Digital Twin-Based Three-Dimensional Visual and Global Monitoring of Assembly Shop-Floor

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ABSTRACT

Aiming at the requirements of rapid response and production efficiency improvement in the assembly shop-floor, a three-dimensional (3D) visual and global monitoring method for the assembly shop-floor based on the digital twin is proposed. The paper analyzes the monitoring objectives, objects, and methods of assembly shop-floor, and constructs a global monitoring framework of digital twin-based assembly shop-floor. Then, three key technologies of realizing global monitoring shop-floor are described: current-time data perception and collection, current-time information-driven digital twin generation, and state monitoring and optimization based on digital twin. Finally, a global monitoring prototype system is designed and developed to verify the effectiveness of the proposed method.

CCS CONCEPTS

• **Information systems**; • **Information systems applications**; • **Enterprise information systems**; • **Enterprise applications**;

KEYWORDS

Digital twin, Assembly shop-floor, Global monitoring, 3D visual monitoring

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1 INTRODUCTION

Shop-floor is an important unit for the organization and execution of production in the manufacturing industry. The global monitoring of the assembly shop-floor is to continuously monitor the human flow, material flow, and business flow during the operation of the shop-floor through various data acquisition and processing methods, thereby assisting the managers to make decisions to optimize the operation of the shop-floor [1, 2]. Through the global and current-time monitoring of the assembly process, the rapid response and optimization of assembly shop-floor requirements can be achieved, and the orderly and smooth progress of production can be guaranteed. On this basis, the efficiency of product assembly can be improved [3, 4].

In recent years, with the continuous development and improvement of automation and information level, new-generation information technologies such as IoT and mobile internet, as well as the popularization and application of various types of sensing equipment in the manufacturing shop-floor, a large amount of current-time data such as environmental awareness data, machine operating status data, and sensor data, unstructured multimedia data including video, audio, and photos inevitably will be produced. Therefore, the assembly shop-floor data present a typical 3Vs characteristic of big data [5, 6], that is, Volume (i.e. large amount of data), Variety (i.e. variety of data, diverse data forms), and Velocity (i.e. data generation speed). In addition, due to the features of the assembly shop-floor such as frequent production disturbances, dynamic and open production environment, the shop-floor manufacturing data also show uncertainty, high noise, and variability. However, the current current-time monitoring of the shop-floor is mostly based on 2D electronic Kanban, in which the amount of information displayed is far less than that of 3D, and the assembly site cannot be realistically displayed [7, 8].

In recent years, as one of the enabling technologies of intelligent manufacturing, digital twin (DT) technology provides a clear, novel, and feasible implementation path for realizing the virtual-real integration of cyber-physical systems (CPS) [9, 10]. Digital twin shop-floor (DTS) is one of the specific applications of DT in the product manufacturing stage. It aims to achieve the optimal production control of the shop-floor through the bidirectional mapping and interaction between the physical shop-floor and the virtual shop-floor. It can not only display the operating process and status of the assembly shop-floor intuitively and realistically in the form of 3D models or animations, and realistically display the operation process and state of the assembly shop-floor in the form of three-dimensional (3D) model or animation, but also record the historical fragments during the assembly process, thereby laying the foundation for subsequent process traceability [11, 12]. It can be said that the emergence of DT technology provides a new means to realize 3D global and visual monitoring and optimization of assembly shop-floor, and scholars have also done many researches in this area. For example, Zhang et al. proposed a DT-driven cyber-physical production system framework, which is divided into five levels, of which the physical layer, network layer, and database layer are the main body of data perception. The data collected from sensors, robots, AGV, RFID, and CNC machine tools on the physical shop-floor are transmitted and stored in the database, [13]. Zheng et al. proposed a full-element information perception framework in the information processing layer of the DT framework, involving various perception technologies [14]. Zhang et al. made a comprehensive analysis of various perceptual data in the production process on the shop-floor, and constructed a twin shop-floor model [15]. Wei et al. comprehensively analyzed and described the shop-floor manufacturing big data, and proposed a data-driven active perception model and technical architecture of manufacturing IoT events [16]. Qi et al. used XML to encapsulate various DT services and realized the interaction of information through a unified information template. In order to realize the data interaction between different systems, Schroeder et al. proposed a DT modeling method based on AutomationML and verified the effectiveness of AutomationML model in data interaction through a specific case [17]. Aiming at the problem of shop-floor visual monitoring, Zhao et al. proposed a 3D visual and current-time monitoring method [3]. Guo et al. proposed a shop-floor modeling framework based on DTs to solve the issue of lack of current-time interaction between physical space and information space in aerospace structural parts manufacturing shop-floor [18]. Liu et al constructed the DT system of the shop-floor production process [19].

Based on the above analysis, it can be seen that the current research on visual monitoring of DTS is still insufficient, which is mainly reflected in the following aspects: (1) The traditional 2D Kanban monitoring is a fragmented display with a small amount of information. Meanwhile, the 3D monitoring is not comprehensive enough, mostly focusing on element status monitoring and synchronous mapping of the process, and lack of monitoring covering the full elements and shop-floor business. (2) Due to the lack of information correlation between the various monitoring systems, structured monitoring cannot be realized, and it takes a lot of manpower and material resources to trace the key historical fragments.

Therefore, this paper focuses on the assembly shop-floor, especially the discrete assembly shop-floor of aerospace products. Because of the difficulty of realizing comprehensive, accurate, and current-time monitoring of the operation status and product's technical state, and the effective organization and management of the data generated in the assembly process, this paper carries out analysis and research from the aspects of the full element, the full business, and the whole process, and a DT-based 3D visual and global monitoring method is proposed, and the global monitoring prototype system of assembly shop-floor based on DT is constructed.

2 CONCEPT AND CONNOTATION OF GLOBAL MONITORING OF ASSEMBLY SHOP-FLOOR

Global monitoring of assembly shop-floor refers to monitoring the full elements, full business, and whole processes of assembly shop-floor operations through various data acquisition and processing methods, to realize current-time data acquisition and information feedback in time, and to meet data requirements for different levels of shop-floor personnel. On this basis, the effective control of the assembly process can be achieved. The full elements on the assembly shop-floor mainly including personnel, equipment such as mechanical arm, inspection equipment, measuring equipment, test equipment, multimedia data acquisition equipment, and material transportation equipment, materials such as parts, components, light engine, standard parts, homemade parts, main ingredient, fixtures and tools, and production environment. The full business refer to the combination of production elements on the assembly shop-floor according to certain relationships and processes under the influence of driving factors such as production orders and jointly perform specific tasks to be completed, such as assembly plan, material transportation plan, and technical problems processing. The whole processes mainly include the product assembly process, process of material flow, personnel flow process, and the environment change process.

2.1 Objectives of Global Monitoring of Assembly Shop-Floor

For manufacturing companies, the substance of the production process is the process of appreciation of product value. The target of monitoring is to increase the controllability of the entire production system and continuously improve the production process to achieve optimal production control and production efficiency. For different complex aerospace products, the production processes are diverse, and there are many reworks and repairs in the assembly process. Additionally, the planning layer is separated from the execution layer. The paper-based information transmission approach leads to a long feedback cycle, and the planning layer cannot obtain the assembly site information in time [20].

Therefore, the basic goal of assembly shop-floor monitoring is to collect current-time data of the production status of the assembly shop-floor, and to visually process and timely feedback the data to reflect the current-time status of the assembly shop-floor, and then realize the control of the assembly shop-floor.

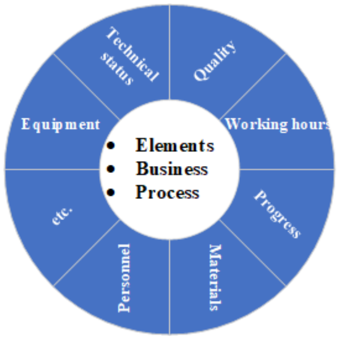

Figure 1: Objects of Global Monitoring on the Assembly Shop-Floor.

2.2 Objects of Global Monitoring on the Assembly Shop-Floor

The monitoring objects refer to the information related to the monitored targets, which mainly include technical status, quality, working hours, progress, materials, personnel, and equipment, etc [9], as shown in Figure 1

- Technical status refers to the functional and physical characteristics specified in technical documents and achieved in products. Technical status management plays an important role in the assembly quality control of large and complex products. Therefore, the implementation of technical status monitoring is very necessary. Besides, the main goal of product assembly is to ensure the delivery time, so it is very important to monitor the progress by collecting and processing the on-site progress data and feeding back it in current-time. On this basis, the managers can adjust the assembly plan to ensure that the assembled products are completed on schedule.
- The realization of product quality is the primary goal of the production process. It is an important means to ensure product quality to monitor the quality in current-time during product assembly and deal with quality problems in time and ensure that every assembly link meets assembly requirements.
- Working hour is one of the basic elements of cost control in product assembly enterprises, which is not only the basic data of workers' salary, but also the direct embodiment of production efficiency and production capacity. Monitoring the working hours can assist managers in adjusting working hours plan in time to realize the balance of the production line, and avoid the bottleneck or waste caused by excessive idle time.
- Additionally, there is a large variety of parts in some complex products. The monitoring of materials can not only master the position and status of each part, but also provide a basis for the adjustment of material plan, which can ensure the balance of inventory and avoid the interruption of the production process due to insufficient inventory or the increase of inventory cost due to too large inventory. Personnel and equipment are the embodiment of shop-floor production capacity. It is convenient for shop-floor functional departments to make operation plans and production schedules by monitoring the status of personnel and equipment.

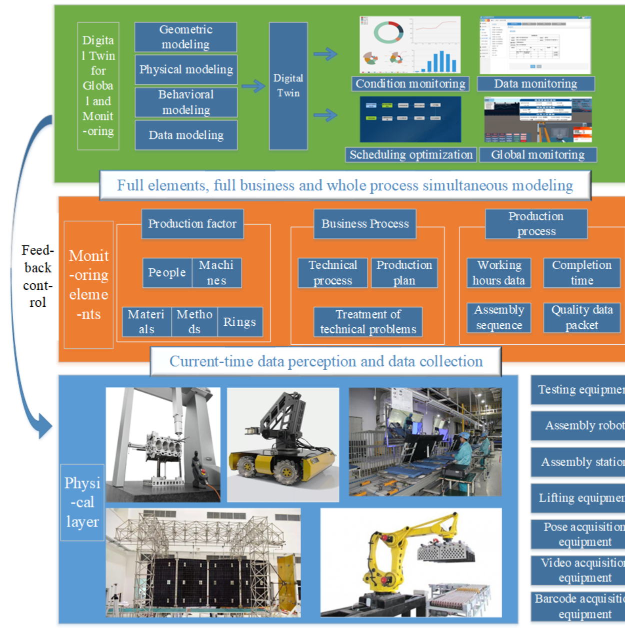

Figure 2: Framework of Global Monitoring for the Assembly Shop-Floor Based on Digital Twin.

3 GLOBAL MONITORING SYSTEM FRAMEWORK OF ASSEMBLY SHOP-FLOOR BASED ON DIGITAL TWIN

DTS is the integration and fusion of physical shop-floor, virtual shop-floor, information system, and twin data. Physical shop-floor and virtual shop-floor interact with each other and bidirectional mapping in current-time through an information system and twin data [21]. In order to realize the 3D visual and global monitoring of the assembly shop-floor, it is necessary to analyze from full elements, full business, and whole processes. A global monitoring framework of the DT-based assembly shop-floor is constructed as shown in Figure 2. The physical shop-floor is a physical layer, which includes all physical hardware involved in the assembly process, such as testing equipment, execution unit, auxiliary equipment, assembly station, acquisition equipment, etc. Through current-time data perception and process data collection, data related to full-element including personnel, machines, materials, and environments, data related to full-business including technical process, operation plan, and technical problems, and whole-process data such as working hours, completion time, assembly sequence, and quality data are obtained. On this basis, the components of the virtual shop-floor model map the physical shop-floor from geometry, physics, behavior, and data dimensions. Finally, the virtual shop-floor model can feedback and control the physical shop-floor.

4 TECHNICAL MEANS FOR 3D VISUAL AND GLOBAL MONITORING OF ASSEMBLY SHOP-FLOOR

4.1 Current-Time Data Sensing and Process Data Collection of Assembly Shop-Floor

The data generated in the assembly process can be divided into seven categories: production progress data, actual working hours, personnel data, machine equipment data, production logistics data, production quality data and reverse problem data [22].

For data related to manufacturing resources including production personnel, machine equipment, and materials, the barcode technology and other Internet of Things (IoT) technology are used to perform manufacturing resource information identification. And then, collection points of the manufacturing process perception information are designed to build a product-oriented manufacturing IoT network on the shop-floor to achieve a current-time perception of manufacturing resources. The data relating to manufacturing resources such as production personnel data, machine equipment data, and production logistics data are classified as current-time sensing data. Production progress data, actual fact-hour data, quality data, and reverse problem data are classified as process data. The collection of current-time sensing data will drive the generation of process data. The definition of each type of data and the collection method are shown below:

- Production progress data collection: Production progress data includes production progress of work stations, production progress of model products, etc. For instance, in the daily operation plan, when assembly workers start and end the daily operation plan, the information of start and completion will be collected, and the required completion time and actual completion time will be compared, and the daily operation plan will be marked as "lag", "not started" and "completed". "not started" and "completed", and get the process completion data according to the time period and work station, and count the production progress data of the work station.
- Actual working hours collection: In the daily operation plan, assembly workers will fill in the actual working hours after self-inspection and inspector check. And then they are summarized to form data such as personnel working hours, shop-floor working hours, and model working hours. The actual working hours combined with rated working hours are one of the data used to evaluate labor and production capacity.
- Production personnel data collection: Production personnel data includes personnel on duty information, the number of completed operations and personnel status information, etc. When the operator enters or leaves the work station, the work station RFID reader reads the RFID tag on the operator to complete the on-duty information and off-duty information record. Job completion quantity is obtained by extracting the completion data from the daily operation plan and then counting the number of completed tasks. The personnel status information is based on the operation execution data in the daily operation plan to determine whether the personnel are free.
- Machine equipment data collection: It refers to the status data of inspection and measurement equipment, intelligent lifting platform, posture acquisition equipment, and tooling, which is one of the data used to evaluate labor and production capacity, including operating status, operating parameters of instruments equipment, idle quantity, and equipment utilization rate, etc. There will be corresponding sensors on the machine equipment for collecting the operating parameters of equipment, and the operating parameters can be informed of the operating status of the equipment and some related data.
- Production logistics data collection: The main logistics data collected are material distribution data, material usage data, material inventory data, and material demand data. The quantity of material inventory refers to the quantity of material in each warehouse, and the inventory data will be updated when the material is inbound and outbound. The material demand data comes from the material data in the process file, and the material data will evolve into the material demand data of the corresponding task after the process is instantiated.
- Production quality data collection: It refers to the process quality information, including inspection documents, related photos and videos, and on-site problem handling data, etc.
- Reverse problem data collection: including technical problem data and on-site problem data. Technical problem data refers to the problem data generated in the process of assembly execution and related to technical documents, including design problem data or process problem data. On-site problem data refers to the problems that occur in the shop-floor site, except for quality problems, technical problems, and their processing data, mainly including material shortage, temporary personnel transfer, insertion of temporary tasks, etc.

4.2 Current-Time Information-Driven Digital Twin Generation

The digital twin for the assembly shop-floor is a digital representation of the physical shop-floor [23], which is capable of continuous self-optimization and self-improve with the production process data.

Figure 3 illustrates the basic framework of current-time information-driven DT modeling. Among them, the monitoring data contains the generation of the full elements, the full business, and the whole processes, which are the basis for the establishment of the DT model for the assembly shop-floor. The mapping from physical shop-floor to virtual shop-floor is the core to realize the 3D visual and global monitoring in the DTS. First, according to the actual situation of the assembly shop-floor, the physical objects are instruments equipment, production personnel, materials, environment, business processes, etc. Through information management systems, the current-time relevant data of each physical object on the shop-floor are collected. And then, the information is stored in the object database through the parameter mapping mechanism,

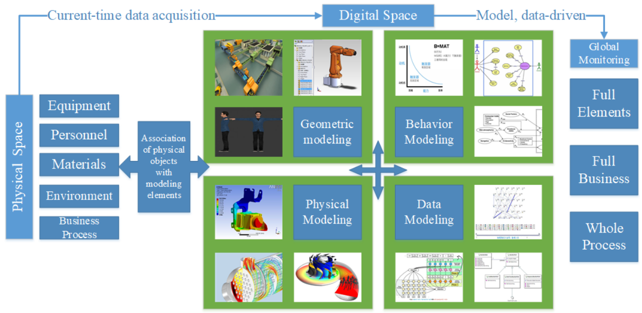

Figure 3: The Modeling of Current-Time Information-Driven Digital Twin.

and the information objects in the object database have a unique identification. Meanwhile, the information objects and modeling elements of the physical model are associated through unique identification, and the data runs through the global of shop-floor scene layout, station layout, information collection, and information processing. On this basis, the component attributes are set and modified to complete the DT modeling of geometric features, physical status, behavior, and data information of the assembly shop-floor.

4.3 State Monitoring and Optimization Based on Digital Twin

The DT can dynamically display the product assembly progress and current status in the product 3D model. It also can display the assembly quality characteristics data directly in the 3D model and automatically compare it with the design data to assist the operators in decision making.

- Dynamic visualization and monitoring of the assembly shop-floor. Based on the manufacturing system entity, we build a 3D dynamic and visualized monitoring model of the manufacturing system through the synchronous modeling. First, a series of relational models are established for the state changes of production events. And then, through the dynamic invocation of these relational models, a 3D model of the manufacturing system is generated. Furthermore, the production plan and simulation parameters are imported to establish a dynamic model of the production process, thereby forming a dynamic and visual monitoring interface of the assembly shop-floor to realize a high-fidelity mapping between the actual operation of the production shop-floor and the simulation operation results of synchronous modeling.
- Production scheduling optimization. Obtain the planning information of production scheduling and the execution information of the assembly plan from the DT for the shop-floor. And obtain the execution condition of the production tasks by comparing the two. Once the assembly tasks deviate, rescheduling is performed according to the rules of processing disturbance events to optimize the production plan and ensure the smooth execution of the assembly plan. New scheduling rules are given or scheduling parameters are optimized based on the analysis of the scheduling result data.
- Current-time monitoring of manufacturing resources. By obtaining the status information and location information of manufacturing resources such as personnel, assembly units, materials, instruments equipment through the DT, and calculating the data information such as personnel idle ratio, the utilization rate of assembly units and instruments equipment, and material usage at the current time. Then, the coordination mechanism of production resources is established, so that the use of production resources can be quickly adjusted once the production plan is changed.
- Current-time monitoring of product quality. For product quality, by monitoring a large amount of quality problem data, the causes of quality problems can be accurately located in current-time and quality problems can be dealt with in a timely manner.
- Product quality analysis and optimization. For the long-term accumulated product quality data in the DT, use dynamic Bayesian, neural network, and other data mining methods to deeply analyze the causes of product quality problems and get the main influencing factors of product quality. On this basis, products and production lines can be optimized.
- Material optimization and distribution. For the logistics process, through the analysis of shop-floor inventory and logistics data, combined with the production beat and other actual production data to give procurement recommendations to reduce the inventory backlog, such as giving the purchase amount and purchase frequency of a standard part under the conditions of ensuring normal production.

During the production process, the data about the status conditions of equipment, materials, and personnel are obtained from the production shop-floor in a timely manner through current-time data acquisition equipment and are transmitted, analyzed, and counted through data transmission technology. And then, a series of relevant models are generated with programs or external integration tools. Furthermore, the simulation results are analyzed and verified. Finally, a screen reflecting the current production process is generated and transmitted to the graphic visualization server in a timely manner, so that the visualization and dynamic monitoring of the whole production process is realized by accepting the screen transmitted from the visualization server, including the operation status monitoring of production progress, the operation status monitoring of machine equipment, and the operation monitoring of material consumption and logistics flow. On this basis, the managers can have a clear and intuitive understanding and mastering of the operation of the manufacturing system to make decisions.

5 IMPLEMENTATION AND POTENTIAL APPLICATIONS OF THE DIGITAL TWIN-BASED GLOBAL MONITORING SYSTEM FOR ASSEMBLY SHOP-FLOOR

5.1 Global Monitoring Prototype System of Assembly Shop-Floor Based on Digital Twin

Based on the above research on the DT-based global monitoring method for the assembly shop-floor, a DT-based global monitoring system is designed and developed, as shown in Figure 4. A static

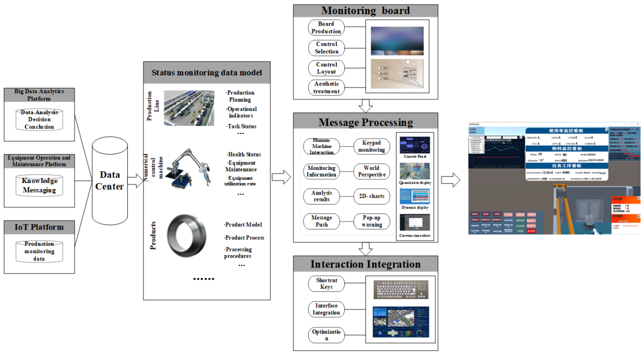

Figure 4: Schematic Diagram of a Global Monitoring Prototype System Based on Digital Twin.

shop-floor logic model and a static shop-floor 3D model based on the static resource information of the production shop-floor are first established. And then, the dynamic operation of the simulation model is driven by the current-time production data collected online, so a synchronous modeling system with a high fidelity mapping to the actual shop-floor on the virtual simulation platform is obtained. Furthermore, based on the dynamic current-time simulation of the synchronous modeling system, the important indexes specified by the shop-floor are monitored, quantified, and visualized in the form of graphs and charts to reflect the shop-floor operation conditions, together with accurate figures and image simulation. Finally, the operating status of the production system is analyzed and evaluated, to provide a current-time warning of abnormal data, analyze bottlenecks as a whole, and optimize the production process.

The system takes the shop-floor layer, equipment layer, and product layer to be monitored as the object, and establishes the index system consisting of current-time status indicators and process operation indicators. Meanwhile, the index calculation models are established and the operating status index calculation formulae at multiple levels of the shop-floor are integrated and managed to form an algorithm library. On this basis, index calculation through historical data and current-time data are performed, the index calculation is updated through current-time data flow, and the current-time dynamic updated indexes are updated as the visualization monitoring shows different display effects in the way of a bulletin board, which is convenient for the shop-floor managers to integrate the monitoring of the shop-floor status, and the historical fragments can be quickly located and viewed through the structured monitoring data. Moreover, the future task status can be predicted and warned. Finally, the dynamic visualization monitoring of the full element, full business, and whole process of the production shop-floor can be realized based on the DT in the IoT environment.

5.2 Potential Applications of the Global Monitoring System of Assembly Shop-Floor

By building a digital twin for the assembly shop-floor that includes all elements, all business, and all processes, multi-level, multi-dimensional, multi-time-scale, and multi-spatial-scale monitoring applications can be realized.

- Multi-level monitoring: Based on the manufacturing system entity and current-time information-driven synchronous modeling, a 3D dynamic and visual monitoring model is constructed. According to the different monitoring requirements, different monitoring interfaces can be switched to realize the monitoring of production tasks and fault information at the equipment layer, unit layer, production line layer, shop-floor layer, and factory layer.
- Multi-dimensional monitoring: Through the structured data collected in current-time, the data can be displayed from multiple dimensions according to the user's concerns, so as to realize multi-dimensional monitoring, such as current-time monitoring of manufacturing resources, logistics distribution, and quality data package.
- Multi-time-scale monitoring: The collected structured data can be associated with time, so it can realize current-time online monitoring and monitoring at a certain time in the past based on the constructed DT. Moreover, the future task peak, quality status, and complete set of materials can also be analyzed and predicted by means of the accumulation of historical data and the superposition prediction algorithm.
- Multi-spatial-scale monitoring: the traditional 2D monitoring is difficult to overlay spatial scales, while the global monitoring based on DT is based on 3D, which can naturally overlay spatial scales to complete the multi- spatial-scale monitoring, such as the specific storage location and storage layer of materials in the 3D warehouse, crane transportation of materials, AGV transportation of materials and other information.

6 CONCLUSION

DT technology provides a clear idea and implementation path for realizing the virtual-real integration of CPS. Its appearance provides a novel approach for realizing the 3D global and visual monitoring and optimization for the assembly shop-floor. In order to realize the rapid response and optimization decision-making of assembly shop-floor to greatly improve productivity, this paper proposes a DT-based 3D global and visual monitoring method of assembly shop-floor, and a prototype system for global monitoring of assembly shop-floor based on the digital twin is developed, which can realize the global and dynamic monitoring of all elements, all business and all process on the assembly shop-floor. It also provides a reference idea and framework for the follow-up in-depth study of structured monitoring and the realization of multi-level and multi-dimensional monitoring.

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