Virtual Twins as Integrative Components of Smart Products

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Abstract. Current ICT developments in the areas of micro-devices, hardware infrastructure as well as internet and software technologies lead to a change of the physical products we know today. Traditional products are becoming smarter every day. The product generation meeting these innovations is called "Smart Products". As a driver of the 4th industrial revolution these Smart Products will dominate most industrial sectors in the future. Product related data and the management of this data along the entire product lifecycle in the PLM context are becoming core components of these Smart Products. This is especially true for the tremendous amount of operational data generated by the Smart Products during their use phase. However, the management of Smart Products' data related to a magnitude of heterogeneous product models (virtual product twins) will be crucial for the persistence of industrial companies. This paper illustrates that the virtual product twins have to be considered as integral components of Smart Products by giving concrete examples for the application of various virtual and physical products in different lifecycle phases.

Keywords: PLM; Virtual Twin; Smart Product;

1 Introduction

Recent innovations in the fields of information and communication technologies (ICT) have a huge impact on physical products. These products affected mainly by the "Internet of Things" are called "Smart Products" [1]. Smart Products (SP) are Cyber-Physical Systems (CPS) defined as intelligent mechatronic products capable of communicating and interacting with other CPS by using different means such as internet or wireless LAN [2]. However, the central basis for Smart Products has to be seen in combinations of software (e.g. big data analytics) and hardware developments (smart devices) as well as communication infrastructure innovations (e.g. LTE). Furthermore, embedded micro-devices (e.g. micro-sensors) allow physical products to interact with their environment.

A survey from the academic society for product development (WiGeP) among more than 60 engineering managers from German industrial companies underlines the current transition from traditional physical products to network-based systems. More than 60% were already working on projects related to the 4th industrial revolution while only 3% haven't already taken first steps into action. [3].

A main challenge concerning the management of SP-related data lies in the collection, integration and transformation into information in order to be valuable for an enterprise network. Due to the fact that Smart Products are intelligent and adaptive to their environment the management of the virtual product models become more and more important. The necessity of being able to predict the performance of a Smart Product or to manage for example product instances that are acting autonomously increases as the creation value doesn't end with the selling of the product [4].

This paper introduces a concept of virtual and physical product twins. It points out relevant product models such as CAD models and data like condition data of product components that build up the base for the virtual twins of a product. Based on these characteristics it will be shown by considering the example of a self-driving car that virtual product twins have to be regarded as integrative components of Smart Products. From this point necessary models and data that allow the creation of a virtual twin are analysed and systematized in a general way considering the whole product lifecycle.

2 From traditional products to Smart Products

The term "smart" is generally related to expressions such as clever, intelligent, agile, modern and intuitive. The characteristics of a Smart Product can be described considering components of a car (see Figure 1) [5].

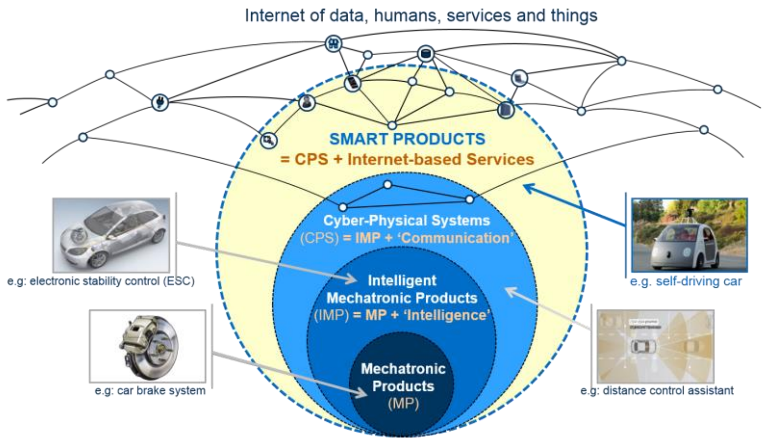

Fig. 1. Classification of products [6].

The process of becoming "smart" starts in this example with mechatronic systems, as they form a hybrid system consisting of a connected mechanic and electronic unit such as a car brake system. Intelligent mechatronic products evolve from mechatronic products. They are enhanced by a certain intelligence that allows them to adapt themselves according to their environmental awareness e.g. electronic stability control (ESC), which detects and reduces situational loss of traction. If intelligent mechatronic products are communicating with their environment and are acting accordingly they can be labelled as Cyber-Physical Systems (CPS). These CPS can be described with the help of a distance control assistant which is constantly in interaction with the car's environment in order to react situationally to the road behavior of other cars.

Lastly, CPS connected to the internet of data, humans, services and things (internet of everything) are called Smart Products. An example for such a Smart Product is a self-driving car, which combines all the above mentioned systems and is additionally connected to the Internet. The car is able to adapt and react accordingly to its environment and has therefore an awareness of its surrounding, e.g. by communicating with traffic lights while approaching an intersection. Nevertheless, it must be trackable where the exact position of the car is at any time as well as the car needs to know when the gas tank is below a certain level, react to temporary obstacles like construction yards or if the city introduces new one-way streets for example. This interaction between different kinds of data like environmental data or assignments, product models with all product-defining data and physical product data does not only apply to the phase of the car's lifecycle when it's actually driving on the street but has to be considered from the very beginning of the products' lifecycle until the end.

3 Virtual twins of Smart Products

Originally the term "virtual twin" was introduced in NASA's technology roadmap "Modeling, Simulation, Information Technology & Processing". It was defined as an integrated multiphysics, multiscale simulation of a vehicle or system that uses the best available physical models and sensor updates to mirror the life of its corresponding flying twin [7,8]. In other words, a virtual twin is a virtual copy of something physical modelled to behave realistically. Considering a Smart Product the virtual twin can be regarded as the notion where the data of each stage of the product lifecycle is transformed into information and is made seamlessly available to subsequent stages [9]. However, it is necessary to distinguish between a physical product lifecycle and a virtual product lifecycle as every physical phase of a products' lifecycle has a corresponding virtual lifecycle phase. In these lifecycle phases models and data can be found that can be located either in the virtual or the physical lifecycle of a product. For example, a geometric virtual product model during the product development phase matches with the physical prototype. The virtual production planning is linked to the physical act of production. During the product use phase, the virtual product use management assures the operation of the product and the virtual End-of-Life-Planning (EoL) is connected to the physical End-of-Life phase of the product lifecycle. Figure 2 shows dependencies between the physical product lifecycle and the virtual product lifecycle whose physical output, data and product models merge to a physical respectively a virtual twin. The physical twin can be considered as the physical output corresponding to the physical lifecycle phase e.g. a prototype or later the product. The virtual twin however is a mix of data and virtual models that build a copy of the physical twin.

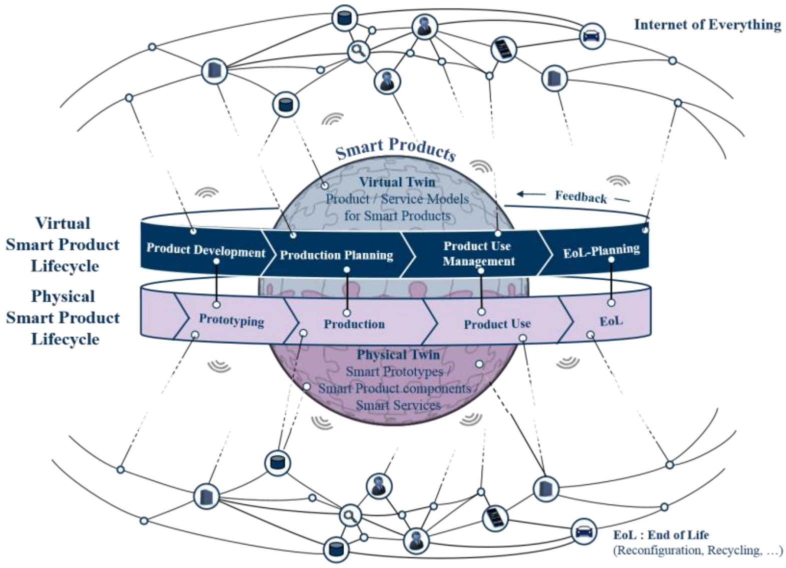

Fig. 2. Relations between the virtual and the physical smart product lifecycle.

As for the product development and the production phase the integration of models and data between the physical and the virtual product lifecycle has been addressed for many years and thus today is established in wide parts. In the product development phase for example functional important geometries of car engine components (e.g. cylinder heads) lie within tolerances of ± 0,2 mm for casted shapes [10]. In general companies wait for the physical parts to become available in order to assemble a prototype and to inspect the quality as well as the build process. However, this can be time-consuming and costly if unsuspected errors occur despite using techniques like N-body simulation for example. Commercial solutions allow to predict the final quality of the design long before physical parts have to be manufactured. This can be realized for example by building a virtual twin in a CAD software with all the geometric information necessary (e.g. tolerances) and by linking this with a PLM-software where the product structure within the bill of materials (BOM) as well as a basic description of the build process is added. By simulating the build process of the assembly of many engine blocks possible interferences can be detected and solved by redesigning even before any prototype is manufactured [11].

During the production planning it is crucial to link the results of the product development phase with the manufacturing planning. Process plans for example that contain bills of materials can be updated in real time from the development phase. If e.g. the engines of the car were initially designed with cambelts but are now redesigned for reducing wearing parts by using cam chains this information can be passed directly from the designers to the manufactures. By establishing a new manufacturing operation the changed components can be assigned to it and a detailed production plan with time assignments to each individual step can be built [11]. Additional data from machines such as installation space or production speed as well as working plans, process plans, factory plans or product models like CAD data can provide a simulation of the production process to check productivity or most efficient manufacturing routes possible. Finally, after the production plan for a product has been assigned the production can be executed. The virtual twin helps to surveil the performance of the production by assuring that resources are getting allocated to the adequate machines. This guarantees a flexible production or assists the quality control e.g. by comparing clearances from the development phase with the actually produced clearances by putting product model data in context with machine data.

After the product has been produced it reaches the product use phase. During this phase the use and enhancement of virtual product models increases with the "intelligence" of a product. Considering a Smart Product as described in chapter two as a CPS connected to the internet of data, humans and services the generated amount of data and the involved virtual models are manifold offering a huge spectrum of possibilities. A virtual twin of a Smart Product can for example support the physical product regarding its (predictive) maintenance or services. E.g. behavior models like safety or diagnosis systems or sensors at the Smart Product provide a dashboard with information such as the amount of fuel or the tire tread. Deducing from this data from different sources like physical product data (e.g. vehicle speed or load weight) and environmental data (e.g. road pavement or weather conditions) a virtual twin can react to situations in real time that could have led to dangerous situations based on low tire tread for example by activating assisting systems in a dangerous curve on a slippery road. Therefore, not only the above mentioned physical product and environment data in combination with the product models are crucial but also internet-connected services that make the car aware of the upcoming curve, such as a navigation app or the possibility to communicate with other cars for example. This however increases the need for the integrated management of the different product instances. This is due to the fact that every self-driving car has issues, such as the fuel or tire problems, that has to be monitored individually as all of the products are getting utilized differently. For example differs the distance covered by every car as well as the history regarding the amount of people transported, the type of roads used such as city streets or highways or the landscape the car has been driving through in regard to flat lands or mountainous areas. Product instance management is also affected by the individual maintenance history concerning the condition and functionality of the products' components but also regarding services or new business models like availability-orientated models, in which a customer has to rely on the availability of a car within a certain amount of time when he needs to use it. However to be able to manage each instance with a virtual twin data from the physical lifecycle such as the condition of car components (e.g. tire tread) or car behavior (e.g. speed) as well as data about the environment (e.g. weather) has to be matched with the corresponding product models such as the bills of materials, CAD data, software versions of e.g. assisting systems, material data, simulation data and diagnosis models and so on. This agglomeration of data can then manipulate the physical twin appropriate to the situation.

Lastly, the EoL-Planning of the virtual product lifecycle is connected with the EoL of the physical product with the help of their corresponding virtual and physical twin. One possible application is for example the reconfiguration of a Smart Product as the product itself or at least parts of it get either recycled or cater for a new or broader purpose. This can mean e.g. that software updates have to be executed where again data about the condition of the car (e.g. current software versions) has to be matched with environmental information (e.g. a navigation app where recently new built streets influence the traffic) and with instanced product model data. But also new operational purposes like using the car with a trailer for example or exchanging a component with a new one made from a different material can be simulated and its performance can be predicted.

A core question concerning the introduction of Smart Products is, which components of the virtual and which components of the physical lifecycle models and data have to be considered and how they have to be connected and integrated in order to get additional information in form of a virtual twin. Therefore, interdisciplinary (mechanics, electronics and informatics) models as well as physical product models and parts have to be combined to filter data that has to be transferred into context-specific information as for example the application of electronic stability control (ESC) in a car mentioned before.

This applies on the one hand to the virtual and physical product lifecycle phase of each lifecycle stage but on the other hand also to the seamless linking between the lifecycle stages. Figure 3 shows an overview of some important models and physical components that have to be considered and where their sources can be located.

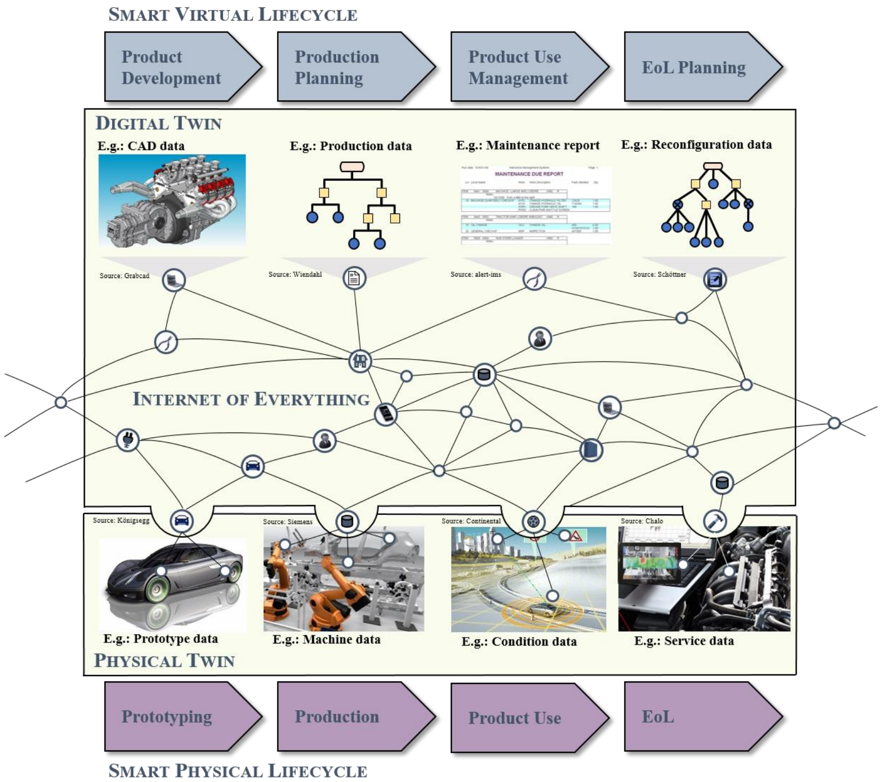

Fig. 3. Models and data exchanged between the lifecycle phases.

For the product development phase, the virtual product lifecycle includes for example CAD data, such as 3-D geometry models of parts and assemblies of the (self-driving) car. Further simulation data for e.g. finite element method to test the strength of connected components or kinematic properties is analyzed. Structural models about the product are handled in bills of materials. They include the basic assemblies of the product such as components implemented into the engine of the car. The physical product lifecycle at the development stage can contain the prototype with sensors that collect condition or test data, which can be part of the virtual twin. Prototypic realizations of the (self-driving) car can measure for example aerodynamic or tribological properties. This means all data from all the physical twins over the whole physical lifecycle gets collected, e.g. by sensors, and transferred into a cloud that belongs to the virtual twin. At the development stage for example a prototype with sensors can collect condition or test data. Prototypic realizations of the (self-driving) car can measure aerodynamic or tribological properties. This allows a real time mapping with data from the virtual lifecycle phase such as simulation data. By densifying all these data e.g. crash test data can be used to scale and simulate crashes with different environmental characteristics such as impact speed or angle.

During the production phase virtual data necessary for the virtual twin are e.g. process or production data for the time management of different sections of the car-production process. This includes the planning of materials as well as using CAD models to simulate a production environment with workspaces or NC-data to program machines in order to work according to the production plans. Also bills of materials with information about the stages of production are depicted in the virtual data of the production phase. The physical product lifecycle has information about production related data like the quantity of output or quality of produced components for example. The geometry of the car can be measured if they lie within tolerance ranges or measurement data can be collected if the produced parts fulfil the assigned job. Condition data such as information about the status of machines or even the product can help to assign and to bring autonomously material to machines in the sense of a self-optimizing factory so that capacities are exploited in the most efficient way.

Regarding the use phase on the virtual lifecycle phase for example software like firmware or apps with different versions need to be considered. These can refer to electronic assistant systems such as lane departure warning systems (LDW) for example, which means that the car is using simulation models itself while driving. Apps with map-systems for cities or assignments for the self-driving car as well as reconfiguration data to extend or change the purpose of the car are crucial data in this phase. Bills of materials are also part of this phase as they display service parts that had to be changed such as the cambelt for example. Simulation data based on feedback processes from the product can be used to simulate different scenarios, e.g. analyze if the self-driving car is able to drive a road with a certain gradient while being loaded with 65% of the permissible weight. Therefore, information about the condition of components, which are available with the help of sensors, are necessary. This data has to be densified collectively from and analyzed individually for every car so that each situation can be evaluated and solved independently. This includes also information concerning the environment of the car such as traffic signs or weather conditions in order to react in real time according to context.

The virtual lifecycle data during the EoL-phase focuses mainly on the question how to proceed with the car after it has fulfilled its primary purpose. This concerns reconfiguration data regarding different possibilities to use the car or at least parts of it. Therefore, material data about the condition of components has to be evaluated whether they can still be used in a different way. Again reconfiguration data is of importance in order to trace any new parts that have been built in during the use phase just as in the example of the exchanged cambelt above. If however no other purpose for the components can be found recycling data from the scrapping process can be collected in order to gain information for future actions. The physical counterpart to these data has to be collected by sensors from every instance as condition data. This is crucial for the tracing of replaced parts in every car for example.

Regarding the described physical and virtual lifecycles it became apparent that during the first two lifecycle stages (product development phase and production phase) the virtual lifecycle phase seems to be the dominant data source for the virtual twin to provide a benefit. Mainly CAD data as well simulation data or BOM suffice to make first assumptions about the behavior of a prototype. The same during the production phase where the product efficiency can be estimated with the virtual twin before one physical geometry has been produced. This however shifts during the last two lifecycle stages as condition data of components as well as environmental data are of high importance in order to actually influence the physical product with the help of simulation or behavior predictions by the virtual twin.

It becomes also obvious that some models and data can be found in more than one phase, such as CAD data and BOM as well as the stated importance of condition data during the product use phase or the EoL phase. This applies though for different kinds of models or physical lifecycle data depending on the product and what kind of information should be obtained with the help of the virtual twin. If these data und product models can be classified or systematized in a more detailed way, it might be possible to predict the degree of autonomy of a Smart Product or what kind of statements and with which certainty can be expected by the virtual twin.

4 Current research approaches towards virtual twin concepts

Most existing research activities in the area of lifecycle integration focus on different engineering methods that aim at the provision of an infrastructure, e.g. feedback management systems, to support either the seamless integration of different lifecycle phases or the integration of the virtual and physical product data in a certain lifecycle phase.

Eigner et al. developed a System Lifecycle Management (SysLM) as an engineering backbone for the description of complex product systems in the context of Smart Products. This approach offers an exchange of information among different disciplines such as mechanics, electronics and informatics for the whole lifecycle and integrates the management of services [12]. A cross-discipline specification technique for the system design was also introduced by Iwanek et al. in order to solve the discipline-spanning problems evolving from Smart Products regarding mechanic, electronic and informatics components [13]. Another approach in order to combine mechanical, electrical and software engineering along the lifecycle was introduced by Gausemeier et al. [14]. Durão et al. introduced an integrated component data model based on Unified Modeling Language (UML) to create a connected environment in manufacturing based on Cyber-Physical Production Systems (CPPS) where CPPS and Smart Products can store and exchange data throughout the entire lifecycle [15]. This approach aims specifically at breaking the isolated consideration of the virtual and physical lifecycle by introducing a concept for an integrated data model. A seamless introduction of the whole physical lifecycle phases was approached with the help of a Product Ontology (ONTO-PDM) [16]. This aims at facilitating the interoperation of all application software that share information during the different phases of the physical lifecycle.

An approach to support the integration within a lifecycle phase was introduced by Kubler et al. with a methodology for the management of product instances by using RFID technology [17]. An ontology-driven approach for sustainable product development in combination with decision making was also introduced by Stark and Pförtner. The ontology (OBISO) was validated on material decisions during the engineering process of a pedelec and follows the goal to provide a better usage of feedback information [18].

However, these approaches tend to focus only on one problem as they aim at integrating data either along the lifecycle phases or the virtual and physical product data within a lifecycle phase. A comprehensive consideration using both virtual and physical product twins and the identification of necessary product models or physical product data is missing today.

5 Conclusion

Every industrial product will have to face the impacts of the 4th industrial revolution in one way or the other. Physical products are getting smarter than ever due to their ability to communicate with their environment. This produces a huge amount of models and data that are connected to the Smart Product along its lifecycle and that need to be systemized and integrated in-between themselves. The virtual twin can be considered as a virtual reflection of a Smart Product. It integrates the management and analysis of these virtual models and data with data from the physical Smart Product and allows the simulation of scenarios based upon the aggregated information.

This paper pointed out the characteristics of Smart Products evolving from recent ICT innovations. Deriving from that point the concept of a virtual and a physical lifecycle was introduced by explaining the connection between every single lifecycle phase with the help of a self-driving car as an example for a Smart Product. It was shown that virtual twins can be regarded as the virtual copies of physical products along the entire lifecycle. Afterwards, models and data from the virtual and physical lifecycle were assigned to each lifecycle phase. It became obvious that some models and data were found in every stage so that the management of them can be seen as a crucial factor for the creation of a virtual twin. In future works a more detailed analysis of the impact of different models or product data might lead to a tendency of what features of a virtual twin can be realized, for example with the help of a maturity model.

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