# Digital Twins of existing long-living assets: reverse instantiation of the mid-life twin

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**Abstract**

The added value of long-living assets declines during their lifespan, especially if they do not undergo regular planning-intensive maintenance and retrofits. Here, the Digital Twin (DT) concept can support by representing the physical asset's most recent state, typically based on data and information from product creation. However, in the depicted domain, the stakeholders of the product's Mid-of-Life often do not have access to the early phases. Therefore, as often presented in current concepts, creating a holistic Digital Twin is not feasible. Instead, in the Mid-Life phase of long-living assets, only a use-case-specific and demand-actuated Digital Twin is attainable. This instantiation requires a solid procedure, which will be elaborated on in this work.

**Keywords**

*digital twin, long-living assets, retrofit*

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## 1. Motivation

Long-living assets are often characterized by high value and complex structures on the technological and system level, as well as multiple and changing involved stakeholders in roles like the designer, manufacturer, owner, maintainer, or retrofitter. Therefore, continuous Product Lifecycle Management (PLM) and its subordinate topic, Product Data Management (PDM), face numerous data-intrinsic challenges such as the level of detail and model fidelity but also stakeholder-interrelated ones like accessibility or confidentiality [1].

Maintaining highly sophisticated and ever-changing systems or integrating new components requires solid planning and engineering efforts in the Product Usage phase. These tasks rely on a comprehensive digital as-is data basis, also known as the asset's Digital Twin (DT), contrary to the available data and information in practice. Especially for long-living assets, the product's Mid-Life stakeholders usually do not have sufficient access to information from the early phases caused, e.g., by market-based segregation of the OEM and subsequent service provider or by data that originated before the current rise of the importance of digital data and the technological ability to handle and also exchange it [2].

Typically, DTs are based on knowledge and information derived from the product's early lifecycle phase that must be constantly updated with data, often sensor-based acquired, to form the product's as-is or current state [3]. Therefore, non-continuities in the data flow, thus missing necessary information in the product's Mid-Life, require a retrospective acquisition and creation. In this work, the result of this procedure is called the *Mid-Life-Twin (MLT)*, as depicted in Figure 1. This work will elaborate on an approach, a process model, to instantiate this Digital Twin. The main objective is not to establish the MLT as a new term but to indicate the deviation between the Digital Twin concepts commonly defined in the literature (s. Section 2.2) and the practice of instantiating DTs for long-living assets in different domains, independent from the product creation.

Besides the usage, activities' objectives in a product's Mid-of-Life (MoL) are usually the asset's life extension and preservation. Some strategies include replacing, refurbishing, maintaining, or de-rating [4,5]. In contrast, the activity retrofit updates the asset with new technology and innovations, so essential to keep a long-living asset profitable and sustainable – benefiting not only the owner but also the resource-limited environment. Out of the MoL activities, retrofit usually requires the most comprehensive digital replica of the asset; therefore, this work's scope is constrained to this activity.

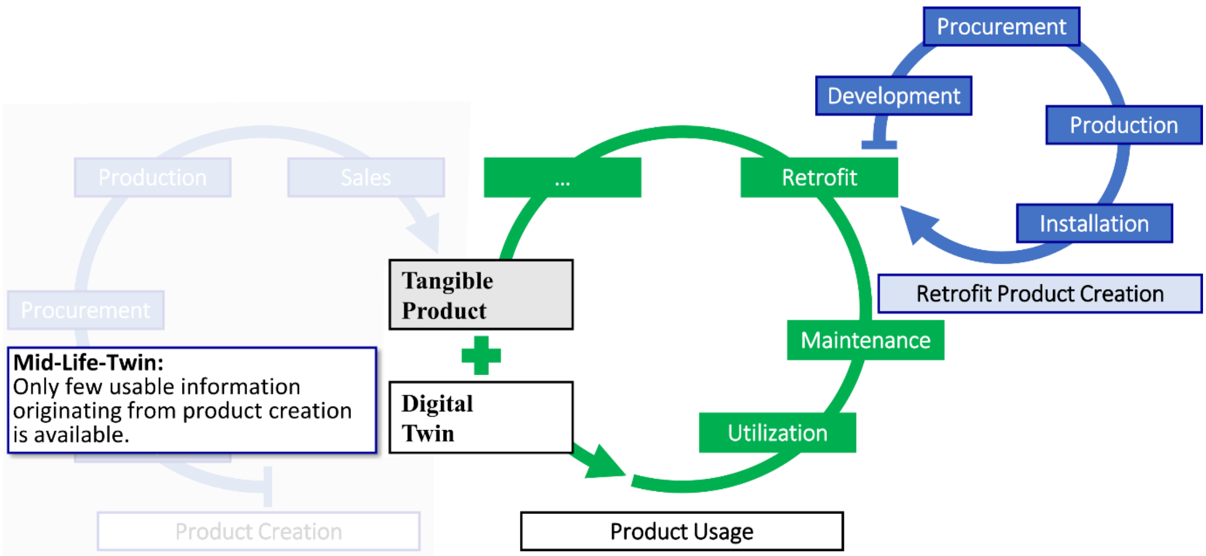


Figure 1: The use case and challenges of the *Mid-Life-Twin (MLT)* (derived from [6]).

This work is structured as follows: First, in Section 2, related work is presented, covering retrofit examples in different domains, referencing the standard Digital Twin definition and a common process model in Data Science used to frame the subsequently presented approach (s. Section 4). In Section 5, the derived process model is applied to an example use case in order to demonstrate its capabilities.

## 2. Related Work

### 2.1. Retrofit of Long-Living Assets

Retrofit as an asset's life extension driver, increasing its added value or decreasing its environmental emissions, is applied in different domains, but primarily for long-living assets where the sub-systems technology evolves faster than the asset itself and modifications are more economical than the disposition or rebuilding from scratch.

An example of the last driver is building retrofit with objectives like introducing energy-saving technical measures, e.g., increasing heat insulation performance [7]. Digitizing, managing, and using a building's data in its complete lifecycle is subject to Building Information Modeling (BIM), similarly to the concept of PLM. Since, especially for long-existing buildings, not all necessary data is digitally available, data acquisition by, e.g., laser scanning, is a core challenge in as-built BIM [8] that also includes generating model-based and linked information based on the 3D scans [9]. The data and information gap in BIM for new construction projects is far less than for existing buildings due to the recent awareness of continuous and collaborative data management. For existing buildings, technical, cost, organizational, and legal challenges or missing or obsolete data inhibit a consistent BIM [10].

The need to acquire the as-built environment in production plants or factories is closely related to the previous examples. Similar to buildings, all these assets have their unique history and lifecycle, where the creation of an up-to-date digital production system twin enables various planning processes digitally, like retrofit and refurbishment [11]. An "as-is" or "as-build" (terminology depends on the domain and the point in time of expected changes) data collection is used in different domains in the context of retrofitting. Examples are, e.g., the naval [12], offshore [13,14], and aircraft [15,16] industry, using 3D scanning technology and subsequent processing strategies. Besides the sensory-based data acquisition, in this work's proposition (Sec. 4), an overview of data collection methods to bridge the outlined gap of missing data between an asset's initial and later in-life phase will be presented.

### 2.2. Digital Product Twin

The *CIRP* Encyclopedia *of Production Engineering* defines the Digital Twin (DT) as "a digital representation of a unique active product […] within a single or even across multiple lifecycle phases", where the product is either a tangible/intangible asset or a service [17]. In practice, the holistic, interconnected representation of the complete product or asset is not necessary or feasible. Digital Twins serve purposes and thus must only represent the needed component and (sub-)system [18]. According to the previously cited references and common understanding found in literature, the DT is based on models (Digital Master) from the product's development (BOL) [3], as depicted in Figure 2. Thus, there is an intrinsic need for a Digital Master to instantiate a Digital Twin for the respective asset.

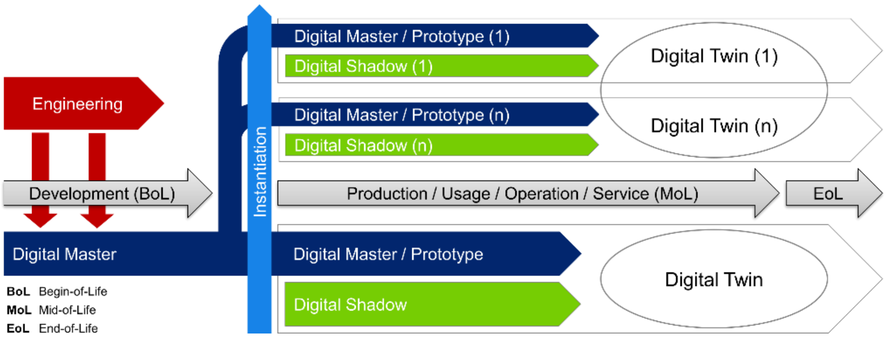

Figure 2: The Digital Twin Concept (based on the illustration by [3]).

Contrary to this continuous concept in terms of the life phases, within the presented scenario of this paper, the information from the Engineering phase (red arrows) at the Begin-of-Life (BoL) does not exist and, thus, the Digital Master needs to be created differently. Previous Section 2.1 outlines examples from different domains, where data collection and subsequent data modeling are one of the main tasks in deriving and instantiating an asset's DT, also termed Twinning. For this activity, in Section 4, a process model from analysis to collection and data preparation is presented.

### 2.3. Learning from Data Science

Due to the challenge regarding the data collection and processing the scenario in this work contains, a view on domains frequently facing similar challenges stands to reason. Subject to Data Science is handling data in high volume, e.g., datasets containing millions of entries, using defined concepts and procedures. Usually, data is categorized as structured, semi-structured, or unstructured data [19] and characterized by the *5 Vs of Big Data* (volume, variety, velocity, validity, veracity, and value) [20].

One of the most applied process models in Data Science is the *CRoss-Industry Standard Process for Data Mining* (CRISP-DM), that "encourages best practices" application- and industry-neutral, dividing the data mining process into six phases: business understanding, data understanding, data preparation, modeling, evaluation, and deployment [21]. Within these six phases (s. Figure 3), the model proposes different subordinate steps, e.g., *Determining Business Objectives* or *Collect Initial Data*, that the operator performs data- and demand-specific. The model defines a best practice on a structural level; the specific formulation of actions executed in a single work step and task is up to the user. The model advises what needs to be incorporated in general. That also allows for the addition of custom steps and extension of given tasks and procedures. Therefore, CRISP-DM is broadly accepted and implemented worldwide [22]. Intentionally, the process model refers to the steps of data mining, extracting information, and discovering patterns in large datasets. Section 4 will show that the model also suits our proposed approach due to its flexibility to fit various analytic tasks.

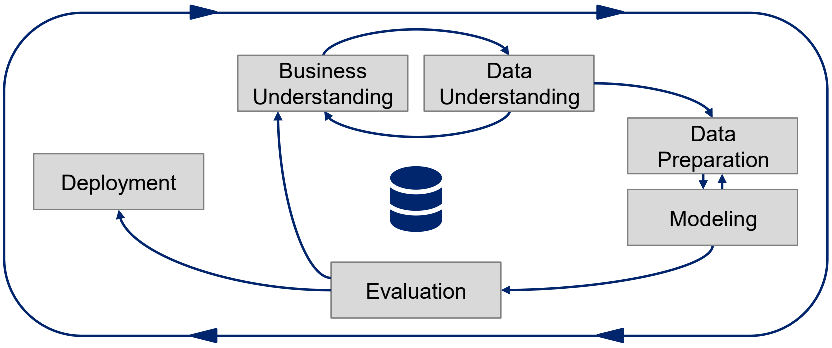

Figure 3: The CRISP-DM process model [21].

## 3. Methodical Approach

A representative and field of application for the depicted scenario were identified within aviation. The basic situation was analyzed more closely in cooperation with a leading maintenance and retrofit company. Especially the availability and necessary data and information to plan and perform aircraft-cabin conversions were considered. In Section 5, this use case is presented. An elementary part of the presented work was to frame the process with CRISP-DM into an overarching process model feasible to be established and form a baseline adaptable to other Digital Twin use cases.

## 4. Process Model

This section derives a general process model of instantiating a Digital Twin in an asset's MoL (mostly) independently from its BoL phase. There are primarily two DT design concepts: data-based and system-based [23]. The first focuses on data and its modeling, e.g., in IoT platforms like PTC ThingWorx [24], with the primary objective to structure and link sensory-based gathered information in data models without extensively modeling the asset's system characteristics. In contrast, the system-based design process starts with modeling the system of interest at, e.g., its logical, physical, or functional level. Herefore, an engineer needs a much more in-depth technical insight and understanding [23]. Besides isolated system- or data-driven modeling, combinations and linkages are required depending on the requirements' extent of the twin's purposes [16].

Since the data-driven approach is usually top-down (from data to the asset's insight), compared to the system-driven design process (bottom-up), and the pre-requisite of missing knowledge from the BoL, the process model follows the data-driven design approach. However, it indeed allows for later system or discipline-specific model integration.

In order to follow the data-driven approach, the procedure is framed by utilizing CRISP-DM (s. Section 2.3) and its six phases as a superordinate procedure to derive the Digital Master and Digital Shadow (s. Figure 4). The individual tasks will be formulated and extended in the following sections while focusing on the specific challenges of the Digital Twin's reverse-instantiation, identifying required but missing information, and acquiring additional data using, e.g., re-engineering processes.

| 1. Business Understanding | 2. Data Understanding | 3. Data Preparation | 4. Modelling | 5. Evaluation | 6. Deployment |
|---|---|---|---|---|---|
| a. Determine Business Objectives<br>b. Assess Situation<br>c. Determine Goals<br>• Identification of required resources<br>d. Produce Project Plan | a. Collect Initial Data<br>b. Describe, Explore, Verify<br>c. Analyze Completeness<br>• Identification of missing data<br>d. Acquire Additional Data<br>• External Collect<br>• Manual Acquisition<br>• Sensory-based Acquisition | a. Select Data<br>b. Clean Data<br>c. Construct Data<br>d. Integrate Data<br>e. Format Data | a. Select Modelling Technique<br>b. Generate Test Design<br>c. Build Model<br>d. Assess Model | a. Evaluate Result<br>b. Review Process<br>c. Determine Next Steps | a. Plan Deployment<br>b. Plan Maintenance/ Monitoring<br>c. Produce Final Report and Review Project |

Figure 4: Process model to instantiate the MLT (highlighted in green: changes to the CRISP-DM model [21]).

### 4.1. Business Understanding

The *Business Understanding* phase is the upstream point aiming to define the overall project from a business perspective up to **Producing a Project Plan**. In the steps, **Determine Business Objectives** and **Goals**, the DT's value-adding application(s) must be defined while constraining the scope to specific achievable goals based on the application(s). An application may aim at monitoring, simulation, prediction, or verification [25]. For the chosen application, a discipline expert must then define the necessary models and needed data while also

**Assessing the Situation**, which means gathering everything by inventorying available data resources to software. Without looking into the data, the goal is to determine everything already at hand.

### 4.2. Data Understanding

With the start of the second phase, *Data Understanding,* data will be accessed for the first time. Closing this phase, everything needed is available, although the data might still be unwrought. CRISP-DM includes four steps starting with the **Collection of the Initial Data** and ending with the **Verification of the Data Quality**. In between, the collected and loaded data will be analyzed during the steps **Describing** and **Exploring**. At this point, all easily accessible data sources have been collected, analyzed, and verified. In the context of the MLT, the presented procedure extends CRISP-DM by adding two subsequent steps: **Analyze Completeness** and consequently **Acquisition of Additional Data**. Instead of integrating these in the other *Data Understanding* steps, they are classified as novel to emphasize the subsequent execution to prevent redundant data acquisition. Since the original *Data Understanding* steps are straightforward to adapt, the following scope is constrained to the two newly added ones.

### 4.3. Analyze Completeness

The user defines in the **Determine Goal** step all required resources for the necessary discipline-specific models, e.g., a geometric Boundary Representation (B-rep) or a logical control model (s. [26] for further examples), based on the MLT's specific application. All accessible data were collected and analyzed within the previous steps after identifying the easily available data silos. In this phase, the user must dive into the data itself and assess whether all needed information can actually be drawn from the given resources. The user can continue with phase 3 of the process model if all necessary information is already available. Otherwise, the identified gap must be closed by proceeding to step (2.d.) – the acquisition of the missing data and, thus, the main task required for the reverse instantiation.

### 4.4. Acquire Additional Data

While some information may already be available, e.g., from previous projects or applications, there is a need to acquire additional data. This phase can be categorized into three main groups: external collection, manual and sensory-based acquisition. However, how the additional information is acquired depends on the data and the new resources that can be identified and accessed.

Some information may be easily acquired in terms of cost and effort by **requesting** them **from external** stakeholders, like manufacturers or suppliers, e.g., delivered in the form of unstructured textual data or even modeled ones like a CAD file. However, in the case of long-living assets, data and information often may not be accessible, either because of intellectual property regulations or more apparent ones, e.g., the original suppliers are not enterprising anymore.

If the asset is accessible, some information may be **acquired manually**, e.g., visually or using simple measuring devices. Besides much other information, simple geometric information or a Bill of Materials (BOM), ideally with serial numbers, can be acquired this way. Any operator with physical access to the relevant area of the asset can generally perform these manual activities with or without the need to take it out of operation.

If data of more volume, velocity, or variety is necessary, **sensory-based acquisition**, e.g., using 3D-scanning technologies, can be a data provider. However, access to the asset for a longer timespan and probable taking it out of operation is required, as the acquisition or sensor installation processes take time. Additionally, this acquisition is not finished with the scan itself, but the data needs to be processed further. The VDI 5620 "Reverse Engineering of Geometrical Data" [27] is a guide for performing this task as it also considers factors like accuracy, processes, and required hardware; recommended if the operator requires deriving, e.g., an asset's geometric model.

While the acquisition strategy depends on the application, model to derive for the Digital Master, type of data, and accessible sources, as introduced in Section 2.3, data science distinguishes between structured-, semi-structured, and unstructured data. This taxonomy can guide a discipline expert in choosing an acquisition strategy depending on the type of data. A generic overview of acquisition strategies for different domains and their respective constraints is out of this work's scope. Instead, an example overview showing a selection of acquisition strategies in the example use case is depicted in Figure 5. Eventually, with additional data acquired, a loop back to (2.b.) in the process model is advised to ensure once more that everything needed is available and sufficient to realize the application.

### 4.5. CRISP-DM Steps 3-6

With the beginning of phase 3, all needed data is available, maybe still unwrought, without context, and not model-based. Phase 3 (*Data Preparation)* includes activities to select the final set of data, filter unnecessary, create data context to gain information, and integrate as well as format everything [21]. For example, the operator may extract the necessary assembly modules from CAD files and export them into another file format. Also, phase 3 will, e.g., include steps of the previously mentioned VDI 5620: postprocessing, data fusion, and registration. Unstructured or semi-structured data need context to derive information and create the necessary data models. For example, textual information from ill-posed modeled files, e.g., PDF files, must be extracted and stored in data models embedded in databases.

In phase 4 (*Modeling*), this now well-formatted and organized information can be used to actually create the required cohesive model representing the digital asset with all its needed facets – the Digital Twin is being instantiated. The models form the Digital Master, while the Digital Shadow consists of the parameters or data that make the Digital Twin an asset's distinct digital instance. Overall, phase 4 includes the **Selection of the Modeling Technique**, **Building the Model**, and **Assessing the Model**. As a guide in choosing a tool, Qi et al. give a comprehensive overview of enabling tools for these activities, including various software capable of geometric, physical, rule, or behavioral modeling [25].

Within the scope of the original CRISP-DM, the next phase is the *Evaluation* of the resulting model facing the overall objectives. In this scenario, this is translated into evaluating whether the resulting model includes all information to fulfill the Digital Twin's application's need defined during the *Business Understanding* phase. In case of failures, loopbacks to the first phase (*Business Understanding*) may result.

Formalized following CRISP-DM, the last phase describes the *Deployment* of the twin's applications and services. The tools will depend on the model types and connection capabilities between the physical-digital or digital-digital spaces (s. [25] for an excerpt on market-available software).

## 5. Example Use Case

An example use case for the presented *Mid-Life-Twin* is the retrofit of an aircraft, during which a part of the cabin shall be updated with new equipment. In order to reliably plan the new cabin layout errorless, minimizing aircraft ground times, an as-is digital representation of the aircraft is required. In the scenario, a third-party company performs the retrofit, as usual in this industry, and the last considerable modification as well as the asset's product creation are more than a decade ago. Therefore, a comprehensive digital representation of the specific aircraft is missing. The aircraft operator plans to perform all following modifications in cooperation with one selected retrofit company. The instantiation of the MLT is intended to allow for easier planning of the current and future modifications and maintenance works.

The use case and twin application are defined within phase (1) of the presented process model. Based on prior modifications, the needed models and information are identified: mainly geometric details and information about the relevant aircraft system interfaces of the specific instance, especially in the area near the modification. Then, it is identified that the retrofit organization already has some generic information about the type of aircraft available (1.b.-c.).

During the first steps of phase 2, the available information is analyzed, resulting in a general overview of the type of an aircraft's critical geometries and dimensions. However, it is also identified that the specific aircraft does not match the generic descriptions because of prior modifications and maintenance (2.b.). Thus, more information about the asset's actual state is required before a representative geometrical and descriptive model can be created.

Within the step of **Analyze Completeness** (2.c.), a list of the needed information to plan the new cabin and modification is derived and categorized by data type. Subsequently, in step (2.d.), different strategies are used to acquire mentioned information. A representative overview of acquisition strategies is depicted in Figure 5.

| | | external collection | manual acquisition | sensory-based acquisition |
|---|---|---|---|---|
| **structured data** | | | | |
| IDs | aft-lavatory model and manufacturing ID | provided by aircraft-owner | verified during inspection | *not feasible* |
| quantities | number of rows affected by modification | | counted via visual inspection | *not feasible* |
| simple geometrics | distance between last row and exit | | measured during inspection | |
| ... | ... | | | |
| **semi-structured** | | | | |
| datasheets | lavatory products datasheets | provided by the manufacturer | *not feasible* | *not feasible* |
| layout plans | cabin layout, interface definitions | provided by the aircraft-owner | *not feasible* | *not feasible* |
| ... | ... | | | |
| **unstructured data** | | | | |
| full geometrics | 3D-Scan of airframe in critical areas | | *not feasible* | performed as per VDI 5620 during modification |

Figure 5: Overview of selected example acquisition strategies used in the described use case.

After the data and information are acquired using different strategies, everything is analyzed to ensure sufficient quality and all required resources are available. At this point, the application-specific reverse-instantiation is started by following the subsequent phases and combining all available information into an aircraft-specific representation – the Digital Twin. Then, data and information are made available to engineers using state-of-the-art PLM software. These can also update the model with new data based on the planned modification. However, the documentation of interdependencies between data and the aircraft schematics like known structure can be further improved, e.g., by using system models, as already presented in past related work [16].

## 6. Conclusion

In contrast to common Digital Twin definitions in the literature, in the case of long-living assets, often a third party needs to instantiate and then update the asset's digital counterpart without much prior data and information. Then, data handling, one of the most crucial aspects of Digital Twins, becomes even more challenging since the presence of a single data and information source is unlikely. This work outlines the data and information gap in this scope and presents a procedure framed by the CRISP-DM process model originating from Data Science. So, the reverse instantiation of a Digital Twin in the concept of the *Mid-Life-Twin* is the retroactive reconstruction of the necessary information to create the digital representation of the physical asset. In essence, this includes the analysis of the needed data for the retrofit, analyzing and collecting information available from general knowledge or the product creation, and identifying mismatches and differences between these two tasks to select appropriate methods to fill this gap. With an example at hand, the two new steps in the *Data Understanding* phase were discussed in more detail. Future work might focus more and elaborate on phases 3 to 6 and their individual steps. However, a more detailed distinction between domains and their specific applications will be inevitable.

As in most publications about Digital Twin applications, generic or overarching process models could be further developed and outlined to create, instantiate, and update a Digital Twin methodically. As CRISP-DM is a guideline to encourage best practices to solve problems in Data Science, a best practice in the form of a process model to assist the creation, instantiation, constant update, and usage of Digital Twins would benefit the industry and research community. This work presented an approach to a process model for creating and instantiating the *Mid-Life-Twin*.

In addition, many software tools on the market enable various functional Digital Twin aspects. However, the various applications make choosing or combining the right ones challenging for any operator. Hence, considering software selection guidelines in these process models is suggested. As the reverse instantiated Digital Twin is based on a variety of single information, the documentation and usage of its metadata like interdependencies could prospectively be improved using system modeling techniques.

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