Assembly Process driven Component Data Model in Cyber-Physical Production Systems

Daniel Strang and Reiner Anderl

***Abstract*—In times of global markets, the cost pressure on manufacturing companies in high-wage countries is increasing. One way to deal with globalized markets is to develop new production systems. The German Federal Government supports an initiative for the research on highly adaptable, cyber-physical production systems called *Industrie 4.0*. In cyber-physical production systems components communicate with assembly stations and other components to guarantee the ideal manufacturing process.**

As part of this initiative the description of communication and decision processes in the assembly systems is researched. Therefore a UML based modeling method is chosen to model the communications and material flows in such a system. The component data model is one central element in the process. In the model knowledge about the individual components can be stored and used to make decisions in the assembly process.

During the communication process components exchange relevant knowledge, which is available in the component data model. This is required to define what components should be assembled to a final product and on which manufacturing station the work should be done. It guarantees low costs and a high flexibility in the assembly process. In this paper the relevance of the component data model in assembly processes and on the process models is shown.

***Index Terms*—component data model, cyber-physical production systems, Industrie 4.0, process model, systems engineering**

I. Introduction

The initiative *Industrie 4.0* of the German Federal Government is aiming to achieve a highly flexible production. The goal is to manufacture small batches of products at minimal costs. For that purpose cyber-physical production systems are used. They consist of components, transportation facilities, and manufacturing stations with sensor and actor technology as well as communication interfaces. Hereby components are able to communicate and interact with their environment. The goal of the initiative is to enable products to plan their own production, decentralized. On the one hand the new production systems offer new opportunities to the production planer, but on the other hand they increase the complexity of the production process. To handle cyber-physical assembly systems the project “Smart Factory IT” (SmartF-IT) is focused on IT solutions in this research area. Examples are an assisting software to understand decisions in the assembly process, simulations of machine or human based manufacturing and integrated real time data visualization.

Based on the principles of systems engineering, the modeling of cyber-physical assembly systems and processes is needed to illustrate the relationships and interactions before implementing IT solutions. All relevant information can be shown in a simplified way, evaluated easily and used for the IT solutions.

The component data model is a key element of models in cyber-physical production systems. It manages the necessary information for the process and the way it is stored for the future activities of the process. With the information the communication processes are initiated and decisions are made based by the comparison of information (e.g. a component and a machine).

In this paper the influence of the component data model in a meta model and a process model of the cyber-physical production is shown. Based on a look on the state of the art, the concept of modeling the relationships and interactions is described and demonstrated on an example of an assembly of a pneumatic cylinder.

II. State of the Art

A. Cyber-Physical Systems

The basis of modern manufacturing systems are cyber-physical systems. The principle of cyber-physical systems is “cyberizing the physical – physicalizing the cyber” [1]. That means, that everything that is existent physically is represented in the virtual world, and everything that is represented virtually is exists in the physical world.

Cyber-physical systems are defined as systems with embedded software [2]. These systems

1. use sensors to record data and affect physical processes by actors,
2. evaluate and save data and interact with the physical and virtual world,
3. connect with each other and communicate via interfaces,
4. use global data,
5. use human-machine interfaces. [2]

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In the manufacturing environment cyber-physical systems are called cyber-physical production systems. They use smart machines, storage systems and production facilities, that are able to exchange information autonomously, trigger actions and control each other [3]. In this context *Internet of Things* and *Big Data* are two research areas that result from the development in the area of cyber-physical systems. *Internet of Things* represents the networking of all objects in such a factory. Further information can be taken for example from Kopetz [4]. *Big Data* research treats the high amount of data in cyber-physical systems. A management for data in cyber-physical production systems is required [5].

B. Smart Products and Smart Factory in the context of Industrie 4.0

The manufacturing based on cyber-physical production systems uses Smart Resources to produce Smart Products.

Smart Products are mechatronic products that are equipped with additional embedded systems. They enable communication between several Smart Products using the modern internet technologies [6]. Smart Resources are based on the same principles for manufacturing stations, tools and manufacturers.

Smart Factories are academic research factories, like the one in Kaiserlautern, Germany, developed by the DFKI. They represent the entire control technologies of industrial manufacturing and serve as a research and development platform for projects on future manufacturing and Smart Products [7].

Industrie 4.0 is one of the research areas that can be demonstrated in *Smart Factories*. The idea of the initiative is to use cyber-physical systems such as Smart Products and Resources in a Smart Factory to manufacture products in a highly flexible and efficient way. Thereby aims are to produce small batches (batch size 1) with low costs [3] and to enable an individualized production process.

C. Modeling Principles in Systems Engineering

Systems Engineering is an approach to develop complex systems or products with all divisions of a company involved [8]. For Systems Engineering some methods that define a strategic way for the development already exist.

An often applied method is the V-model which is defined in VDI 2206. It defines several steps like requirement analysis, system design, domain-specific design and system integration [9]. The W-model in Figure 1 is a strategic process based on the V-model. It adds a virtual system integration based on a data management system to the existing method [11]. The modeling is seen as a basis for a product development in the V-model as well as in the W-model approach.

By Anderl et al. *Smart Engineering* is defined as a method to design and dimension Smart Products. Therefore knowledge of sensor technologies, actuator technologies, control logics and communication protocols is required [6], which is also necessary to design cyber-physical production systems. Smart engineering can be used for that domain.

Modeling is done with elements of the Unified Modeling Language (UML). It is defined by the Object Management Group [12] and used for various applications.

UML provides a variety of diagram types that can be classified into structure, behavior, and interaction diagrams [12].

Structure diagrams describe the structure and the relations of a system [8]. Examples for these are class diagrams and package diagrams. These two will be used in this paper for a meta model to describe the role of the component data model in a cyber-physical production system.

Behavior and interaction diagrams are suitable to represent processes with the interaction between classes of a structure diagram [8]. This is used to show the assembly process in the factory of the future.

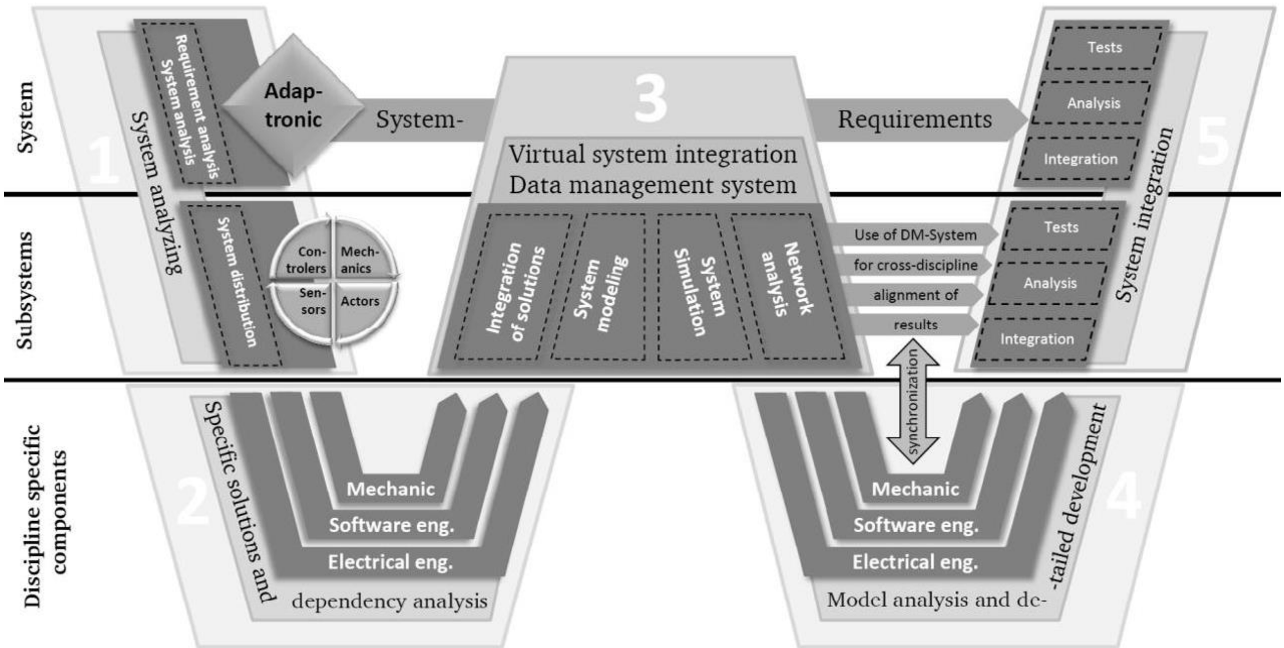

Fig. 1. W-model for the development of adaptronic systems, in [10]

D. Component Data Model

The components in a production pass through several value added chains. These are for example production, usage and recycling. These chains are represented in the component life cycle (Figure 2). In opposite to the product life cycle [14] the component life cycle was developed to visualize the single phases from the component view [13].

For the assembly process it is necessary to take a closer look at the value added chain of the production. This is shown in Figure 2 for a cyber-physical production.

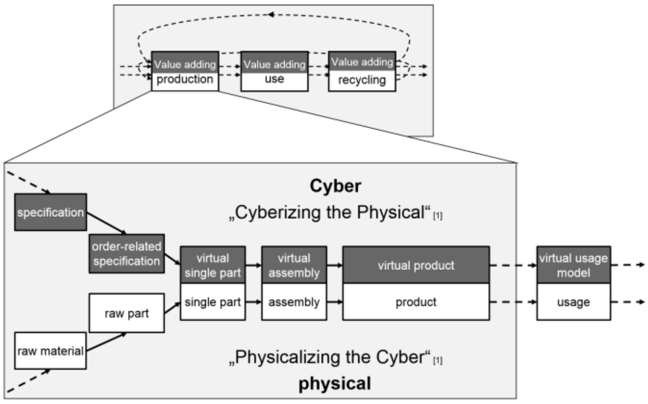

Fig. 2. Component life cycle [13]

The phases in the physical world lead from the raw material to the final product. In an ideal cyber-physical production system all phases have a representation of themselves in the virtual world.

The component data model is the individual representation of each component. It is used to store data of the real production process [13]. A similar approach is the semantic product memory defined by Wahlster [15]. It allows the contextual retrieval of information [16] using ontology based representation [17]. The component data model exceeds the product memory by allowing component data to influence the production planning and controlling processes [13].

The component data model consist of a core model and several partial models. One partial model is the model of the production. It can be divided into two specific models: manufacturing of the single parts and assembling of single parts to a final product. Relevant for this paper is the partial model of the assembly. In here data that resulted from the product development and the manufacturing or occurred in the assembly process can be stored. This data is stored because it might be relevant for future steps in the value added chains.

The component model is the instantiation of the component data model [13]. That means it only represents one single component.

III. CONCEPT

The component data model is relevant for all phases of the life cycle. Data that might be relevant for manufacturing, assembling, using, quality or recycling issues can be added to it.

Knowing this, it is obvious that the component data model has a key role in the modeling process. The modeling process is necessary to develop and understand the complex relations and processes of a cyber-physical production system.

One task of this concept is to model the relations of participants in a cyber-physical assembly process and their influence on the assembly process.

As stated before a representation of relations is made with a structure diagram. To describe the structure a UML package diagram is taken. For the participants and the detailed interactions a class diagram is used. These two form the meta model of the cyber-physical assembly process.

Five packages are defined in the package diagram. These are:

1. Resources
2. Component
3. Process
4. Deviation management
5. Organization

Figure 3 shows the packages and the classes of the class diagram in a simplified way.

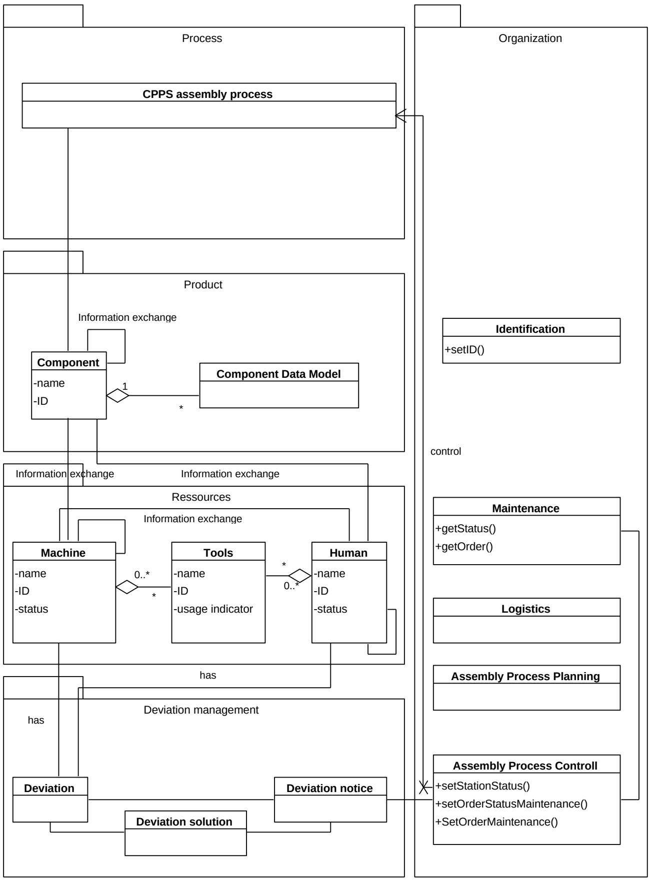

Fig. 3. Meta model of the cyber-physical assembly process

The *resources* contain the assembly stations, with machines, human resources, tools and their sensors and communication interfaces. In the package *product* the component itself is represented with an aggregation to the component data model. The *process* represents the assembly process, which is shown in a behavior model later on. Since problems in the processes or at resources should be detected and solved as fast as possible, a *deviation management* is necessary. Therefore an analysis and classification is indispensable. The *organization* include the process control and planning, the logistics, and maintenance. For identification there is a central class that organizes the ID for each resource and component.

Figure 4 gives an example how the component data model in the meta model with some attributes and operations may look like.

Component Data Model
-single part ID -single part dimension -single part tolerance -assembly ID -assembling station -assembler -assembling date -tools -order name -oder specification -order due date
+getSinglePartID() +getSinglePartDimension() +getSinglePartTolerance() +getAssemblyID() +getAssemblyStation() +getAssembler() +getAssemblingDate() +getTools() +getOrderName() +getOrderSpecification() +getOrderDueDate() +getManufacturingInformation()

Fig. 4. Component data model in the meta model

In the component data model of Figure 4 some attributes such as order information, quality of the single parts, assembly members, single part and assembly ID or used assembly stations can be stored. For the assembly process it is necessary to describe only attributes of the partial model of the assembly. In the partial model data that might be relevant for the merging of the single parts to an assembly is stored.

To describe the behavior of instances of the class diagram an activity diagram is used. With this type of diagram it is possible to visualize processes. Originally it became part of UML to present the behavior of software.

For cyber-physical production systems it is possible to use the activity diagrams of UML, but it is necessary to define some new rules for the visualization. These definitions are collected in the UML-based description method AssemblyML.

In classical UML actions and activities for software development are defined. These can still be used for cyber-physical production systems. They are connected to other activities and actions by object and control flows. In the modelling of manufacturing processes it is required to differentiate between material flow and communication. Therefore the material flow is matched to the object flow and the communication to the control flow. In cyber-physical production systems a lot of communication and data exchange is done without any material flow. The data exchange is nevertheless relevant for the assembly process and especially for the decision processes in manufacturing. Components, manufacturing stations, tools and manufacturers are connected with each other via communication interfaces. The usage of these interfaces need to be represented in the process model.

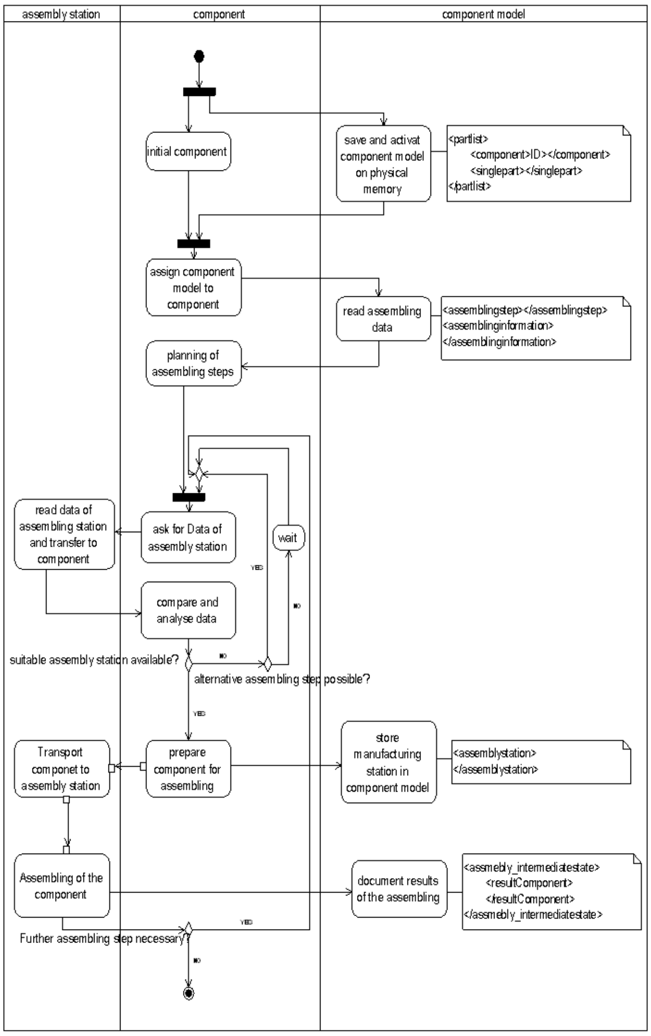

Fig. 5. Process model and component model in an activity diagram

In Figure 5 a simplified decision process model is shown. Three swim lanes are needed to clarify the affiliation of the actions in the process model.

1. Assembly station
2. Component
3. Component model

In these swim lanes all actions are sorted into groups regarding their main influence on the process.

The first step is to define the initial component of an assembly. Simultaneously the component model can be instantiated, be filled with components (e.g. manufacturing information) and assembly relevant data (e.g. individual parts list), be activated, and assigned to the initial component. With the activation the component model is able to provide data and to save new incoming data for further issues.

After the component model is assigned to the initial component, assembly data is taken from the component model. In the example of Figure 5 this is data about necessary assembling steps, which is produced by the production planning or by assembly specific information that is individually collected for this component.

As soon as the relevant information is identified the decision process of the assembly process can be started. The component uses its communication interface to contact assembly stations that can be used for the following assembling steps to collect data of these stations. This data is compared with the information of the component model.

Based on this analysis an assembly station is chosen. If there is no assembly station available that can perform a step at the current time, it will be checked whether another assembling step can be done first. If that is not possible, the component has to wait until an assembly station is available again.

After defining an assembly station the component is prepared for the following assembling. The chosen assembly station is stored as new information in the component model.

The first material flow is happening before the actual assembly process. By the logistics the component is transported to the assembly station. The assembly station confirms the delivery of the component and starts the assembling. In the example of Figure 5 it is not relevant whether the manufacturing is done manually, automatically or a hybrid assembly process.

The data that is produced during the assembly of the product is saved in the component model. In an ideal process this is done in real time to underline the cyber-physical aspect of the process. Everything that is happening during the assembly of the product should be represented in the virtual world.

When the assembling step is completed successfully a query for following steps must be done. If there are following steps stored on the component model the decision and assembly processes start again, otherwise the manufacturing is completed. The finalization of the assembling need to be stored on the component model again to initiate the following life cycle phase.

IV. Sample Solution

To illustrate the advantages of the component data model an example is shown based on components of a pneumatic cylinder. In this example the bottom part, the case and four screws are taken to simulate one assembling step.

In Figure 6 these parts are shown in a 3D CAD model.

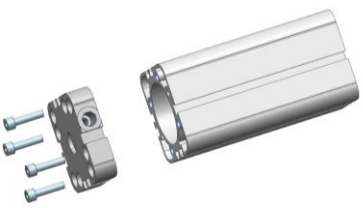

Fig. 6. Components of the pneumatic cylinder

A. *Individual parts list*

Initially the single components need to be evaluated. The aim is to find a bottom part and a case that fit together regarding the tolerances.

It is necessary to analyze the single components in two ways. First it is important that all single parts are used and that there are no rejected single parts. The second aspect is to combine the single parts in a way, that there is a minimal size difference between the bottom and case length and width.

For the analysis the component data model is useful. The fact that in the component data model the actual size with actual tolerance of the real part (here 3D scan) is given, is illustrated in Figure 7. That is a difference to the product data model in which the tolerance range is given.

Fig. 7. Product data model and Component data model of a single part [13]

An analysis can be started with the actual tolerances of the bottom parts and the cases. Therefor an algorithm is used. It combines two single parts regarding the two aspects that were described before.

It is possible to create an individual parts list by the algorithm, which combines ideal partners for the assembly process and guarantee minimal rejection rates.

The individual parts list is saved to the component model in the *assembly relevant data* and used in the assignment of the components to an assembly.

B. *Decision Process*

In this case the decision process is limited to a decision for a manufacturing station. Since there is only one manufacturing step, a decision for a manufacturing step is not needed.

Besides the tolerances, the torque profile for the screws, presumed knowledge about the component and required tools are relevant information that needs to be on the component model.

This information is compared to the information at the manufacturing stations. Here the data about the assembling knowledge at the station and the available tools and their characteristics must be stored. After a comparison the most suitable assembly station is chosen and the component will be transferred to the station to start the assembly process.

C. *Assembly Data*

There is a lot of data from the assembly process that can be stored in the component model. Relevant information that might be interesting in the future is for example:

- used manufacturing stations,
- used tools,
- used assembly machines,
- time and date of the assembling,
- manufacturer(s),
- quality information,
- influences on future steps,
- used single parts.

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If there is more than one assembling step it is necessary to save the order of the steps. Problems or differences between the assembling order and the original production planning should also be traceable for service or quality purposes.

V. Conclusion and Future Work

In this paper a way to represent the cyber-physical production process is presented. By using basic modelling components of UML it is possible to visualize the decision process and assembly process of smart products in an assembly line which is based on technologies of the initiative *Industrie 4.0*. To fulfill all requirements, like visualize communication and material flow, some new definitions are introduced (AssemblyML).

The component data model is a method that enables the structured data storage for components. It is necessary for the process modeling and the processes itself. The component model, which is an instance of the component data model, ensures that all decisions are based on individual information of the component and all decisions and results that are accomplished are logged in there.

With an integrated component data model the cyber-physical production processes are possible to achieve. It supports all parts of the development of the production system, of the process planning and the process control. Even in other value adding chains this model is of high relevance.

For a full contemplation of the cyber-physical production process it is necessary to take manufacturing and the manufacturers into consideration. For the manufacturing of the single parts there already exist some researches regarding manufacturing networks [18]. Also a research concerning human models in the cyber-physical production process is currently in progress [19].

For these research areas a component data model is of high relevance. Therefore a different partial model of the component data model must be defined and a structure for these needs to be assigned.

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