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Digital twins of product families in aviation based on an MBSE-assisted approach

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Abstract

In this paper an approach to combine the basic concept of Digital Twins with research in product family development applied to civil aviation is presented. Concomitant benefits but also challenges regarding the management of information are introduced as well as the possibility to solve them by using the tools and methods of Model-Based Systems Engineering. As this conjoins three different topics, the basics of each of them in reference to the approach is introduced before they are subsequently combined. In the process, respective past and future research is presented as well.

Keywords: Digital Twin, Product Families, Aviation, Aircraft Cabins, MBSE

1. Introduction

Lately, concepts like Digital Twins have arisen in different contexts, likewise in product development. While applying this concept to different kind of products allows to solve given problems or assist in specific tasks, like the improved planning of maintenances, new challenges arise. Especially the acquisition, storage and management of the needed information, geometric or of a different kind, poses a problem that needs to be considered [1]. This is especially true in regards to the aviation industry. With aircrafts being one of the most complex products in mass production and with many specialties in terms of their product structure, long lasting lifespans as well as a multitude of maintenance and retrofit processes, in aviation digital assistance is desired more than with many other products. While these products are typically organized in the form of product families, the number of components often reaches a manifold of thousands. The lifespan of aircrafts frequently lasts up to 30 years and each cabin needs to be individually adapted to the specific aircraft. Because of the many modifications an airframe encounters during its lifespan, consistently updating the information about each aircraft is particularly time consuming. Thus, the information is often outdated or just not available, which leads to errors and results in the retrofit of the aircraft cabin being inefficient [2]. All this results in the efficient data acquisition, management and association becoming a new challenge by itself. Independently, the approaches of the Model-Based Systems-Engineering (MBSE) have become an interdisciplinary digital tool to counter said challenges of handling data and meta-information [3].

In this paper, an approach to apply the general concept of Digital Twins in combination with MBSE-techniques to civil aviation will be presented, along with the resulting benefits but also foreseeable challenges. Hence, a basis for the Model-Based support of a Digital Twin of product families of aircraft cabins is possible, which increases the efficiency of the retrofit and enables other subsequent services. As this paper combines three different aspects of product development, namely the essentials of model-based system engineering, product families and the concept of Digital Twins, each of these aspects is presented separately in chapter 2. During each of these chapters, at first the very basics are presented before respective work in the

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context is described. After that the approach of combining these topics to depict a concept of Digital Twins in aviation is introduced in chapter 3. Subsequently, the presented approach is discussed before finally a summarization as well as an outlook is given.

2. Essentials

2.1. Model-Based Systems Engineering

Since years creating and storing geometric information using digital CAD-models instead of plain sketches has become totally normal. However, meta-information is often still managed using documents and spreadsheets, sometimes even only in drawings or notes. With the growing complexity of products and the ongoing digitalization, this meta-information is now often stored and management in form of models, in this case so-called meta- or system-models. These models are often created using the modeling-languages UML or SysML. This model-centric approach and the used methods and tools have become known as Model-Based Systems Engineering (MBSE). [3,4]

2.2. From Products to Product Families

Traditionally, in product development single products are developed. To take the customer and its individual demands more into consideration, nowadays there is a shift to develop modular product families instead. These families consist of multiple similar, but slightly different product variants, allowing the customers to choose variant best matching to their needs. However, with the resulting increased internal variety of components the management of the product family becomes more important and challenging. Besides the classical geometrical information, meta-information, including the relation between the product variants themselves, but also between customer requirements and the best matching product variant, are needed to be managed and stored. [5]

Numerous methods for developing modular product structures have evolved, to assist the development of product families and optimize product family structures, to reduce internal variety while maintaining external variety. The Institute of Product Development and Mechanical Engineering Design (PKT) developed the Integrated PKT approach for developing modular product families, which contains numerous method units for reducing internal variety while leaving external variety unaffected. These methods use numerous data that are not linked to each other. Since not only individual variants but entire product families are considered, the data preparation is additionally complex and errors can occur. [6]

Seiler et. al. have shown, that accessing the digitally stored meta-information by applications, tools like product-configurators can be realized. These configurators can assist the developer but also the customer to create or choose the best matching variant based on individual factors [5], and possibly even create the respective models of the configured product variant.

2.3. Product Families in Aviation

While the basic principle of managed product families has been used in aviation widely, it stands out because of mainly two factors. On the one hand, aircrafts consist of a huge number of components and relations in-between them. On the other hand, aviation has to deal with comparatively small numbers of productions of each single variant. This does not only apply to the aircraft itself but also to cabin interiors and monuments like galleys and lavatories [7]. Their product variants need to be individually adapted to match the specific aircraft model [2] and also the requirements of the customer, in this case usually the airline. Combining these factors, the requirements regarding the handling and management of information are even higher compared to other product families with a smaller number of variants that each are produced more often.

2.4. MBSE-approaches for aircraft cabin monuments

This section shows how the model-based approach can be used for the exemplary implementation of variant and modular aircraft cabin monuments. The aircraft cabin is characterized by a high variance and contains for example the seats, kitchens (galleys) and toilets (lavatories). In the aircraft cabin industry, methods for developing modular product families, such as the Integrated PKT approach, are ideal to meet the individual airline customer requirements with the lowest possible number of internal, variant components. To analyze the product structuring of a novel aircraft cabin monument and its flows, the data model of the modularization methods of the Integrated PKT-Approach can be used. Model-based support during development helps to process the complicated and extensive data volumes of aviation and to modify them consistently during methodical further development. [8,9]. On this basis, a modular product family for aircraft cabin monuments could be developed by means of a model-based approach, which takes into account different life cycle phases [10]. Also, for analyzing the modular product structure of aircraft cabin interior, model-based support can be used. [11] Modules of different aircraft cabin systems (such as lavatory and galley) can be represented in an MBSE model and, for example, their links and flows can be displayed (see Fig. 1).

Fig. 1 shows a section of the model of a combination of a galley and a lavatory, used for the analysis of the flows and their interfaces. The flows within the combined Galley and Lavatory monument can be modeled in the modeling language SysML using internal block diagrams.

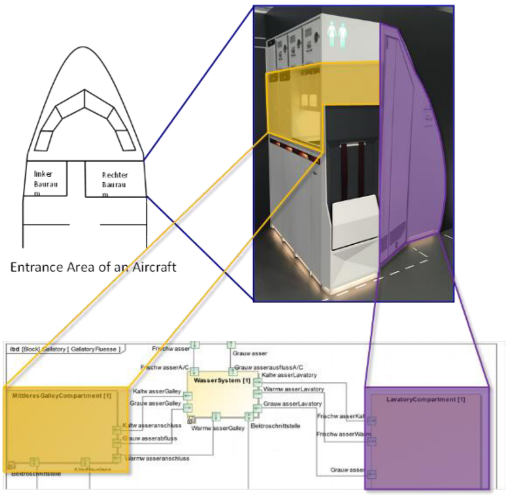

Fig. 1. Flows and their interfaces for a modular aircraft cabin monument in SysML according to [9] and [11]

Both the Middle Galley Compartment Module (colored yellow) and the Lavatory Module (colored purple) have water connections, as shown with the modeled connections *cold water connection*, *grey water connection* and *hot water connection* [11]. By exploiting synergies between the different modules, interfaces such as the same water connections can be saved. In order to integrate further data and information of the aircraft cabin and to increase the consistency of different data elements, lightweight design can, for example, be consistently linked and modeled with modularization in the sense of Modular Lightweight Design. [12]

2.5. An introduction to Digital Twins

Today the term Digital Twin is ubiquitous and can be found in many research projects, approaches and publications. The uses cases reach from factory design or robotic assembly lines [13,14], maintenance applications [15] and predictive maintenance approaches [16] to, among others, digitally managed electric grids [17]. While the details of the different concepts of all these use cases will not be elaborated on, the very basic common concept is presented before the general understanding with regard to this paper will be stated. While the concept of Digital Twins can also be applied to processes, the focus hereinafter will be on products.

The Twofold of Twins - the basic concept of Digital Twins of Products

During product development a future product is usually represented using digital CAD-models and nowadays additionally using meta-models as stated in chapter 2.1.

During the production these models are used to produce the real product, or a multitude of them. From then on, the real products are usually not further linked to the digital representations. Another trend in product development is the strive to keep the connection between the produced product back to the models it originated from during the development process. As each single individual produced instance will encounter its specific circumstances during its life phase and thus, have its specific characteristics and adaptations, they all have to have their own specific digital representation that incorporates these.

Hence, the concepts are always based on the twofold of twins - one physical, the other digital. A Digital Twin therefore is a digital model or representation linked to its specific Physical Twin [1,17,18] and for n physical products there need to be at least n Digital Twins.

While the general structure and the majority of the information in each of these Twins may be identical, they all have their very own distinct manifestations and vary in details. Thus, if possible, the models originating in product development make for a good initial dataset for the Digital Twins, as also described by Stark et. al [1]. This Base-Data then has to be updated or extended with the Actual-Data of the respective Physical Twins. This principle of the Twofold of Twins is visualized in Fig. 2.

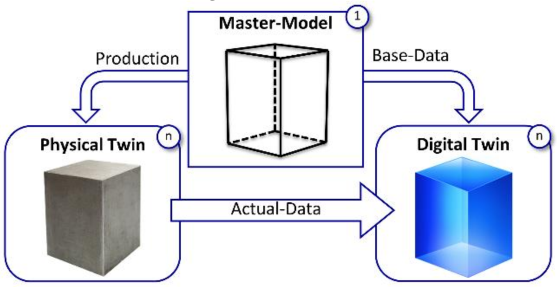

Fig. 2. General Visualization of the Twofold of Twins

In general, how this link between the Physical and Digital Twin is established and what kind information about the physical product are represented in the Digital Twin is not clearly defined but rather relies on the specific implementation and use case.

As presented in past works, one obvious example are geometric representations of the actual physical object, especially regarding small deviations from the originally designed CAD-model that occurred during the production because of imprecisions. Yet, also adjustments by the customer or changes over time, like wear and tear, may result in deviations. Depending on the implementation itself, the Digital Twin can be used to enable different innovative applications, like predictive maintenance or a detailed documentation of the usage of the product, which can be used for instance during the development the next generation of products. [19]

Product development methods, that benefit from available data of previous generations, like the modular lightweight design of aircraft cabins, would benefit from an implemented Digital Twin as well [12]. Besides this mainly geometric information, there are other possibilities of digital representations of a physical product, like an accumulation of sensor-data mirroring the very state of the product.

2.6. Digital Twins of Products Families

Applying the described concept of Digital Twins, not to a single product but to a whole product family, a few further adjustments have to made. As the structure of the product family and its variants can be modeled, the origin of each Digital Twin does not lie in the model of the product (variant) but one level above, in the Master-Model of the product family. This single Master-Model of the product family provides the basis for each product variant {1, 2, …, m} and its specific Master-Model. Similar to the datasets of the Digital Twins, the product variant Master-Models are identical in many aspects but differ in some manifestations and details. As stated in chapter 2.2, product configurators can assist the generation of the product variant's Master-Model. During the production, the physical product {1,2, …, n} is created based on these models. Likewise, these models can be used as the Base-Data to create the products Digital Twin when supplementing with acquired Actual-Data of the product during or after the production. Regarding geometric information, this can be assisted for instance using 3D-Scanners. [2,19,20]

From then on, the basic principle of Digital Twins as presented applies. To remain a Digital Twin, adjustments of the Physical Twin by the user and changes over time have to be regularly implemented in the Digital Twin as well. This overall concept is depicted in Fig. 3.

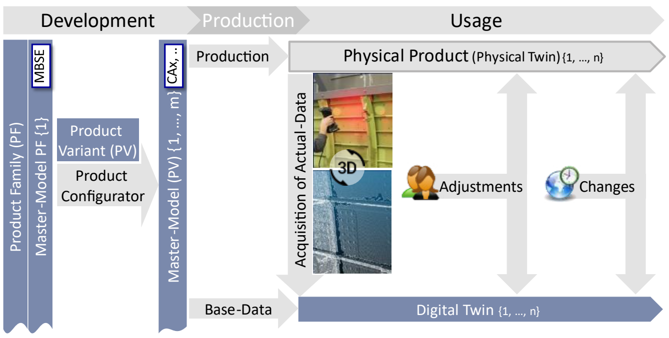

Fig. 3. The origin of Digital Twins in Product Family Design, c.f. [15]

Once the information is accumulated in form of a Digital Twin, they can be used for example to perform quality inspections at the end of the production or for many other applications during later life-phases. This link to the product family's information can also be used in later lifecycle phases, as it enables an ongoing flow of information about existing products back into the digital dataset of the product family, thus, enabling a multitude of more benefits. For instance, this information can be used during the development of new product variants or the next generation of existing ones. [19]

3. Digital Twins of Product Families in Aviation assisted by MBSE

While concepts of Digital Twins including their benefits, mainly applied to military aircrafts and focused on structural predictions, have already been presented, for example by Tuegel [21], this paper focuses on aircrafts in civil aviation and the relating circumstances and possible benefits. While some circumstances are alike, there are many differences between these two fields of aviation.

3.1. Digital Twins of Aircrafts in Civil Aviation

Connecting the previously presented topics and applying them to civil aviation, its special circumstances compared to other categories need to be considered once more. Unlike with many other products, aircraft undergo a much more vigorous measures in terms of maintenance, repair and overhaul (MRO) as they are literally taken apart every few years during C- or D-Checks.

Additionally, every approximately 7 to 8 years an aircraft is retrofitted with a complete or partly new interior. Also changed customer requirements of an airline can lead to the need to exchange an existing aircraft cabin and replace it with a new one. This alone has multiple effects on the concept of Digital Twins. The planning of the maintenance and retrofit procedures could benefit hugely if there was a Digital Twin of the specific aircraft with all needed information. Yet, effectively these processes are planned mostly based on established timescales, observations during smaller intermediate maintenances and generic geometric information. However, after years in service and many MRO-actions the actual geometry divers from the once produced airframe in many aspects. Especially during the retrofit, this often leads to problems fitting the new cabin modules into the existing airframe because the exact geometrics of the airframe are just known the moment the aircraft is disassembled. The design and manufacturing of the new parts however has already been finished at that time. These complications lead to the aircraft being grounded for a longer time, which increases the overall costs. The approach of using 3D-Scans to perform premature clash-analysis between the designed cabin and the specific airframe was already presented and represents a good use case for Digital Twins in civil aviation. [2,22]

The bigger maintenance checks could benefit from more detailed information about the actual state of the aircraft as well, as this would lead to a better planning of the overhaul activities for example using predictive maintenance approaches. [15,23]

Detailed information, as they might be stored in a Digital Twin of the specific aircraft would facilitate both these processes a lot. Although the origin of these information poses a challenge, the processes they would assist also provide an opportunity to acquire them. Because the aircraft is disassembled, both during the C- or D-Checks, as well as the retrofit at least partly, at this point in time the needed information could be acquired for example using 3D-scanning technologies. Even though the information can assist during this very process only to some extent, from then on, they can be used for all future processes of the specific aircraft. The information about newly installed or replaced parts can be gathered during their development, or prior to the actual installation. Ideally the accumulated information is assigned to the specific aircraft's serial number and managed by either the operator, or maintenance facility. The management of the resulting amount and variety of information however remains another challenge as besides the actual geometric or sensor data there are meta-information that needs to be incorporated likewise.

3.2. Assisting the data handling using MBSE

Even tough individually collecting this data for each aircraft quickly accumulates to big datasets, these datasets also share a commonality, as they each represent a similar product. This is similar to the situation during the product family planning, where the product variants of the product family also share a communality but differ in details. Weilkiens presented a method to model variants with SysML [24]. Based on this, Hanna et. al. presented an MBSE-approach that uses SysML for the methodical development of modular product families while ensuring data consistency [25]. This approach, as well as the experiences described in chapter 2.4, of assisting the data handling using MBSE lay the ground for an analogical approach regarding the holistic handling of aircraft datasets. Albeit in this case the bulk of information needs to be stored using classical content- or data management systems, the relations between single pieces of information or between datasets can be documented using system- or meta-models. An important aspect of this setup is to ensure a consistent relation between the MBSE-models and other files like CAD-models. In case of aircrafts, their individual manufacturer's serial number can be a good starting point of a distinct assignment. Nevertheless, a sophisticated and consistent structure of the repository is inevitable. The information about the product families might include a distinct ID of possibly available data-elements, supplemented by a defined schema to allow for various different types of data-elements regarding the same object. Often manufacturers already have such unique part-numbers in place, which also may be used for referencing specific parts. The combination of the stored information and the modeled meta-information allows the accumulation of datasets to be used in new ways: Because of the provided product family structure missing information of a specific aircraft can roughly be extrapolated from the master-model or adapted from another stored aircraft and used in the specific instantiated Digital Twin.

The actual state of a real aircraft is acquired and feed in the Digital Twin Instance of the specific aircraft where the information is stored or updated assisted by the known meta-information.

Based on Fig. 2 this further extended concept is exemplarily visualized in Fig. 4. The actual state of the real Aircraft is acquired, exemplarily shown by a 3D-Scanner (Fig. 4 left). This Actual-Data is then feed into the digital Instance where this time-specific information is either stored as a new dataset or used to update an existing one. While for instance geometric information, like 3D-Scans of part of an airframe, are stored traditionally, for the respective interrelationships like linkages or interfaces (Meta-Information) metamodels are used (Fig. 4 right).

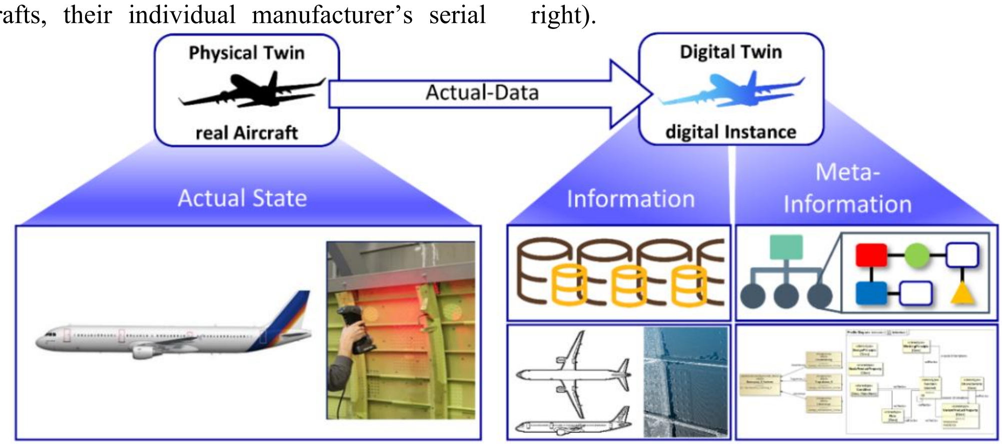

Fig. 4. The Digital Twin instance of a real Aircraft is based on classily stored Information and Meta-Information

4. Summary and Outlook

In this paper a conceptual approach to implement the concept Digital Twins to civil aviation, especially aircraft and aircraft cabins was presented for the first time. The approach to implement these Digital Twins is based on research in the fields of modular product family design, the tools and methods of Model-Based Systems Engineering. The basics of these topics were presented in chapter 2 before they were combined to form the overall approach in chapter 3.

While the shown example depicts this approach applied to a complete aircraft, the first step in the ongoing implementation is to apply it to parts of an aircraft, mainly those related to the cabin as well as the cabin interior itself. As presented in chapter 2.4 the foundation to do so has already been laid by past research activities. The already presented usage of 3D-Scans to improve the retrofit-processes of aircrafts represents just one of the use cases. Besides these mainly geometric-focused approaches, another possible application of Digital Twins is already partly in place, albeit in another context: Most aircrafts transmit a selection of relevant information about the state of the aircraft and many of its sensors live back to the airline's base using technologies like ACARS/VDL2. The content of the transmitted information is not enough to fully represent the aircraft in entirely but the airline already has a digital dataset of the most important parameters of each single of their aircraft. These information are detailed enough to plan smaller maintenance activities on the ground even before the aircraft has landed at its destination. [23,26]

Likewise, the US Airforce uses information about each flight mission of each airframe and applies, for example the encountered g-forces, to a digital representation of the specific airframe to document its sate as well as improve the maintenance planning. [21,27]

The presented concepts show that there are multiple use cases and already some partly implementations of Digital Twins in today's aviation, but also that there are more possibilities to be explored, and fields of applications to be implemented. The MBSE-assistance enables the utilization of the existing product families to facilitate the overcoming of the otherwise complex relations of aviation products. Thus, the presented approach enables the realization of Digital Twins as a groundwork to implement a variety of services and processes that will reduce failures and abbreviate long lasting and constitutive operations.

Consequently, the attainment of different aspects of the presented approach is part of recently started research projects and will continue for the coming years.

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