DEVELOPMENT OF A DIGITAL TWIN FOR AVIATION RESEARCH

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Abstract

The application of digital twins is increasing in several fields. Mirroring the current state of the asset and making predictions of the future state are the main purposes of digital twins. Inside the German Aerospace Center (DLR), an internal project is set up to find methods, technologies and processes for digital twins. Several institutes are contributing to the project, including institutes in the IT domain like the Institute of Software Methods for Product Virtualization or the Institute for Software Technology on one side, and the aviation engineering domain on the other side, e.g. the Institute of Flight Systems, the Institute of Composite Structures and Adaptive Systems and the Institute of Maintenance, Repair and Overhaul. In order to demonstrate the capabilities and identify new development opportunities of digital twins, three different use cases are defined. These use cases include the virtual product house, the virtual engine and the research aircraft. For the research aircraft use case, the digital twin can be seen as a research tool within the organization. The research questions of the project are addressing several information technology related issues like data formats, data sizes, data storage concepts, provenance, and security. Additionally, the project addresses the definitions of the digital twin, the digital thread, and the application layer as well as a common digital twin vision. The next steps in the project are the implementation and demonstration of first prototypes for the individual use cases. This paper gives an overview over the project results and the developments for digital twins. The aim is to digitally map aircraft and their components with all their characteristics and relevant data.

List of abbreviations

ADS-B	*Automatic Dependent Surveillance - Broadcast*
AR	*Augmented Reality*
CARA	*Computer for Advanced Research in Aerospace*
CPACS	*Common Parametric Aircraft Configuration Scheme*
DBMS	*Database Management Systems*
DLR	*German Aerospace Center*
FH	*Flight Hours*
GB	*Gigabyte*
HMI	*Human machine interface*
IT	*Information Technology*
M2M	*Machine to machine*
MBSE	*Model-based systems engineering*
MRO	*Maintenance Repair and Overhaul*
SQL	*Structured Query Language*
VirTriP	*Virtual Engine Plattform*
VPH	*Virtual Product House*
VR	*Virtual Reality*

1. INTRODUCTION

Data-driven value creation platforms are becoming increasingly important in the economy. One part of this is the digital representation of real existing assets. Solution key element is the creation of digital twins, which are supposed to store real behavior digitally in the best possible way. In order to derive the greatest possible benefit from digital twins, they must be equipped with intelligent functions, not only to represent a data store, but also to develop models and tools for the future from existing data. A wide compatibility, suitable interfaces and a stakeholder-neutral and independent setup are key requirements. One possibility is the prediction of wear or failure of the asset or a component. For this reason, the DLR has launched the internal project Digital Twin,

- which aims to explore the methods, tools, and processes for such digital twin and
- the provision of suitable digital twins for research aircraft to enable interdisciplinary data-driven research at DLR.

The main goals of the project are:

- Development of a vision and roadmap for a digital twin and its deployment.
- Definition of requirements and boundary conditions for a digital twin.
- Development and provision of the methods / resources (IT) required for the creation of a digital twin.
- Implementation of a digital twin with basic functionalities and demonstration using suitable use cases.
- Development of a roadmap and preparation of further projects on the digital twin with concrete alignment

2. PROJECT SETUP

The project started in January 2019 and will run for three years. It is subdivided into four main work packages, as shown in figure 1.

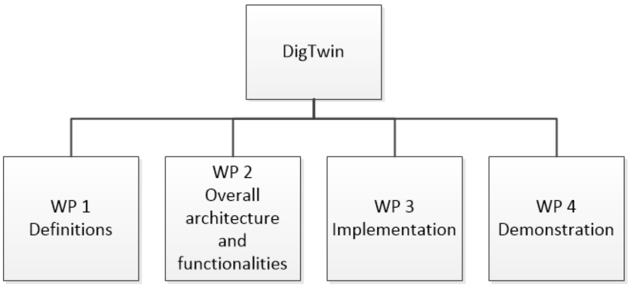

Figure 1: Project Setup

In the first main work package, a common definition and vision for digital twins in the DLR has been formulated and a suitable roadmap for their implementation has been defined. The elaborated definitions are presented in chapter 4. In addition, a literature review on the topic of digital twins from different perspectives was conducted. The following topics were considered:

- Data management systems
- Visualizations
- Manufacturing
- Model-based systems engineering (MBSE) for aircraft design
- Production engineering and
- Aircraft maintenance.

A brief overview of the literature review is given in chapter 3.

In work package two, the basics for the creation of a digital twin were worked out. The work package was divided into six sub-work packages:

- Data management
- Software interfaces
- Hardware basics and interfaces
- Data acquisition and provision
- Data analysis, development and forecast
- Import and export of components

The third work package contains the detailed implementation of the principles developed in the second WP. For the demonstration of the developed capabilities, the following use cases have been chosen:

- Research Aircraft
- Virtual Product House (VPH)
- Virtual Engine Platform (VirTriP)

The use case Research Aircraft can be considered as a research tool. In the DLR, the digital twin will be used as a platform for researchers to access and share existing data across departments and institutes. The other two use cases are regarded as research objects. As a research object, the main focus is to develop the processes, tools and methods needed for digital twins. The use cases are described in chapter 6.

The fourth work package contains the demonstration of the different versions of the digital twin and their functionalities at the end of the project.

A total of eleven institutes are involved in the project. They can be divided into aerospace engineers and IT experts. On the aviation institute side, the following institutes are involved in the project:

- Institute of Propulsion Technology
- Institute of Structures and Design
- Institute of Composite Structures and Adaptive Systems
- Institute of Flight Systems
- Flight Experiments
- Institute of Maintenance, Repair and Overhaul
- Institute of Test and Simulation for Gas Turbines
- Institute of System Architectures in Aeronautics
- Virtual Product House

On the side of information technologies the following institutes are involved:

- Institute of Software Methods for Product Virtualization
- Institute for Software Technology

3. STATE OF THE ART

For the project, a literature research was carried out under different aspects. A Scopus analysis on the topic of digital twins clearly shows the increasing importance of the topic in science. With the search term *(TITLE-ABS-KEY (digital AND twin))*, 3,905 documents were found (ref. to Figure 2). While prior to 2015, the number of documents per year is very steady, an exponential increase of publications can be observed for the last 5 years. Barth et al. subdivided the importance of the topic into three different stages. Having started with the formation stage until 2011 and having passed through the incubation stage up to 2014, the topic has reached the growth stage [1].

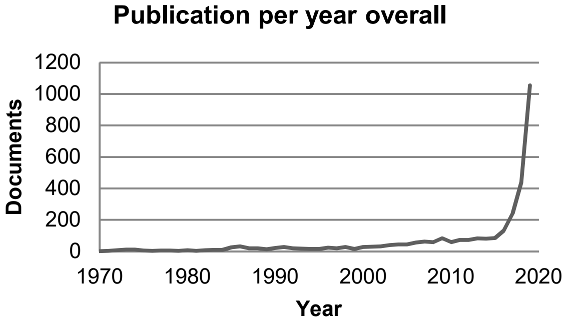

Figure 2: Publication per year for "digital twin"

Limiting the search term to aviation with the following search term *(TITLE-ABS-KEY (digital AND twin) AND TITLE-ABS-KEY (Aircraft OR Aviation OR Airline)* results in significantly less publications with only 193 documents (ref. to Figure 3). However, the development in the last five years is similar to the general trend.

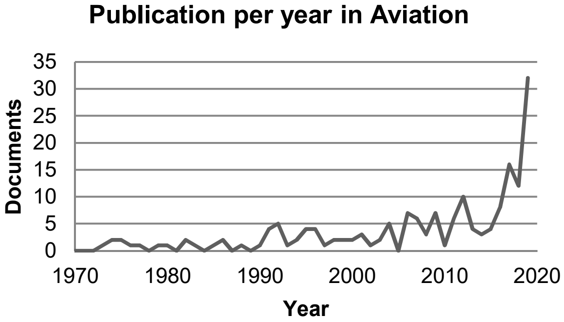

Figure 3: Publication per year for "digital twin in aviation"

In the course of the project, the state of the art has been examined from different perspectives by the respective specialist institutes. In this paper, we provide only a short overview for better understanding.

The first perspective reflects the state of the art in the aviation industry. All major aviation companies have been working on platforms for some time now, e.g. to enable the component wear prediction, in order to optimize their maintenance strategy. The most significant developments towards digital twins in the aviation industry are:

- Aviatar (Lufthansa Technik): An open platform that offers the variety of digital MRO products and services via numerous apps. [2]
- Skywise (Airbus): A common reference platform for all major airlines to improve operational performance and business results and to support their own digital transformation, respectively. According to the developing organization, the platform is already improving the performance of industrial operations, enabling the delivery of improved aircraft and equipment designs and better service and support offerings based on deeper insight into internal operational data. Currently, there are four application areas for customer maintenance, fuel consumption, safety, and labor. [3]
- Predix (General Electric): A solution which focuses on the acquisition and analysis of data from industrial machinery. It provides analysis on an industrial scale for Asset Performance Management (APM) and operational optimization by providing a standard method for linking machines, data and people. [4]
- PROGNOS (Air France Industries and KLM Engineering & Maintenance): A platform with focus on monitoring and analyzing the performance of aircraft systems and components to predict parts failures. [5]
- AnalytX (Boeing): A decision making assistant to optimize operations and to provide insight into the future of the product. This gives the user more time to evaluate, plan and manage solutions. It includes three categories of analytics-enabled, combinable products and services. [6]

All of the different plattforms have the problem of stakeholder borders, which restrict the plattforms to gain the highest possible usage out of data.

In production, a digital twin is used to support data recording, storage and processing. Typically, a distinction is made between a digital twin of the production system and the component. In manufacturing, measurement and production data are used in particular for quality monitoring or general observation of deviations. Kitzinger et al. [7] gives an overview of the various possible applications of a digital twin. Negri et al. [8] gives an overview of different definitions of the digital twin and their application areas in connection with cyber physical systems. Semantic models for data representation have proven to be particularly suitable for linking and accessing various manufacturing data. [9] The application of ontology for the control of sensors or the handling of sensor data is proved to be suitable by Dey et al. [10]. In the field of aircraft structure manufacturing, the need for a digital twin is very clear. Röpke [11] provides an overview of the networking of the vertical and horizontal value-added levels in the future manufacturing process of aircraft components and overall structures. Röpke also goes into more detail about the wishes and ideas of the “Airbus” company, which are to be achieved in production by using a digital twin.

To improve collaborative work between project partners from different departments of the design process, the DLR has been developing the data model CPACS. The Common Parametric Aircraft Configuration Scheme (CPACS) is a data model and communication platform that provides parametric descriptions of aircraft systems and design processes through establishing a common technical language. These systems and processes comprise

- Aircraft and their components (fixed wing aircraft, helicopters, engines, fuels, material data),
- Airlines,
- Airports,
- Flights,
- Missions,
- Study results and
- (Process) tool information.

As an example the individual aircraft components are assigned to a hierarchy and the links between them are defined. [12], [13] As this scheme is developed for the design process, a similar solution must be developed for the operation in the project digital twin.

The use of dedicated modern and suitable database management systems (DBMS) is indispensable for the realization of digital twins. According to [14], a DBMS should comprise the following functionalities:

- Data storage, retrieval and update
- Metadata description
- Support for transaction and concurrency
- Database recovery
- Access Management
- Remote Access Support
- Data Quality Management

A comprehensive ranking of different systems according to their current popularity together with information about the underlying technology can be found in [15]. The most prominent database management systems categories are relational DBMS and NoSQL-DBMS. Relational DBMS are an established standard and look back on several decades of continuous development and stabilization. They are based on tables with rows and columns. The rows of different tables can be linked via unique keys [16]. The established language for communication is the Structured Query Language (SQL). Well-known representatives are Microsoft SQL Server, MySQL, Oracle and PostgreSQL. A comparison of basic properties of current systems can be found in [17]. The basic idea of NoSQL systems is to move away from strict table schemas and to relax strict consistency requirements in favor of tailored data structures and communication concepts that can address certain problem classes particularly efficiently. On the one hand, there are large binary (and thus unstructured) data sets without links to each other such as model data or user profiles, on the other hand there are highly linked data, for example from social networks. Harrison [18] and Kleppmann [19] give a good overview of NoSQL systems. Four categories of NoSQL DBMS are currently distinguished: key-value stores, document-oriented DBMS, column-oriented DBMS, and graph-oriented DBMS. [13]

As a last point, possible visualizations for the digital twin were considered. This includes the review of a possible hardware for the implementation as well as the current status of realizations in the context of aircraft maintenance. Since aviation maintenance is a practical topic, the number of scientific publications is very low. Safi et al. [20] gave an overview of science, training and applications of augmented reality (AR) in aviation in his paper. In a previous work of DLR, a scenario where a remote expert visualizes the digital twin of an aircraft component [21], an airbrake, on the HoloLens was demonstrated.

4. DEFINITIONS

In order to efficiently develop a suitable architecture that can serve the needs of all the involved participants, a common understanding of the essential terms and their respective scope had to be defined in the project to align with other stakeholders at DLR. For this purpose, questionnaires were sent to the participating institutes in the project. The respective individual definitions were examined for similarities and subsequently consolidated. Among others, the following terms were defined:

- Digital thread
- Application layer
- Digital twin

Van der Walk et al. provide in their paper a wide-ranging literature research on the scope and meaning of the term digital twin. They clearly show that the term and the scope can differ significantly depending on the use case or the aim of the digital twin. In the analysis, the most frequent character traits of digital twins were shown for eight dimensions [22].

Table 1: Dimensions of a digital twin (based on [22])

Dimension	Characteristics
Data Link	Bi-directional
Purpose	Processing
Conceptual Elements	Physically Bound
Accuracy	Identical
Interface	M2M | HMI
Synchronization	With
Data Input	Raw Data | Processed Data
Time of Creation	Physical part first

4.1. Digital Thread

The consolidated definition of the digital thread was defined in the project as follows: *"The digital thread is a concept that represents a chronological storage of information and data for one or more physical or logical objects across product life cycles. The concept realizes a Single Source of Truth and allows a complete traceability of any data throughout the entire life cycle"*.

This means for us, that the digital thread is the connection between the digital aircraft (for example: digital design, test, and certification), the digital twin, and the data generated during operation, respectively.

4.2. Application layer

The application layer was defined in the project as follows: *"The application layer represents a collection of software tools for solving specific problems. The functionalities provided by this layer can range from simple monitoring to complex simulations and multidisciplinary optimization. Data necessary for the applications or generated by the applications are stored and provided via the digital thread. The application layer can also be opened for external tools"*.

In our case, the application layer contains the tools developed for the digital twins, which are necessary for data processing, data preparation, but also for scientific knowledge acquisition. The tools, however, do not necessarily have to run on the same computer.

4.3. Digital Twin

The definition of the digital twin, which was developed at DLR, reads as follows: *"The Digital Twin is a uniquely identifiable digital representation of a physical or logical object for one or more purposes. It is irrelevant whether this object will only exist in the future, actually exists or no longer exists. The digital twin links information and data stored in the digital thread in order to be able to represent the characteristics, status and behavior of an object with regard to different aspects. In addition, the Digital Twin has access to the application layer and thus enables interoperability between applications such as models, simulations and predictions in order to functionally describe and predict the object. The Digital Twin can be hierarchically composed of several Digital Twins and reference other Digital Twins. As long as the Digital Twin represents a physically existing object, the current state of the physical object is synchronized into the Digital Twin in a timely manner"*.

In the following a comparison with the dimensions of van der Valk et al. is done. The data link dimension is also bi-directional in the DLR definition, as interoperability is established between the digital twin, the digital thread and the application layer. The purpose is also the processing of models, simulation and predictions. The dimension conceptual element differs a little bit. According to our definition, the digital twin can also be used for a logical model, and therefore it is not necessarily physical bound. The accuracy is the same in both definitions; the digital representation should be identical. The interfaces are not fully described in our definition, but machine to machine (M2M) part could be seen in the application layer and its interfaces. Also the human machine interface (HMI) is part of the project, where virtual reality (VR) applications and front ends are developed. The last three dimensions, synchronization, data input and time of creation are also congruent with the characteristics of [22]. Therefore, the definition of the DLR is congruent with most of the definitions which were part of the analysis of [22].

5. FIRST PROTOTYPE

In work package two, a first prototype of a digital twin for research aircraft was developed. For the prototype development an example data set from the DLR experimental aircraft with the registration D-ATRA is used. Since the data structure of the data acquisition systems are similar, this example is applicable to other DLR aircraft In this first prototype, basic functionalities were developed to enable the development of applications for the digital twin. Among other things, this involved:

- Data storage,
- Interfaces,
- First visualizations,
- Linking of databases,
- Read in data and
- Creation of surrogate models on the basis of real data.

To create an effective research tool at DLR, several institutes are directly involved in the development. One goal is the creation of a single source of truth, which promises the necessary benefits for different users via different applications or interfaces. For example the Institute of Maintenance, Repair and Overhaul will process system data to conduct research on prognostic maintenance, while the Institute of Flight Experiments would like to visualize the test data and the flight trajectories after the performed flight. Thus, the requirements of the these institutes are different, but both require the same data in many parts. The digital twin should avoid duplication of data sets.

6. USE CASES

In this chapter the three different use cases in the project are presented. The wide spread of the use-cases is chosen, to develop the different processes, methods and tools to identify the highest possible usage within the DLR.

6.1. Research Aircraft

The use case Research Aircraft includes the development of digital twins for the various flight test aircraft of the DLR. Research aircraft are usually equipped with basic and additional experimental measurement systems, which provide a huge variety and volume of data. At the same time, models or calculations have partly been developed in various research facilities, which either extend the digital twin with applications or store the acquired data back in the digital twin. The data and capabilities are made available to researchers at DLR via various interfaces. The approach is intended to enable data-driven research in the aircraft field across all institutes in the future and to ease the process of data provision and rights management. It is also possible to transfer results back to the digital twin. Furthermore, the digital twin should offer the possibility to outsource computationally intensive programs to the DLR cluster CARA. [23] An overview of the DLR research aircraft can be found in [24]. For the first prototypical developments, the project is concentrating on the A320 D-ATRA, as a lot of data has already been collected for the aircraft over its life cycle. Approximately 3,000 text files with the different sensor values are created per flight. This results in a memory requirement of 2.4GB/FH for this research aircraft. On the one hand, this data shall be used for research questions. On the other hand, the digital twin shall enable visualization. Figure 4 shows the basic interaction between the digital twin, applications and various databases. The fusion of data with other databases can create new opportunities for research. For example, by integrating weather, performance and ADS-B data in combination with research aircraft data, machine learning models could be developed that can determine the behaviour of parameters for flights where the whole parameter set is not available.

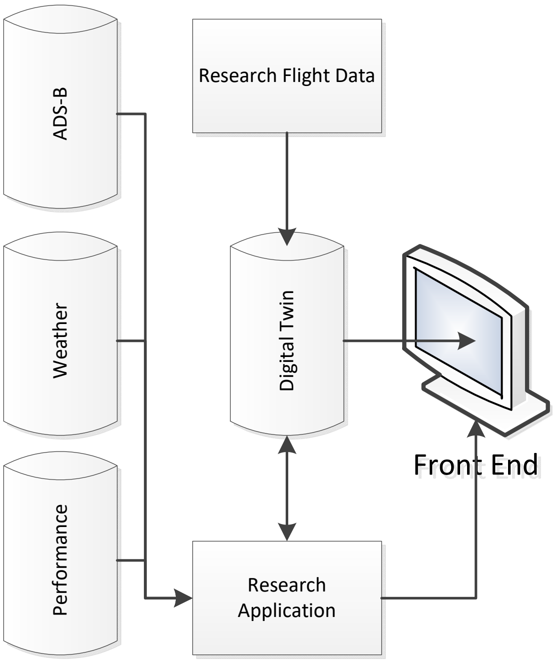

Figure 4: Prototype Principle

The combination of test flight data with external data allows, for example, the development of tools that generate data for loads analysis on the basis of ADS-B data as described by Schulz et al. in [25].

6.2. Virtual Product House

The Virtual Product House (VPH) deals with the digitalization of the development process in order to develop aircraft more efficiently and cost-effectively. This includes virtual testing and simulation-based certification(ref. to Figure 5). [26] The project digital twin focusses on the production and the operation of the asset. Within the VPH Project the digital representation is called digital aircraft, which reflects an aircraft type with a specific desing. In production the digital representation is for one specific serial number. From this point the nomeclature within the DLR is the digital twin, which is covered in the indentical named project.

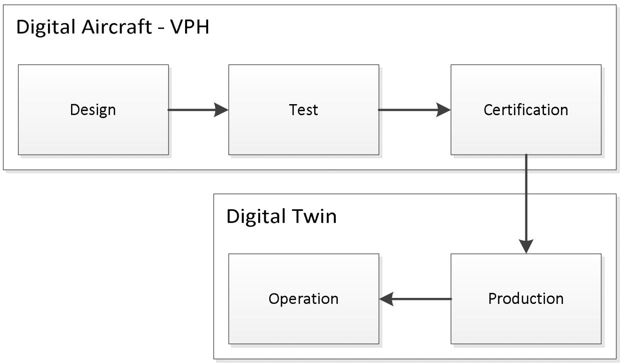

Figure 5: Interaction VPH - Digital Twin

In this project, the entire digitized process is carried out as a common use case using the example of a flap [27]. In the digital twin, two different areas are considered here. On the one hand the interface from design to production and on the other hand the operation of the aircraft or component. The production module focusses on the production of a composite builded panel. In this modul, the production as well as the inline quality insurance will be connected to the digital twin. On the other hand the operation consists of four modules (ref. to Figure 6).

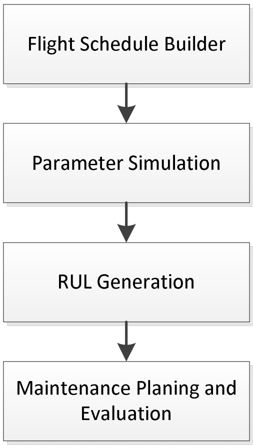

Figure 6: Digital Twin Operation Module Use - VPH

In the first module, a flight plan is created on the basis of the mission profiles transmitted from the VPH and a statistical database analysis, which includes the dispersion of real flown operational profiles. At the same time, it should also be possible to import real flight plans in order to enable evaluation at airline level. In the parameter simulation, a simulation for the flights from the Flight Schedule Builder will be performed based on the DLR test flight data. Only models for the parameters needed to simulate the load on the landing flaps will be developed. These loads will be passed on to the Remaining Useful Life module, where test stand experiments with the pseudo-real data will be performed for individual components of the flap system. The results are then used to derive the forecast parameters, which are processed in the Maintenance Planning and Evaluation Module. Here, the prognosis based task is integrated into the maintenance strategy for the entire aircraft and then the impact is evaluated.

6.3. Virtual Engine Platform

Within the DLR project "Virtual Engine Platform" (VirTriP), the foundations for this virtual engine platform are being laid in close multidisciplinary cooperation between various DLR institutes. In its final form, the platform is intended to offer the possibility of developing, designing and optimizing engine components and assemblies in adapted levels of detail up to high-fidelity analysis in a multidisciplinary manner, taking into account the effects on the overall system. The individual disciplines of structural mechanics, fluid mechanics, thermodynamics and aeroelastics must be considered comprehensively and their respective interactions (e.g. flow-structure interaction) as well as the interaction of the components (e.g. between the combustion chamber and turbine) must also be taken into account in the future. In a first step, the "VirTriP" project will provide a high-fidelity view of the turbine, while the remaining components of the engine will initially be displayed with reduced accuracy (low-fidelity). For validation, DLR's own NG-Turb turbine test rig in Göttingen will be used and its turbine rig will be integrated into the virtual generic engine. The virtual turbine will be calibrated with the measurement data collected at the test stand. Subsequently, the other engine components will be made available in high fidelity, so that the platform should be able to simulate the operating behaviour and life cycle of an engine in service in detail in the long term. [28]

Reitenbach et al. [29] showed the connection between the virtual engine and the digital twin via the digital thread (ref. to Figure 7). In this use case, the project is also developing methods to map the operational life cycle of engines, similar to the use case Virtual Product House stated before.

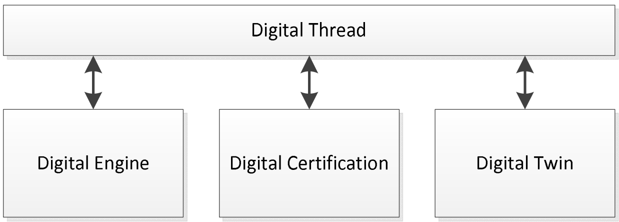

Figure 7: Interconnection of digital engine and digital twin (based on [29])

6.4. Combination of Use Cases

The applications cannot be considered completely separate from each other. The VPH and VirTriP projects follow a similar approach. Therefore, similar possibilities arise in the design of the use cases in the Digital Twin project. In both cases, a representation of a virtual asset is created, which is to experience certain influences over its life cycle. At the same time, the first findings that can be gained from the application of the Digital Twin of the research aircraft are already being applied in the use cases. One example is the extraction of different parameters and their variation for the flap deflection (ref. to Figure 8).

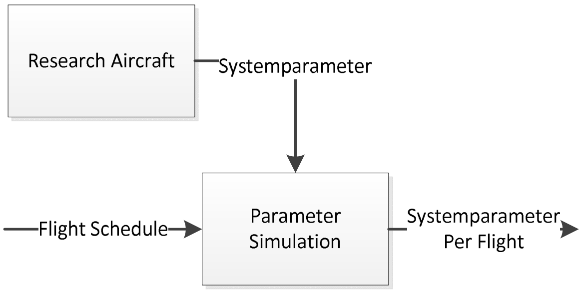

Figure 8: Interaction of Research Aircraft and VPH - Parameter Simulation Module

7. CONCLUSION AND OUTLOOK

This paper presented an overview over the DLR internal project Digital Twin. The project has just reached the halfway point. The work packages one and two are completed. Work package one focused on definition and the state of the art. The definitions of terms within DLR were presented in this paper. Afterwards a short form of the state of the art was presented. In the second work package the theoretical foundations for the development of the digital twin were worked out. The activities now focus on the implementation within the three use cases. In the next one and a half years, the different digital twins will be developed and prototypes will be demonstrated. The approach will enable the DLR to conduct data driven research based on different data sources.

Acknowledgement

The contents of the project and the definitions were developed with the support of all project participants. Employees of the following institutes have worked on the project: Institute of Software Methods for Product Virtualization, Institute for Software Technology, Institute of Structures and Design, Institute of Composite Structures and Adaptive Systems, Institute of Flight Systems, Institute of Maintenance, Repair and Overhaul, Institute of Test and Simulation for Gas Turbines, Institute of System Architectures in Aeronautics, Virtual Product House, Institute of Propulsion Technology and Flight Experiments.

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