The digital twinning approach facilitated the company to develop and implement the required information provisioning solutions. These solutions are all based on a similar core and approach, while reusing modules, making use of the developed information fundament, and further developing new modules. The information provisioning solutions have made it easier for the employees to understand their tasks and streamlines the logistics process around the small assembly activities. The necessity for rework due to the use of outdated assembly drawings has been reduces, as has the time required for orders to be processed due to missing assembly components. Implementing the information

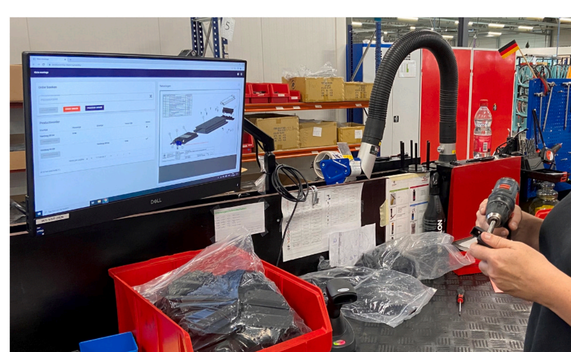

Fig. 9. Small assembly interface for assembly employee.

provisioning solution in the shopfloor has also provided additional data points for analysis, such as order flow and assembly times. The digital twinning approach has ensured for modularity in the solution which has made the development of the interfaces quick and efficient.

8.4. Order flow digital twin

From the initial stages of the case study, the company has indicated a clear interest in simulating the order flow and gaining deeper insights in potential bottlenecks and inefficiencies on the shop floor. The company's long-term objective is to be able to simulate a variety of potential change scenarios, including alternative floor layouts. A digital twin of the order flow was developed to provide further demonstration of the capability of the information provisioning solutions and middleware solution. It is essential for the company that the information provisioning solution offers insight in the existing order flow and any bottlenecks on the shop floor, while also displaying the number of orders and buffers in real time. The information provisioning solution is designed to facilitate the tracking of orders throughout the shop floor, providing department heads with the ability to monitor the location and progress of orders in real-time. The department heads intend to utilise this insight to optimise their planning and enhance the order flow on the shop floor. A three-dimensional representation of the shop floor layout was employed to contextualise the location of orders and associated data. Fig. 10 illustrates the developed solution for the order flow.

The solution led to a better understanding of the buffers surrounding the assembly lines and the quantity of orders awaiting transportation in the warehouse. The company highlighted that the most beneficial aspect of the order flow solution was that it facilitated the identification of data points that were absent and needed to enhance the capabilities to perform bottleneck analysis and scenario simulation. For instance, it became evident that data points were lacking between the paint shop and the start of the assembly line, which is crucial for determining the time an order spends in a buffer. The digital twin model can be utilised in the future to simulate different scenarios' such as changes to the assembly lines, changes in planning and the effect on the flow of the orders throughout the environment. A preliminary time-lapse feature has been added to the digital twin. This feature allows to select a time range and move through historic data points in a selected period. The order flow and movement of the orders will be simulated and represented in the 3D model. Currently, the digital twin is not capable yet of simulating different future scenarios. Further development of engineering models and analysis modules are required to realise this functionality.

In addition to meeting the needs of the heads of the departments, the aim of the digital twin was to illustrate data accessibility and the insights that can be derived from the developed information provisioning solution and middleware solution. Currently, the digital twin has already triggered several requests from stakeholders for information and information provisioning solutions in the organisation. To illustrate, the assembly department has requested for information provisioning solution for the assembly line that are similar to the user interfaces that were developed for the small assembly department.

Fig. 10. Order flow representation.

8.5. Conclusion Case Study

The case study illustrates the effectiveness of the digital twinning approach in developing solutions for information provisioning throughout an organisation. It demonstrates that the approach can be recursive and used to develop specific solutions as needed. These information provisioning solutions are based on the same approach and core, configured with similar modules and information fundament. Therefore, they can be connected to form a large information provisioning solution. This solution can provide the necessary information for decision-making throughout the entire organisation.

The bicycle manufacturer case study shows that the current core structure for information provisioning provides the flexibility to tailor the information provisioning to the needs of the perspectives and stakeholders in the organisation and that the efforts to do this have been reduced. Additionally, the company can access and utilize information for decision-making throughout the organisation without facing previous limitations imposed by the software systems. This has enhanced the company's flexibility and adaptability of their shopfloor and the information provisioning in the shopfloor for decision-making. With the modular structure of the solution, the company is able to adapt to future requirements and stakeholder needs.

The digital twinning approach facilitated a need-based development of information provisioning solutions, which improved their acceptance in the organisation. Furthermore, during the implementation of the information provisioning solution, it became evident that the organisation's mindset had shifted towards an information-driven approach. In addition, it became apparent that to ensure acceptance in the organisation and to realise the implementation of the digital twinning approach, a responsible individual was required in the company. This responsible individual can ensure adherence to the approach and can guide the company in the development and implementation of the information provisioning solutions. Ownership of the solutions had also transitioned from the development team to the respective departments, resulting in increased stakeholder engagement and information requests. This shift in mindset highlights a move away from the traditional process-oriented approach to a more information-driven one.

9. Validation

The aim of this section is to validate the ability of the developed digital twinning approach to facilitate companies in establishing solutions that provide appropriate information for the appropriate perspective to enable better and more informed decision-making. As a basis for this, in line with the research question formulated in Section 1, the ability of a company to gain insights in uncertainties, predictability and verifiability of decision processes and their outcomes made in manufacturing companies is addressed. To address this, this section will elaborate on the correctness of the assumption stated in Section 1, which state that having information available in the right perspective allows to improved decision-making and thus outcomes. Next, the applicability of the digital twinning approach in the context of manufacturing SMEs will be discussed. Finally, this section will elaborate if the digital twinning approach is a valuable approach to achieve the underlying goal of this research of helping companies make more well-informed decisions at all levels of aggregation, leading to effective and efficient shopfloor that maximise the added value.

As stated in the introduction of this section, the assumption needs to be validated if having information available in the right perspective allows to improved decision-making and thus outcomes. The findings of the bicycle manufacturing case study indicate that the decision-making capabilities of the stakeholders have improved significantly since the implementation of the middleware solution. At both operational and tactical level, the company observed that the solution was capable of making the information available and accessible, to contextualise and process data as meaningful information from various perspectives.

Factual underpinning for those observations is provided by the enhanced machine and resource efficiency and the optimized process flow on the shopfloor. These outcomes indicate a causal relation between having information available and achieving more effective decision outcomes.

To validate the digital twinning approach, its applicability for manufacturing SMEs is explored. The case studies in this research cover a range of environments, demonstrating that the approach is not limited to a specific application, company, or shopfloor. This indicates that the approach is generic enough to be applied in a wide range of manufacturing environments. Ongoing research is being conducted with a consortium of three manufacturing companies, where the digital twinning approach is being applied. This research was initiated based on the recommendations of the bicycle manufacturer. The ongoing research provides an evolving validation of the applicability and ability of the approach to facilitate manufacturing companies in the development of an information provisioning solution. The positive outcomes and experiences from the implementation of the digital twinning approach in the case studies illustrate that the digital twinning approach can facilitate companies to develop an information provisioning solution that is company specific. Therefore, applicability of the digital twinning approach to facilitate in the development of a solution for various SME manufacturing companies can be validated.

Both the bicycle manufacturer and the consortium observed that the approach enables them to facilitate decision-making throughout the organisation in an information and need-driven manner. The bicycle manufacturer stated that with the use of the digital twinning approach it became easier to develop information provisioning solutions with a similar core and without the limitations of the previous digital infrastructure. The information fundament allows them to provide access to the relevant information when it is requested and to perform analysis on the data without being hindered by predefined perspectives. Therefore, it can be validated that the digital twinning approach is a valuable approach to facilitate companies in establishing solutions that provide the appropriate information for the appropriate perspective to enable for better and more informed decision-making.

Moreover, the companies observed that the implementation of the digital twinning approach has enhanced their understanding of why and where decisions are made, where and what information is used to make these decisions, and the environment in which these decisions are made. The increased insight in the decision-making process will facilitate a more predictable, certain, and verifiable decision-making process with more predictable and verifiable outcomes. Moreover, the bicycle manufacturer observed that since the information can be structured using different time horizons, and the simulation capabilities allow for the evaluation of outcomes, the uncertainty of the decision-making process and their outcomes can be made more explicit. Therefore, it can be validated that in line with the research question, the digital twinning approach facilitates companies to gain insights in uncertainties, predictability and verifiability of decision processes and their outcomes.

10. Concluding Remarks

This research focused on answering the research question: "How can companies be enabled to make informed decisions while gaining insight in uncertainties, predictability and verifiability of decision-making processes and their outcomes?" This research elaborates on the digital twinning approach, which can support companies in improving their decision-making by enhancing the information provisioning in a timely and perspective-dependent manner.

The case studies demonstrated the value of the digital twinning approach in facilitating companies to develop and implement information provisioning solutions to facilitate for well-informed decisions at all levels of aggregation. In addition, the modularity and recursiveness of the approach for the development of information provisioning solutions allows for the reuse of modules to addressing additional perspectives and needs. The case studies demonstrated that the information provisioning solutions improved the insight of companies to make well-informed decisions that had a positive effect on both the effectiveness and efficiency of the shopfloor.

The implementation of the digital twinning approach in the case studies has highlighted the importance of information-driven development. Many companies are uncertain about where to start and have not yet taken ownership of their digital operations. In the future, the digital twinning approach will facilitate these companies to implement a solution that enables them to make well-informed decisions and increase information availability in their organisation.

11. Future research

This research has demonstrated that the digital twinning approach can be implemented to develop a technical solution that meets the stated requirements. However, achieving a comprehensive solution requires a shift in mindset, rather than opting for sectional and topical solutions that only address symptoms instead of the underlying problem. Future research will investigate methods to enhance the recognition of the significance and value of addressing the underlying problem in companies. Additionally, it will explore how the implementation of information-driven solutions, utilizing the digital twinning approach, can facilitate a shift in this mindset.

Additionally, future implementation in the three company consortia and the case studies, will yield more quantitative results of the outcomes of implementing the digital twinning approach. Moreover, future developments of the approach will concentrate on identifying which and how functions can be automated and how the solution can further incorporate learning abilities to continuously improve the implemented solution based on stakeholder input, needs and future changes.

CRediT authorship contribution statement

Roy Damgrave: Writing – review & editing, Supervision. **Maaike Slot:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Eric Lutters:** Writing – review & editing, Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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