Interconnecting Tailored Work Plans to Smart Products' Bills of Materials

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Abstract. Holistic transition in information and communication technology led to a new generation of smart products. These products are cyber-physical systems augmented by internet-based services, so-called smart services, characterized by a high degree of interdisciplinary components. This results in a tremendous complexity in describing smart products using a tailored bill of materials (BOM) and the consecutive work plans that aim to provide, e.g., production or service instructions for the worker. This contribution focuses on smart product BOMs and their interconnection to work plans while considering new challenges derived from the smart products' characteristics, such as their high interdisciplinarity or real-time feedback data from the usage phase. Therefore, a holistic approach for the description of smart product BOMs and a generic technique for defining work plans and their breakdown structure to be coupled with the smart products' BOMs are proposed.

Keywords: Work planning · Bill of materials · Product lifecycle management · Enterprise IT

1 Introduction

Today's customer expectations of ever faster development of innovative, highly complex, and interdisciplinary smart products, combined with ever shorter production cycles on a global scale, lead to tremendous pressure on companies [1]. A cornerstone of this pressure is the increasing product individualization that changes product requirements between different product generations and within one product generation. Additional drivers are rapidly changing markets that require swift reactions of the companies regarding restructuring a product and thus the corresponding bill of materials (BOMs), which also implicates a restructuring of assembly or manufacturing lines. Further problems refer to the management of the actual smart product BOMs during the use phase, particularly for those parts that are serialized and thus can, and often must, be uniquely identified. The results are enormous challenges, particularly in globally distributed manufacturing sites with heterogenous IT systems in terms of consistent work or manufacturing planning, including the follow-up management during the smart products' usage [2, 3].

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Methodological concepts such as closed-loop engineering [4] as well as data-driven architectures in the sense of a digital thread, which link information from the entire product lifecycle, are becoming increasingly important as digital communication frameworks for streamlining design, manufacturing, and operating processes in order to plan, design, manufacture and maintain technical products more efficiently [5]. However, there is a lack of concrete implementation examples to bring these mostly abstractly described and generally held high-level concepts closer to small and medium-sized enterprises to use the potential of their data in a more targeted manner.

This paper will address these challenges by interconnecting smart product BOMs to work plans from a processual and systemic view. It will be located between different management systems commonly used in product design, resource planning, manufacturing, and usage environments: Product Lifecycle Management (PLM), Manufacturing Execution System (MES) or Manufacturing Operations Management (MOM), Internet of Things (IoT) or Customer Portals as well as Enterprise Resource Planning (ERP) (cf. Fig. 1).

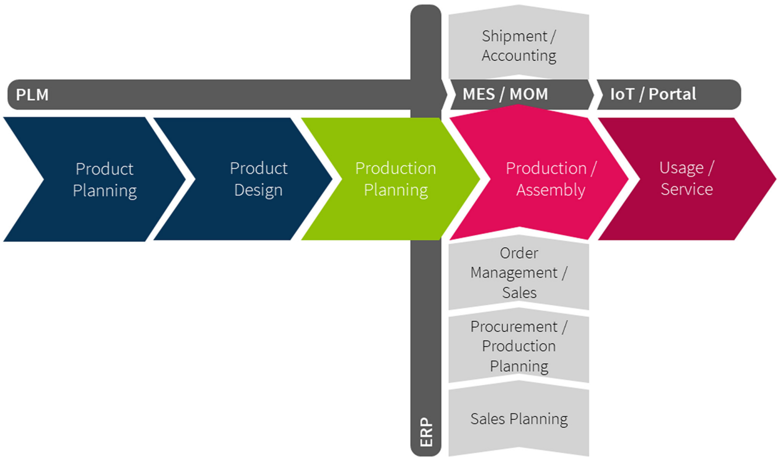

Fig. 1. Process and IT-system overview for the presented approach [6]

The structure of the paper at hand will give an initial overview regarding work planning in engineering and production as well as product structuring methodologies and shortcomings in terms of their interconnection. The following chapter will introduce a concept that considers especially the challenges regarding BOMs and work plans resulting from smart products' characteristics, such as their high complexity. Subsequently, it will be shown how the approach was prototypically implemented and validated. Finally, the last chapter summarizes the findings and provides an outlook on further research activities in the presented context.

2 Work Planning in Engineering and Production

Work planning involves all one-time planning activities for the manufacturing and assembling of products and product components. The goal is to define the sequence of steps for production processes and determine production times. As part of the work planning, it is defined how (i.e., by which method) and where (i.e., on which production equipment) a product or a component is to be manufactured or/and assembled. The work planning is done by creating process descriptions—i.e., work plans—for the production processes of a product from the perspective of the product itself. The plans include the working steps performed to produce an end item, the equipment and tools on which or with the help of which the tasks are to be performed, and times for preparation and performing the working steps [7].

The functions of work planning can be classified as short-term and long-term tasks. Short-term tasks include activities necessary for producing a specific product, such as creating working and routing plans, resource scheduling, bill of materials processing, and programming. The long-term tasks include material planning, investment planning, methods planning, and others. In addition, other activities such as cost planning and quality assurance can be classified as both short-term and long-term tasks [7] (Table 1).

Table 1. Work planning tasks, classified by the temporal dimension of relevance (after [7])

Tasks of work planning		
Short-term	Intermediate-term	Long-term
• Work plan creations • Production equipment planning • Production equipment planning • Programming • …	• Cost planning • Quality assurance • Work planning support • …	• Material planning • Investment planning • Methods planning • …

This contribution focuses on the short-term activities related to work planning and their methodological and tool-wise support; hence, these are described in more detail.

2.1 Short-Term Activities in Work Planning

Work and Routing Plan Creation

A core task of work planning is the creation of descriptions of the working activities and their executional sequence involved in the manufacturing or assembling of a product, an assembly component, or a single part. The basic information of a work plan includes the material to be used, the sequence of work activities, the workplaces at which the different activities are performed, the used tooling and operating resources, and the target times for conduction of the working steps. The definition of used materials in the working process relates to the BOM of an item to be assembled or manufactured. Preparing such bills is another main short-term task of work planning [7].

Bill of Materials Processing
The task of bill of materials (BOM) processing is preparing production-oriented BOMs out of the engineering ones (eBOM). While the eBOM is generally functionally structured and driven by the design structures in CAD, the production/manufacturing BOM (mBOM) considers and depicts product manufacturing stages and additional materials needed in the production process. The items of the mBOM are used to define the inputs and outputs of working activities.

Production Equipment Planning
Production equipment planning encompasses planning, developing, and producing or procuring equipment necessary to manufacture a component. The production equipment to be used in the different stages of the production process of an item is defined in the work plan.

2.2 Interdependence Between Work Plan and Bill of Materials

A work plan defines a process or a sequence of processes by which raw materials and single components are manufactured, processed, and assembled into finished products or parts. Conceptually, work planning can be supported by the Product-Process-Resource (PPR) model. PPR is an established concept for planning and modeling production systems commonly used in work planning methods and production systems modeling, adopted by many contemporary industrial software systems [8, 9]. The entity classes Product, Process, and Resource define the relevant aspect of a work plan, as depicted in the upper part of Fig. 2. A Product represents final and intermediate product types or additional residual materials from the production process. The Process is the central class that consumes intermediate products to produce a final one using resources to execute [10]. Finally, a Ressource is a hardware of software equipment involved in process execution [11].

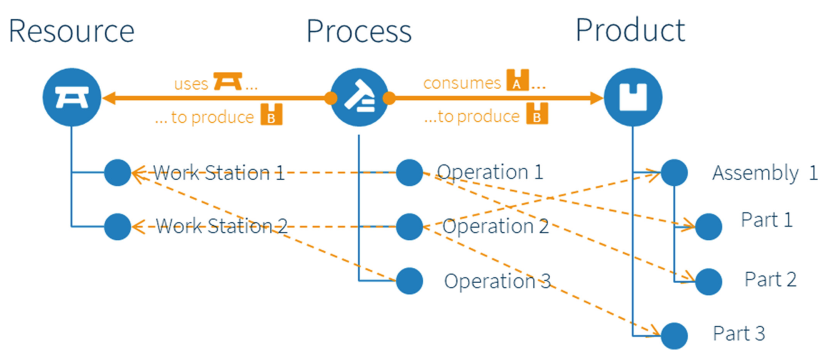

Fig. 2. Exemplary relations between elements of the work plan, materials of the product, and resources according to the PPR model

The entities of the three PPR entity classes are generally structurally decomposable. Further, a product can have different configurations, which vary in their composition.

Thus, there are different bills of materials contained by different product end-items. One such end-item is represented on the right-hand side of Fig. 2. A work plan is valid for a specific product configuration, i.e., it refers to a specific end-item. A work plan is built out of a sequence of operations. The operations refer to positions of the BOM (single parts and assemblies). The BOM positions are handled in the process and represent the material input and output from the process steps. In the simplified example above, Operation 1 assembles Parts 1 and 2 to Assembly 1, and then it is assembled in Operation 2 with Part 3 to the product end-item. Operation 3 is a working step without material input, such as testing or finishing actions.

In summary, a process consumes functions provided by a resource and thereby occupies it for a period of time. It also consumes intermediate products in order to produce an end product. The consumed products define the material transformation for value-creation, while consumed functions of resources define the production capacities. In combination, the two contain all necessary information for production, which is recorded in the form of work plans [10].

2.3 Concept for Integrated, Lifecycle-Spanning Work Planning and BOM Management

A concept for product lifecycle overreaching modeling and software support was developed based on the PPR model. The concept covers product modeling throughout the different phases of its life and considers its representation in a contemporary, integrated information management solution. The lifecycle phases covered by the concept are, as depicted in Fig. 3, the design and development phase, the process and work planning, production operations support, and the usage phase of the end product.

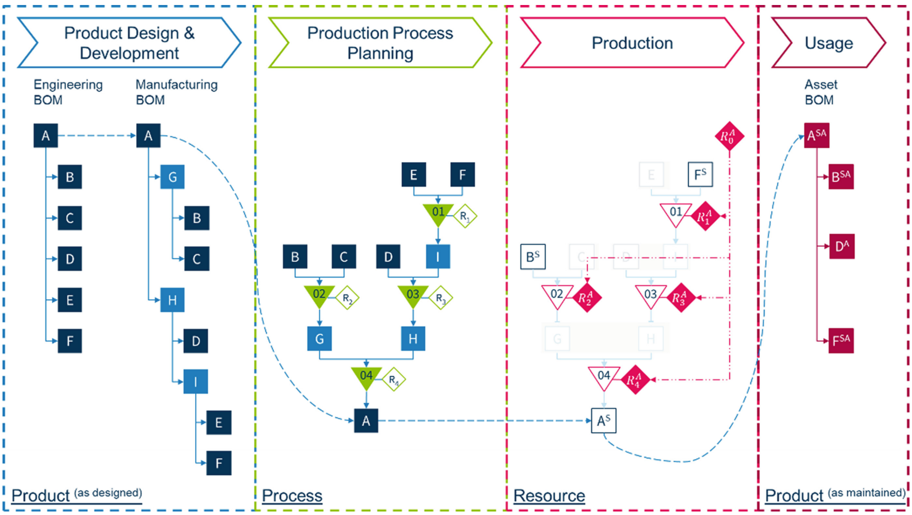

Fig. 3. Concept for integrated, lifecycle-spanning work planning and BOM management

Different product, process, and resource descriptions are necessary throughout these phases, each serving the specific goal of the respective phase. In the product design and development phase, the product is defined in terms of its composition using modular BOMs. An engineering BOM (eBOM) defines the product from a functional perspective, mostly driven by CAD. Next, a manufacturing BOM (mBOM) is derived, serving as a basis for the production process [12]. While it contains the materials of the eBOM, it includes additional intermediate assembly nodes following the assembly stages of the product. In the production process planning phase, the process of building the product is described. Thereby, the process steps consume the materials of the mBOM and transform them into wider assemblies while using the capabilities of the production resources. The process model, input and output material, and necessary resources amount to the work plan. The facility implementing the process is put in the foreground in the production phase. The resources – i.e., production equipment – of the production line model perform operations, which correspond to the process steps of the work plan. While the product and process descriptions of the former two phases have descriptive character, the production line model also serves the manufacturing execution and control. With the completion of the production phase, the unmounted/unprocessed material defined in the BOMs has been transformed into a finished end-product, which is ready to be put into service. The finished product requires a different model in the usage phase, which enables its monitoring, control, and maintenance record. The product in operation is represented by the asset BOM (aBOM), which reduces the structure of the eBOM fitted to the needs of the concrete use case.

2.4 Work Planning and Lifecycle-Spanning BOM-Management from an Enterprise IT-Landscape View

As seen from an engineering perspective, product design and development create several information objects that can be managed in product lifecycle management (PLM) IT systems (cf. Fig. 4). Objects are, for example, product or part-related specifications, describing single skills or functionalities to be satisfied by the product or part increments. Parts can describe generic products, assemblies, or single product-related items. Instantiated parts are represented by the serial object that allows individual identification of each product, assembly, or single product-related instance.

The objects of the work plan essentially describe the process of production process planning. The work plan is detailed by sequence objects, describing individual work processes and operations. Operations can be assigned to one or more sequences, use product parts as in-and outputs, and be allocated to a specific workplace that corresponds to a production resource. As part of the production process planning and the production itself, data from objects in enterprise resource planning IT systems can be relevant, such as from procurement or stocking. However, as the presented approach focuses on the engineering view, these objects will not be discussed further.

A production order is executed to initialize the production process, for example, as part of a machine execution system (MES) or manufacturing operations management system (MOM). This order can include batch size, timetables, or production sites. Each production step is referred to by the operation object, which gives detailed information about the conduction, such as the assigned machine, length, or description. The asset

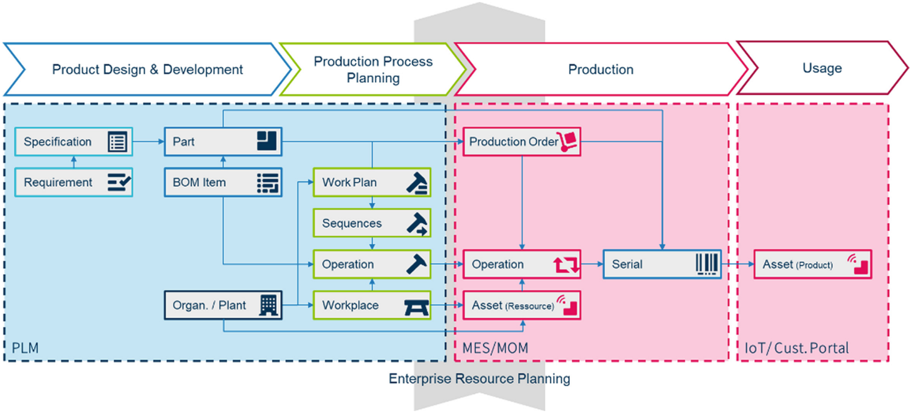

Fig. 4. Systemic view of product lifecycle IT objects from a work planning & production view

object describes the assigned machine (cf. Fig. 3 R^{A}_{0-n}) and thus the existing resources in the production process. It inherits information about the machine, such as properties, component structure, settings, or operating conditions. In addition, it can provide usage and environment data such as measurement data, production order, machine parameters, malfunctions and error codes, or user data.

Serialized objects (i.e., the Serial) refer to the produced product instance (cf. Fig. 3, A^{S}). These product instances can be tracked in their usage phases in an IoT platform or customer portal and thus managed as an asset (cf. Fig. 3, A^{SA}).

3 Implementation and Validation

The implementation and validation of the concept discussed in Sect. 3 were done by using data of an excavator in a prototypical system based on the CONTACT Elements technology. CONTACT Elements is a modular software suite for consistent product lifecycle information and process management combining management, planning, and control solutions from the early product design & development phases to the real-time data tracking in usage as part of an Internet of Things solution.

As part of the product design & development phase, the derivation of an mBOM from the eBOM (cf. ① and ② in Fig. 5) was realized for the excavator example product. The view is generated with the help of the so-called xBOM Manager application in the CONTACT Elements suite, in which a new BOM can be derived from an existing one, e.g., by restructuring, adding new parts and positions, and comparison of different BOM types. The mBOM is then used for the production process planning. In this example, a tracked undercarriage assembly of the excavator is shown. First, production process steps are created for the undercarriage, which reference the parts of the mBOM as consumed materials (cf. ④ in Fig. 5). Then, the workplan is linked to the undercarriage assembly product (cf. ③ in Fig. 5) assembled from the consumed parts. The created work plan consists of the main sequence, can include parallel and alternative ones, and can be visualized in the work planning application alongside further information such as the workplaces, as exemplified in section ⑤ of Fig. 5.

The execution of the production order and the management of the required production lines and their components are carried out in the Manufacturing Operations Management System, which incorporates IoT capabilities. For the production of a defined quantity of products (serials), the production order bundles the operations to be carried out (process), the production lines or machines required as assets (resources), as well as the parts produced or assembled (Material No.) in the operations (cf. ① in Fig. 6).

The production line can be managed via a superordinated asset (or an asset group), including information from the shopfloor, and is visualized via 3D models (cf. ② in Fig. 6). In addition, machines used as resources in the production process can be visualized in the 3D model, including information on their current state, operations, and condition, offering navigation shortcuts to a detailed view of the corresponding asset.

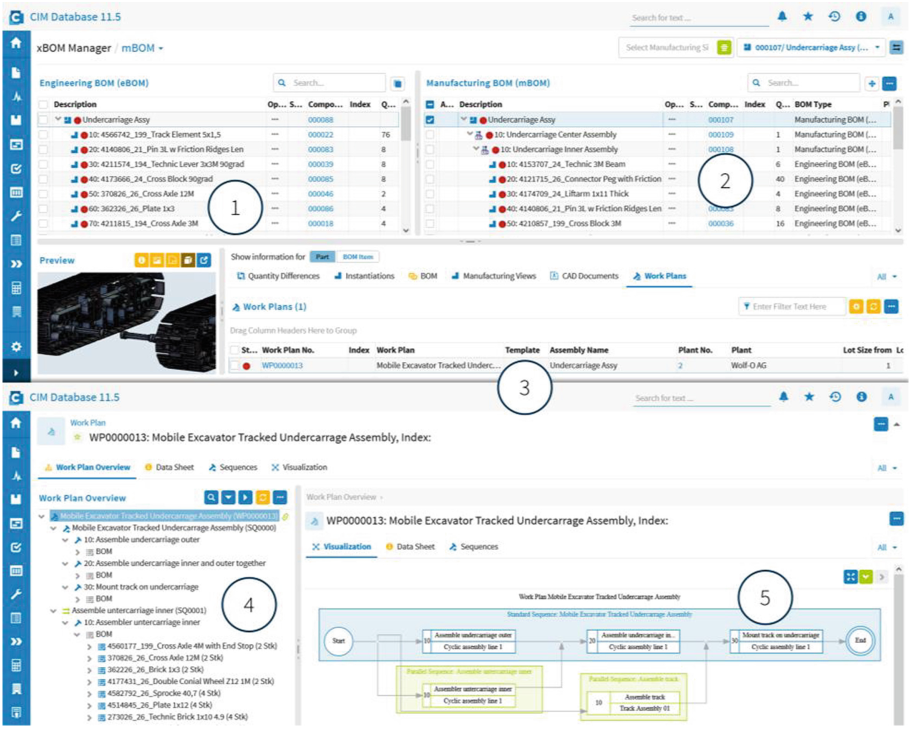

Fig. 5. Visualization of different BOM views and related work plan

The manufactured product can then be managed on a different IoT platform in a customer portal or asset management system to provide various stakeholders with information about the product's as-built and as-maintained states (cf. ③ in Fig. 6), its current state defined by field and analysis data (cf. ④ in Fig. 6), its location and driving route (cf. ⑤ in Fig. 6) or derived business applications such as generated service cases and their execution status. The result is a consistent management all relevant objects such as products, assemblies, or parts in joint BOMs and data structures from early engineering phases, through an integrated production line planning with resource scheduling and routing, to an possible, individual IoT-based asset management of smart product.

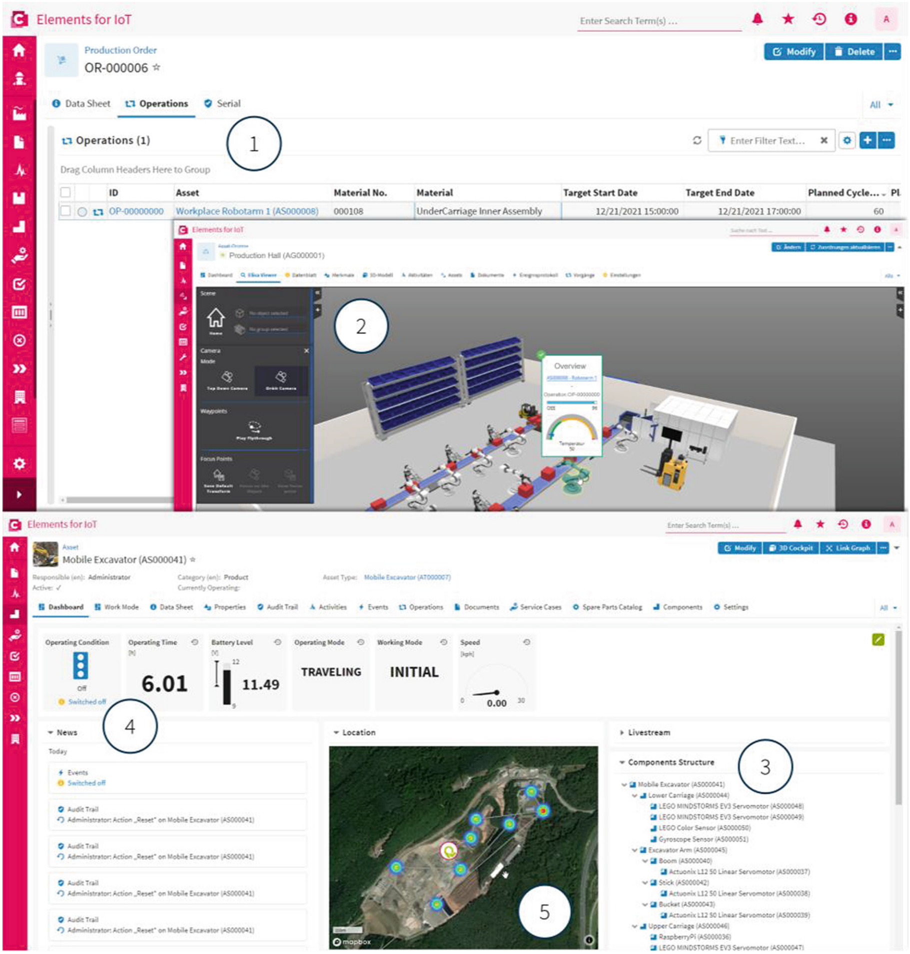

Fig. 6. Production execution management incl. 3D visualization; Asset management in usage

4 Conclusion and Outlook

The contribution presented an integrated, lifecycle-based approach to the information management of smart products focusing on work planning. First, the fundamentals of work planning and related bill of materials processing were elaborated from a methodical perspective, and a product lifecycle-spanning data integration approach was presented. Finally, the protypical implementation of the concept in a state-of-the-art, integrated software solution with a focus on data continuity was briefly illustrated.

Thereby, Sect. 3 dealt with the IT landscape of a manufacturing company. Smart products often consist of components from different manufacturers, and the product of one company can be a part of another product or can be a resource for the production of another company's product or a part of it. Such interconnections raise the question of how companies along a supply chain, especially in the age of Industry 4.0, can define their IT architecture and business models to enable the greatest possible value creation for themselves, their customers, and the end-user. This question will be dealt with in future publications.

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