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The Digital Shadow of production – A concept for the effective and efficient information supply in dynamic industrial environments

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Abstract

Today there are many technical (e.g. vendor lock-in effect) and organizational (e.g. information quality) issues in information delivery. The Digital Shadow ensures a viable information flow, also in the sense of information logistics, between all actors in and outside a factory. The Digital Shadow with all of its subsystems is designed as a next generation information system to allow a more efficient operation of value creation systems. At least, a roadmap for the Digital Shadow of production is presented.

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Keywords: Industrie 4.0; Information system; Internet of Things

1. Introduction

Within the scope of Industrie 4.0, the coordination of information as a resource plays a key role [1,2]. The importance of a Digital Shadow is coming into focus more and more, because the quantities of information people have to deal with increases and will further increase in the future [3–5]. Additionally, information systems will become more complex [6]. System complexity refers to the type and number of system elements and their connections (interfaces) with each other [7].

Focusing actual trends in the production environment (e.g. personalization), future production systems have to be more reactive and versatile to meet external requirements [6]. This applies to information systems as well which means that the supply of needed information has to become flexible and versatile, too. At the moment, information supply works very well in less dynamic environments which include fixed and therefore stable information logistic processes [4].

Today's information systems lack open interfaces [8]. This is due to missing holistic information system concepts but also technical providers who prefer sealed systems. A future-proof information system needs open interfaces and an implementation process allowing different providers to interlink their systems and exchange information across service boundaries.

At the moment, there are few concepts for the effective, efficient and flexible supply of information in an industrial environment (e.g. SIBUS, MSB, Data Warehouse), which address challenges concerning reactivity and flexibility [6,9,10]. Most of them concentrate on the technical implementation and/or on the information and data management and lose sight of the core function of information systems, namely the supply of information meeting consumers' requirements. Industrial companies have to reflect, how they can make their data and information efficiently usable for themselves and in an economic sense.

To address this issue, the concept of the Digital Shadow of production was introduced [11]. The proposed solution extends the existing approaches by providing a holistic service with the main function *data and information supply in industrial environments.* Nevertheless, the way to achieve this vision is a challenge, as many technical and organizational changes are necessary.

In this paper, a roadmap for the Digital Shadow of production is presented. This classifies and explains in detail

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the necessary functions (conceived as micro-services), their role and their development. Companies can use it as a guide for the implementation of their own instance (version) of a Digital Shadow of production. Additionally, the presented vision and roadmap are compared to existing similar approaches.

2. Existing theoretical concepts and first implementations

State of the art approaches comprise concepts as well as implementations in productive use which operate within the domain of the Digital Shadow. Therefore, it is important to understand the differences between them. One of the earliest information management technologies was the data warehouse concept. It is basically a sophisticated and central accumulation of all business relevant data. The core idea behind it is to have a central place to store and access even highly differently structured data and information. This enables processes like data mining and big data approaches [12]. Therefore, it simplifies the reporting and controlling processes. Even though these systems are powerful information management technologies their implementations are highly tailored to the gathered business data and use case. It is not uncommon for users to adopt large parts of the system again and again for each business use, since no general solution or implementation exists. [9]

With the rise of more and more network-compatible devices like sensor and actors, it was possible to gather almost any machine data set from the shop floor. A quite new concept making use of this situation is the digital factory. Here, the core idea is to gather as many data as possible and store them for later use. With this production centric data, it is possible to simulate the whole production process in advance. It enables the prediction, which consequences failing machines would have or the testing of new devices in a completely virtual environment before deploying them into the real factory, thus reducing the risk of serious problems during the rollout [13]. The so-called Digital Twin uses a similar concept. But in this case, the main focus is on the product or in single machines. The idea is to gather all production-related data for a single product, all measurements, calibrations and machine data which are associated with the manufacturing process. With this sort of information, it is possible to provide extended lifecycle management services for the product customer and to provide additional value to them. For example, by observing failing rates in correlation to the previously saved production parameters, predictive maintenance becomes possible and helps to reduce machine downtimes [14,15].

These concepts do not take account of the meaning of information for managing or optimizing the information flow itself. The process of information handling by this means involves rather difficult approaches. Yet, they are needed to realize the concept of a fully automated information system. The first step in this direction is provided by the Manufacturing Service Bus (MSB) which is implemented in the Virtual Fort Knox platform. It allows a fast registration of so-called smart devices and a dynamic, adjustable routing of their exchanged information [6]. The Smart Factory Information Bus (SIBUS) uses a similar approach. It proposes an architecture that allows a multitude of IoT (Internet of Things)-devices like sensors, actors, and machines from the shop floor to send information which is picked up by ERP systems and provides additional value for them. The description of this concept is described in [10].

Currently these data routings are executed manually by an operator and need a high level of manual maintenance. The Digital Shadow, as previously described in literature, shall provide a system for real-time information transmission inside a factory. It is smart enough to control the flow of data optimally, so that a high level of information quality is maintained during operation. In this paper, the concept of the Digital Shadow is described and the vision is clearly laid out. By utilizing meta data about the information itself, a basic understanding of the meaning of the transmitted data should be archived. This helps to control the flow of information to a high degree and paves the way to automatic information flow, quality optimization and better utilization of existing data, even beyond the predictive capabilities of a human technician, as information models can now be created in a highly automated way with machine level intelligence.

3. Vision and function of the Digital Shadow

The vision of the Digital Shadow of production provides a holistic concept for a manufacturing-oriented information (supply) system. The whole vision and functions of the Digital Shadow are described in detail in [11]. The Digital Shadow has one core function, namely the supply of information in a way that meets all respective requirements. Considering this main function, the Digital Shadow itself is a kind of macro-service consisting of different micro-services. The mentioned requirements include classical information logistic requirements. The Digital Shadow has to supply the right information at the right time and the right place in the right quality [11]. From a lean perspective, information supply is an enabling and, therefore, no value-adding process. This is why operation and flexible adaption of the Digital Shadow should require as little effort as possible.

The core function of the Digital Shadow summarizes different sub-functions (micro-services). To supply the right information, the Digital Shadow has to connect elements with an information need or rather with an information demand with the right source of information. From a technical perspective this micro-service could be realized with different directory services containing for example self -descriptions of factory components. According to the specific use case (specific factory) the directory services differ. Central services like directory services form the backbone and must be designed to be highly available. [11]

The Digital Shadow has to control the information flow. This is necessary in order to guarantee the information supply at the right time and to the right place. It is for example possible that the Digital Shadow learns from specific information demands and delivers information automatically at the right time to the right place. Services that enable the control of the information flow process control information (non-value-adding information) and are part of the Digital Shadow. [11]

Meeting all respective requirements also includes the supply of the right information quality, which is probably one of the biggest challenges for future research. Part of this functionality could for example be a service that checks a record for completeness. Within this functionality the Digital Shadow needs also services that decide how to deal with information consumer that needs a record in a specific quality which does not exist in the system. Different approaches for this challenge are discussed in chapter 4. [11]

At least the Digital Shadow has to be able to optimize the existing information basis. This function includes the connection and exchange with other information providing services as well as the cleaning of the existing information basis. For cleaning an information basis the Digital Shadow need services that identify and possibly delete or compress information. [11]

4. Roadmap to a Digital Shadow of Production

It is quite a challenge to realize the Digital Shadow since many technical and organizational changes are necessary. Current developments in the area of information management and information techniques point in the right direction. To support these efforts, a roadmap to reach the complete vision of a Digital Shadow for the production has been developed (see Fig. 1).

The roadmap has a matrix structure which means it has two dimensions. The first dimension addresses complexity levels, which refer to the different functions of the Digital Shadow (see [11]). The second dimension describes the stages of development. For the first stage, there are already concepts or even first implementations. An empty first stage means that no working (realized) concepts exist. The roadmap has four stages. Every stage is a logical unit. Reaching the fourth or rather the third stage of a complexity level means that this level is realized. Every element in this roadmap matrix refers to *digital* data or information. The maximum stage of expansion or rather the ideal state is reached, if the fourth stage of development of the fourth complexity level is realized.

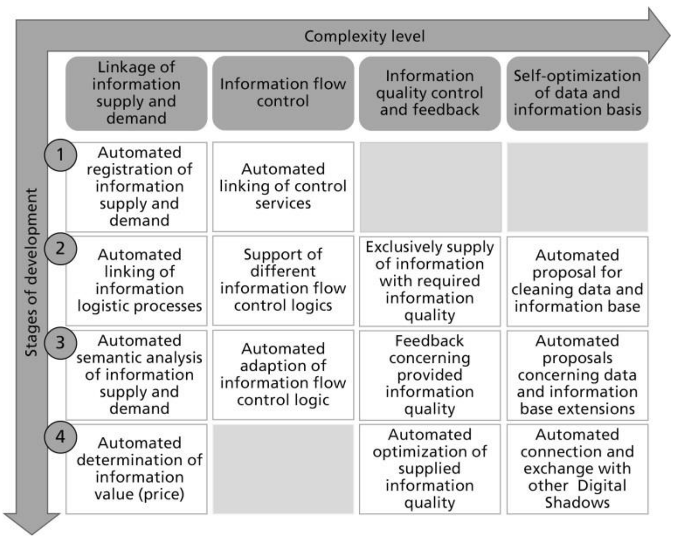

Fig. 1. Roadmap for the Digital Shadow of Production

4.1. The first complexity level: Linkage of information supply and demand

The first complexity level is about the linkage of information supplier and information consumer. On a first stage, the Digital Shadow needs interfaces to its system environment which enables every type of information or data supplier and information consumer to register automatically. Registration means that the registered element informs the Digital Shadow about the semantics of its information demand or supply. Additionally, there has to be a possibility to link system elements manually with each other in a simple way.

On the second stage, the linkage between system elements has to work automatically. Sub-services that provide, process, archive, transform, transfer or use data and information need the ability to connect to each other without manual intervention. To realize this functionality, the Digital Shadow needs different directory services (e.g. registering existing components) that enable information logistic processes to be visible to each other.

Up to this stage, the semantic analysis of services that demand or supply data and information is not automated. Part of this stage is the enabling of the Digital Shadow to automatically analyze micro-services that supply or demand information or data concerning their semantics.

In industrial networks, the information and data exchange will work across company borders. Considering information as a new type of resource they will not be free of charge. Today, there are only a few, less matured methods that determine a price for different information. Considering the fourth stage, the Digital Shadow has the ability to specify the price for the demand of different information.

4.2. The second complexity level: Information flow control

The second complexity level is about the information flow control. The Digital Shadow consists of information processing services which are needed to control the information flow (e.g. a service that checks the plausibility or changes the frequency in which information is transferred).

On the first stage, there has to be a possibility to manually link control services and elements that supply or consume information or data. On the second stage, the Digital Shadow is able to support different information flow control logics as for example the push or pull logic.

Because of the dynamic environment production systems have to be flexible. This flexibility leads to varying information demand. Within the last stage, the Digital shadow reacts to these varying demands and adopts the information flow control.

4.3. The third complexity level: Information quality control and feedback

The third complexity level is about information quality. The provision of information in the right quality is probably one of the most challenging services of the Digital Shadow. On the second stage, the Digital Shadow is able to evaluate information quality. It compares the existing quality with the needed quality and transfers only information that meets the requirements concerning quality. This implies that there is information in the system which is not transferred, because of its low-quality levels.

On the third stage, the Digital Shadow transfers all needed information regardless of its quality. It evaluates the quality and gives (meta) information concerning existing information quality.

On the last stage, the Digital Shadow is able to optimize information quality of supplied information. Concerning the quality dimension, this could be an adoption of granularity or completion of records, but optimizing supplied information quality can also mean that the Digital Shadow searches for another information supplier which offers the same information but with better quality. Example: The Digital Shadow transferred information about the actual weather from a weather service on the internet. Now, a new sensor which records weather data directly is installed. This sensor supplies better and more current data and is from now on being used as a more accurate source of local weather information.

4.4. The fourth complexity level: Self-optimization of data and information basis

The fourth complexity level is about the self-optimization of the Digital Shadow concerning its data and information base. On the second stage, the Digital Shadow identifies data and information that are not used and initiates a deletion or compression process. Every instance of the Digital Shadow (e.g. concerning factory or company domain) needs an individual deletion compliance, which establishes a valuation basis.

The third and fourth stage is about the extension of the data and information base. In the third stage, the Digital Shadow makes automated proposals to service providers concerning the optimization of existing or the implementation of new information suppliers (information generating process or hardware). The fourth stage is about the automated connection and exchange with other instances of the Digital Shadow. These instances could be for example the Digital Shadows of customer or material supplier.

5. Comparison of the Digital Shadow concept with existing concepts

As already mentioned, there are several competing concepts to implement communication flows between production environment components. In Table 1, similar concepts and their advantages and deficits are compared and discussed. The table columns are split into two different categories. The first one contains already implemented concepts which are in active production use. The second one contains defined but not yet fully implemented concepts. Concepts with regard to important aspects of the Digital Shadow are compared.

Table 1. Color-coded comparison matrix of the concepts implementing similar ideas of the Digital Shadow

	Implemented		Only concept	
	Data-warehouse	MSB	SIBUS	Digital Shadow
Automatic registering of N/A components	Red / Yellow	Green	--	Green
Automatic linking of info. logistic processes	Red / Yellow	Red / Yellow	Yellow / Green	Green
Automatic semantic analysis of N/A component	Red / Yellow	Red	Yellow / Green	Green
Auto. evaluation of monetary data value	Red	Red	Red	Red / Yellow
Manual linking of control services	Yellow / Green	Yellow / Green	Green	Red
Auto. adaption of info. flow control logic	Red	Yellow / Green	Yellow / Green	Green
Support of different control logics (push/pull)	Yellow / Green	Yellow / Green	Green	Green
Optimizes control flow on its own	Red	Red	Red / Yellow	Green
Supply of information with req. information quality	Green	Red / Yellow	Red	Green
Feedback of information quality for transmitted data	Yellow / Green	Red / Yellow	Red	Green
Optimizes information quality on its own	Red	Red	Red	Green
Auto. proposal for cleaning data and info. basis	Red	Red	Red / Yellow	Green
Auto. proposal to extend data and info. base	Red	Red	Red / Yellow	Green
Automatic inter-system data exchange	Red	Red	Red	Green

The meaning of the color code is as follows: red means not implemented or the concept does not mention the implementation of this functionality. Yellow/red means, the foundation for this functionality exists but the function is not implemented and it is not planned to do so (yet with some effort and workarounds it might work). Yellow/green means the function is not implemented yet but the concept makes implementation easy or the implementation is already planned for the future. Green means the feature is fully supported (as of implementation or concept). No coloring means either the concept does not mention this feature or it is not clear, whether it does support it or not.

Automatic registration of new components is important to completely automate the system and reduce the workload on humans in order to configure and operate the system. The data warehouse lacks this feature of complete automatic registration since new data sources must usually be manually implemented as new data schemes because of its fixed table structure. Some newer kinds of data like document- based, (data which follows no strict defined and fixed structure) can be added rather automatically, but this is not always possible, since it depends on the use purpose.

The concept of the Digital Shadow makes use of meta information, either described directly via the connected devices or indirectly by its own means. This allows the automatic linking of operation data. Concepts like the data warehouse and MSB expose APIs to steer the data flow programmatically but these control programs are no integral part of the concept itself and must be externally implemented. SIBUS does not directly mention this aspect, but it defines self-describing meta information which will make this task easier to implement. None the less it mentions that all components in its system should be able to retrieve information as needed. However, it does not state the exact process of how this is done. The Digital Shadow with its very high level of information quality handling should enable a data market for information monetization. Yet it is currently unknown how to assign reasonable values to datasets and therefore this feature is even for the Digital Shadow highly speculative.

Most current concepts allow the manual linking of control flows. This means the operational data can be controlled, routed and refined to the needs of the consumer. The Digital Shadow should automatically route such information without the manual external input of a human.

Pull and push information transmission mechanisms are in principle supported by all systems because the concrete way of communication is not defined by the concepts itself. Making use of meta information about information quality, the Digital Shadow is able to select automatically the best transmission route in order to optimize information quality.

Since the Digital Shadow keeps track of the quality of its underlying information flows, it is able to inform all consumer components about the current quality level of the data. Today, to be able to fulfill its operation, the automatic transmission of such quality level meta information is needed.

Only the data warehouse system is able to assess the information quality for example by data mining operations. Even concepts like SIBUS do not operate on an information quality assurance level. They just relay the information to its best possibilities, but do not improve or measure the information transmission channels by its capabilities and reliance. If new components are added to the Digital Shadow which allow a higher degree of transferred information quality, the already established data flows should automatically be adjusted to take this into account. No current system or concept does perform this task of automatic information flow improvement. By utilizing meta information about the underlying data and also by analyzing the semantic meaning of information via e.g. ontologies, the Digital Shadow in its final form is able to identify information redundancies, perform cleanup and information compression tasks. This will lead to an increase in price-performance ratio (since storing data most likely binds resources) as well as will enable it to present smart choices for extension to maximize its very own performance. None the less, by utilizing the deeper meaning of information the shadow should be able to contact other shadow instances to allow the exchange of information under certain circumstances, for example to automatically compare shipping terms from multiple manufacturers.

6. Conclusion and outlook

In order to perform a first implementation of the Digital Shadow, companies should stick to the described roadmap. The step by step approach supports overcoming several technical hurdles.

First of all, the market for technical solutions regarding the intercommunication capabilities of industrial components is highly fragmented and vendor specific. Unifying communication frameworks must be utilized to tackle this problem. The SIBUS technical paper has identified this requirement as well. There are currently efforts being made to standardize data exchange formats. Furthermore, it is hard to categorize information in an automated fashion by understanding its semantic meaning. Previous attempts to make the (mostly) unstructured web content machine readable (known as the semantic web) have been proven to be hard if not impossible, because of the highly variable information contents. However, it is necessary that the semantic meaning of the information is known to the Digital Shadow in order to fully automate the configuration of information flow.

In addition to these technical aspects, there are some conceptual aspects which need further research activities. This includes, for example, the finding of the inherent monetary value of information. In the area of the third complexity level (information quality control and feedback) additional research is also important. At least new markets for exchanging production information and data are needed to commercialize their exchange. Yet, with the rise of blockchain technology aimed for IoT usage and proposals for data marketplaces the first step into this direction is done [16].

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