# A HOLISTIC DIGITAL TWIN FOR SERVICE LIFE EXTENSION PROGRAMS

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**Abstract:** Aircraft are affected by their continuous exposure to the conditions under which they operate. The well-known combination of fatigue, environmental and accidental damages in the airframe leads to a progressive reduction of the capability to carry load. Although the maintenance strategies promoted by the regulatory frameworks ensure that the degraded structure will withstand limit load at any moment, thus solving the safety implications of ageing, there are still significant economic considerations to be addressed.

This scenario is particularly demanding in the case of military products such as tactical aircraft for maritime patrolling missions, in which a strong interaction between fatigue and corrosion appears, combined with a severe usage pattern.

Among the options available to implement a Service Life Extension Program (SLEP) for these aircraft, a digital twin –called Fatigue Digital Equivalent (FDE) in its initial wave– has been selected to determine the condition of the structure by simulating the occurrence, growth and eventual interaction of the different degradation sources. At its core, the FDE is an ecosystem of deterministic and probabilistic models representing all the aspects involved in the airframe's safety including design, manufacturing, maintenance, repair, configuration management and flight operations. The models are then incorporated into a set of holistic analyses used to estimate the remaining useful life of the relevant elements.

One of the main challenges of the construction of the FDE is the integration into a single repository of heterogeneous sources of data, including design information created in many cases years ago, maintenance records generated over the years following different formats and standards, and external in-service inputs provided by the operators. Another relevant activity is the combination of conventional analysis tools with state-of-the-art procedures, such as Machine Learning (ML), in a harmonized process aimed to obtain an accurate assessment of the potential for extension of the structure.

**Keywords:** Ageing, degradation, data-centric, credibility

## INTRODUCTION

Military aircraft are designed to work throughout decades in harsh environments, so structural deterioration is inevitable during their operation. However, because so many and so varied factors –including fatigue, environmental and accidental damages– affect the degradation rate, making accurate quantitative predictions is still a challenging task.

The different airworthiness regulatory frameworks have evolved over the years to promote robust design principles and preventive maintenance programmes aimed to take full account of the effects of ageing, thus ensuring that the performance of the airframe (understood as the capability to withstand limit load) will be kept at any moment.

In practice, sustaining the continued airworthiness of an aircraft type implies the implementation of a wide range of multidisciplinary processes aimed to ensure that every unit will be in a condition for safe operation at any time in its operating life. These processes are heterogeneous in nature but share several basic pillars, such a comprehensive set of conservative engineering models for the prediction, identification and correction of safety concerns, or an intense exchange of information between manufacturers, operators and airworthiness authorities.

Historically, many of the activities included within continued airworthiness have been managed on a case-by-case basis, addressing individually the different incidences that appear, and using a semi-manual document-based way of working. This framework, although undeniable effective, is essentially reactive. Digital twins are intended to take advantage on the generalized progress in computing power to provide a proactive response by understanding the importance of collecting and managing data as a driver of the different processes.

Several years after the initial formulation by Grieves [1], the digital twin paradigm has fostered many efforts to develop terminologies, architectures and applications. Actually, this concept has been continuously selected as one of the top 10 technological trends with strategic values by Gartner from 2017 to 2019 [2-4]. In the aerospace industry, the term 'digital twin' is used to describe applications ranging from proactive determination of removals of components (many times by means of data-driven approaches such as machine learning) [5] to complex physics-based formulations at aircraft level [6,7].

## FATIGUE DIGITAL EQUIVALENT

The roots of the digital twin for fatigue life prediction, or fatigue digital twin, in Airbus Defence & Space can be traced to two previous independent trends: a) the natural transition from the traditional (and sometimes analogic) document-centric engineering practices to a modern digital data-centric philosophy, b) an evolution of the scope of the fatigue analysis methodology from merely conservative to predictive. It was soon realized that the digital twin concept could combine both aspects and enlarge their scope, so the in-house implementation of the fatigue digital twin –called 'Fatigue Digital Equivalent' (FDE)– has been conceived as a technological backbone for providing an enhanced understanding of in-service aircraft in order to achieve a proactive management of the continued airworthiness.

The current definition of the FDE comprises a set of hundreds/thousands (depending on the aircraft type) physics-based medium fidelity analysis models for the as-maintained configuration of each individual Manufacturer Serial Number (MSN). The FDE –as the initial wave of the digital twin evolution– solves the fatigue damage assessment of the airframe using a semiprobabilistic method, mainly for simulating multiple usage scenarios. An upgraded version of the FDE, called FDE+, integrates holistic analysis capabilities along with the upgrade of the fidelity of some models in some hotspots. The FDE+ has been specifically designed to determine the Remaining Useful Life (RUL) of structural components, a vital step needed to support the implementation of Service Life Extension Programs (SLEPs).

The long-term roadmap of the digital twin for fatigue life prediction includes three 'waves' in addition to the FDE/FDE+, which are known by their codenames 'Fatigue Digital Relative' (FDR), 'Fatigue Digital Brother' (FDB) and, finally, 'Fatigue Digital Twin' (FDTw). This roadmap is based on a clear statement of the expected intermediate and end-goals of each wave in order to generate value in all the phases of the development. Thus, the definition of the waves includes the coordinated allocation of progressively more sophisticated features corresponding to five main development axes (Analysis type, Configuration, Modelling fidelity, Structural scope, Degradation phenomena covered), as shown in Figure 1, with several other sub-categories tied to the main ones.

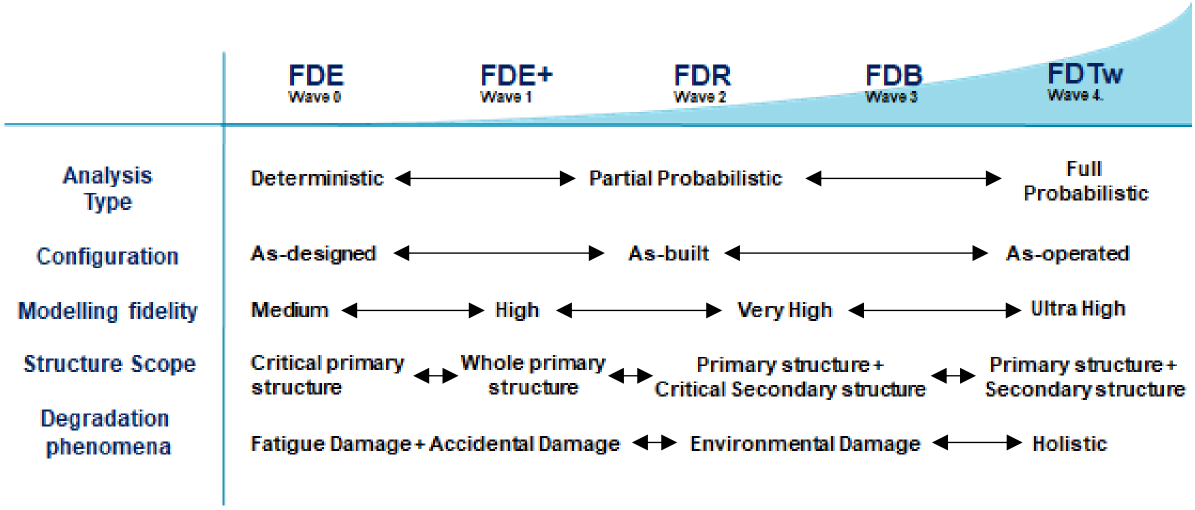


Figure 1: Fatigue digital twin main development axes.

The most demanding development axis of Figure 1 is the Modelling fidelity, as every improvement in this topic implies a highly non-linear increase of the complexity and computational cost of the associated engineering models. Actually, it is considered that the state of the art is only fully compatible with the fidelity requirements of FDE and FDR. The accomplishment of the FDTw, whose definition is a simplified version of the vision of USAF [8] and NASA [9] (i.e., the 'integration of ultra-high-fidelity simulation with a vehicle's on-board integrated vehicle health management system, maintenance history, and all available historical and fleet data to mirror the life of its flying twin and enable unprecedented levels of safety and reliability'), needs addressing numerous physics and computational problems for which there are no clear solutions yet.

The strategy for the construction of the FDE/FDE+ depends on the aircraft type and, particularly, on the moment of the lifecycle in which the digital is implemented. For models already in operation, the digital twin is based initially on a bottom-up consolidation of already existing solutions followed by the addition of dedicated developments to achieve new capabilities (e.g., transition from preventive to predictive maintenance). This FDE/FDE+ for ageing platforms is expected to work in standalone mode. However, the FDE of future programs (or, more probably, the FDR/FDB) is expected to be federated with other digital twins from other disciplines, all of them conceived in the early stages of the design of the aircraft to work in cooperation.

## ARCHITECTURE

Figure 2 shows the architecture of the FDE/FDE+. Following the classical digital twin definition, three essential parts are considered: the physical space, the virtual space, and the interconnection between physical and virtual spaces.

The physical space of the FDE/FDE+ is comprised of the physical system, the physical objective environment and the physical subjective environment. The physical system is defined as the portion of the airframe deemed as susceptible of degradation and, therefore, chosen for modelling. The starting point of the physical system is the 'as-designed' configuration, but it is progressively enlarged throughout the lifecycle of the structure –and, therefore, evolved towards the 'as-built' and the 'as-maintained' airframe–, by incorporating updated knowledge of the physical condition (waivers, inspections, repairs, etc).

The physical objective environment includes the aspects of the physical reality outside of the physical system but affecting it, such as the loading and structural response of the airframe that govern the fatigue damage accumulation in the critical areas, the environmental conditions the structure is subjected to, the findings reported during maintenance outside of the physical system, etc. The physical objective environment provides also data about how the aircraft has been operated in the past.

The physical subjective environment is not linked to any specific feature of the structure, but to the user expectation about the aircraft usage. It mainly contains projections (either qualitative or quantitative, depending on the operator and the age of the fleet) as to how the different units will be operated in the future.

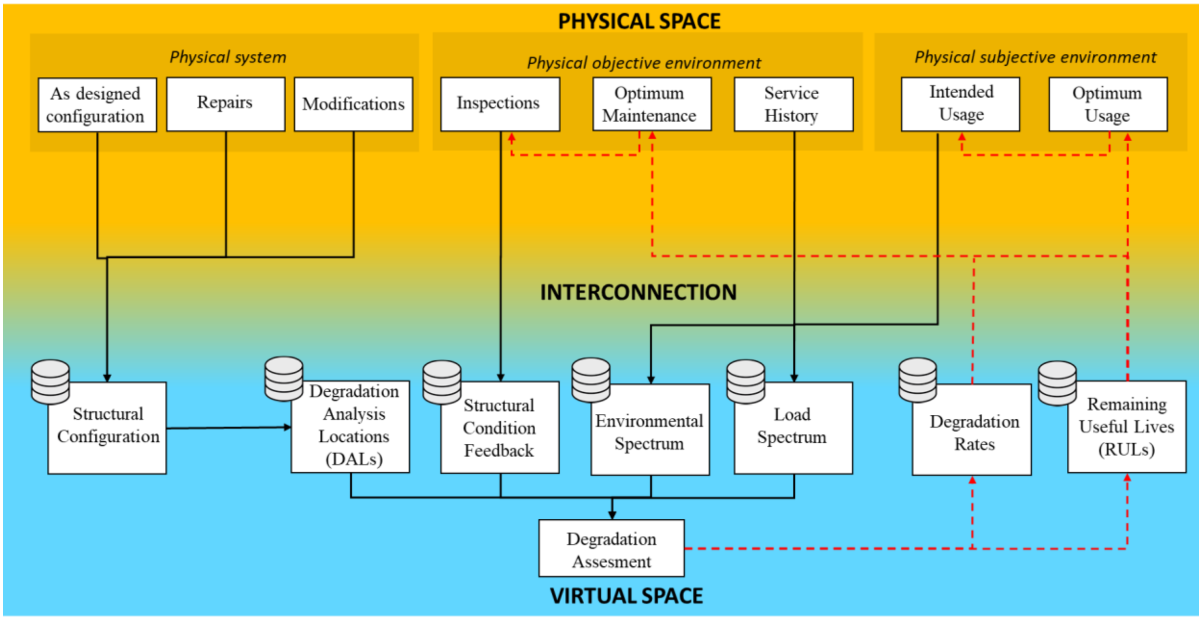


Figure 2: Fatigue Digital Equivalent (FDE/ FDE+) architecture.

The second component of the FDE/FDE+ definition is the interconnection between the physical and the virtual spaces, where data/information is exchanged in two directions: physical-to-virtual and virtual-to-physical. Although digital twins typically rely on a physical-to-virtual exchange of sensor-based data, these sensors can be very expensive to install and maintain, so many aircraft do not have them, or at least they are not usable for twinning purposes. This is particularly true in older models, which are the main scope of ageing assessments. Therefore, the FDE/FDE+ has been designed not to depend only on sensored platforms, using when needed general service history data gathered for each aircraft (flights, flight hours, mission profiles, etc) and then generating detailed load and environmental spectra to evaluate the airframe degradation over time. The physical-to-virtual data flow includes also other items such as changes in aircraft configuration (modifications) or airframe condition data (inspection findings, repairs, etc).

The virtual-to-physical exchange consists mainly on informed decision-making based on systematic structural condition assessments which may include optimum aircraft/fleet operations to minimize degradation (units or base rotations, changes in operations mission profiles, etc) or planning for future inspections or maintenance activities.

Finally, the virtual space is organized in terms of Degradation Assessment Bots (DABs) corresponding to Degradation Assessment Locations (DALs), which are selected to track the critical locations of the physical system and anticipate their life limit .(Figure 3). Currently, the standard FDE includes 200 to 1200 DALs, depending on the aircraft type, and the number is higher in the FDE+ version.

Many of the DABs are based on analytical medium-/high- fidelity life prediction models, as far as they are compatible with the required level of accuracy and the complexity of the scenario. The main advantage of these models is their computational efficiency. When needed, other numerical high-/very high-fidelity models (based on virtual fatigue testing principles [10]) can be used for certain hotspots of interest. So far, the contribution of these models to the FDE/FDE+ is constrained by their significant computational cost.

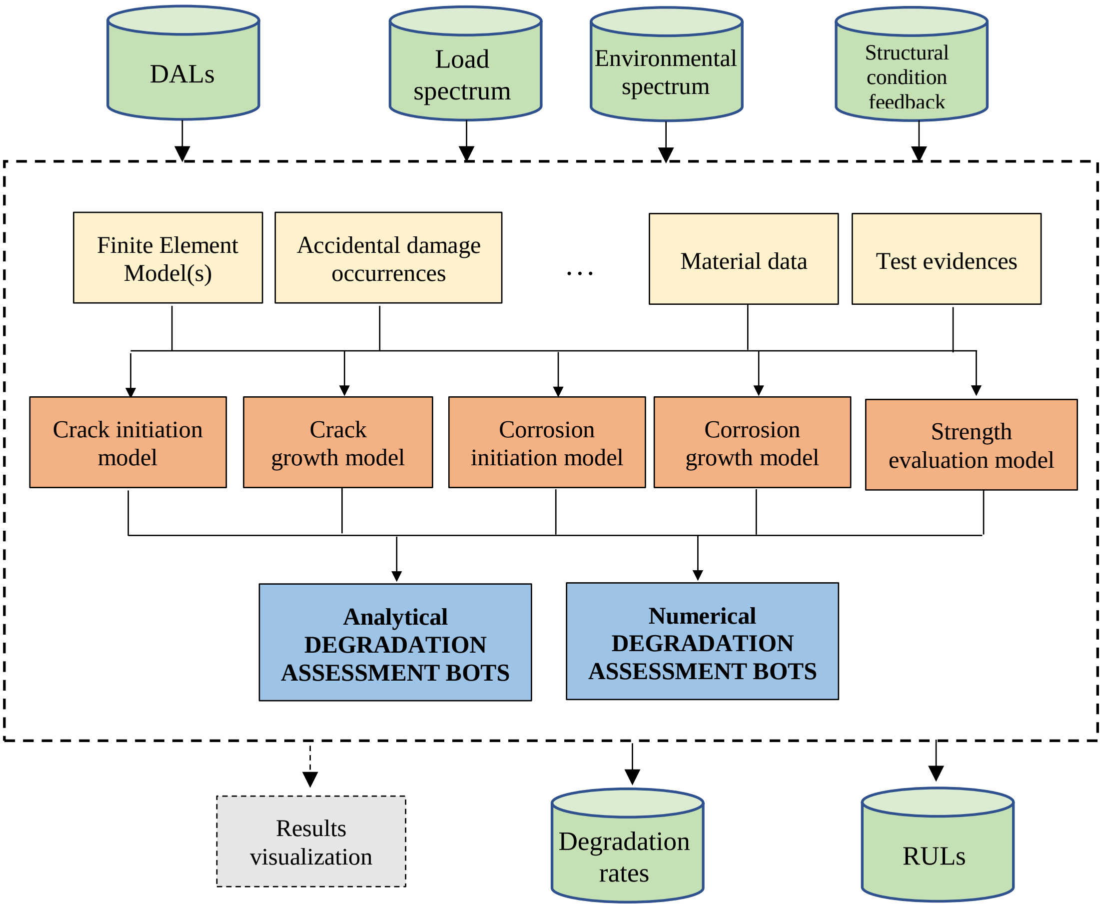


Figure 3: Elements of the FDE/FDE+ virtual space.

Each DAB is a complex combination of computational engines (for crack initiation, crack growth, corrosion initiation, corrosion growth and strength evaluation), which are fed by associated data models (stress concentration factors, initial crack sizes, stress intensity factors, crack growth rate curves, failure criteria, etc). The specific configuration of the bot will depend on the geometrical details of the DAL, the nature of the expected degradation and the type of calculation (analytical or numerical). Findings or nil-findings reported during the inspections of the physical space derived from the approved maintenance program are used to update the affected bots, when needed. Some of the functionalities of the bots are supported by in-house machine learning applications [11].

In practice, the virtual space of the FDE/FDE+ is implemented by means of an ecosystem of 'integrated tools' that work as LEGO bricks (Figure 4). An integrated tool is built by combining one or several 'general/shared tools' (e.g., a tool to find the model that is applicable to a particular structure zone) with other 'specific tools' (e.g., a tool to perform the structure repair analysis for the service repair manual), thus yielding one or several DABs. The resultant tools can be combined with others so new tools can be easily created to enhance an existing process or to create new processes. This flexible and adaptive development methodology enables a quick increase of the range of applications of the FDE/FDE+.

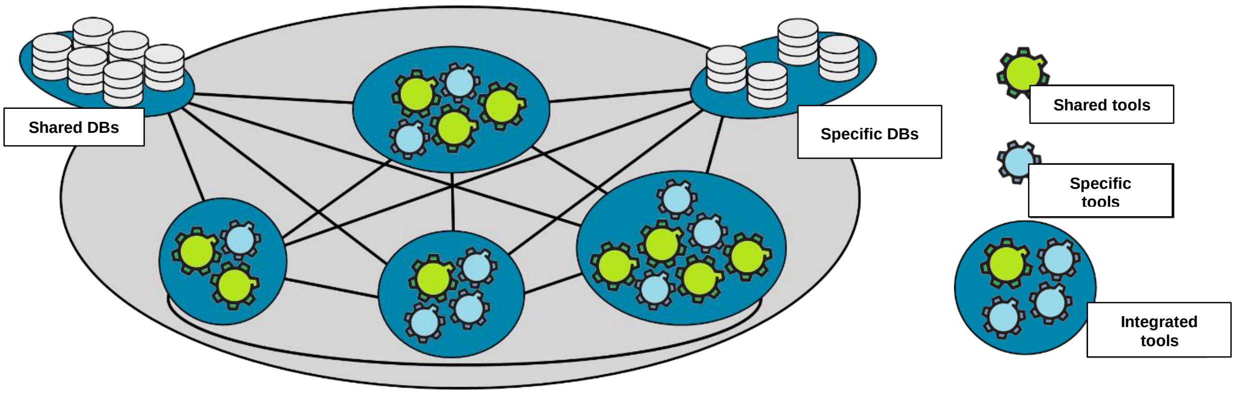


Figure 4: FDE/FDE+ virtual space ecosystems.

The tools of the virtual space need a relevant work of data extraction from many analogic and digital sources before they can operate. This information is incorporated into an equivalent ecosystem of general/shared and specific databases.

## TWINNING CONCEPT

The FDE/FDE+ is initiated at certification date with the creation of a 'Version Type Certificate Equivalent' (VTCE). The VTCE has no physical counterpart, but reflects the 'as designed' configuration and, therefore, contains the nominal design, including the associated structural analysis data. There may be several VTCEs of the same aircraft type (all of them derived from the so-called 'Type Certificate Master Equivalent'), as it is common in the military industry to customize each version and certify it separately. Once the deliveries of specific Manufacturer Serial Numbers (MSNs) start, individual instances of the VTCE, called Version Individual Equivalents (VIEs), are produced containing the specific combination of modifications, manufacturing waivers, inspection findings (or nil findings), changes of usage, etc that make each airframe unique (Figure 5).

The VTCE and the VIEs have different roles within the continued airworthiness management. The VTCE is basically used to comply with the formal regulatory requirements in force, which are based on the type definition of the aircraft and not on individual aircraft. As such, the VTCE is also updated with modifications and changes of usage, but following different criteria than the VIEs. On the other side, the VIEs are used as aircraft replicas to perform individual condition assessments, support special activities such as the determination of eventual grace periods for the execution of maintenance activities, and be the basis for the implementation of life extension programs by estimating holistically the Remaining Useful Life (RUL) of individual structural components.

## DATA MANAGEMENT

The operation of the FDE/FDE+ involves complex collections of heterogeneous –but highly interrelated– data generated by numerous sources, including both internal and external stakeholders involved in the continued airworthiness processes (Figure 6), so it is crucial to consider a mechanism of permanent integration between the digital twin and these sources to organize and maximize their effectiveness.

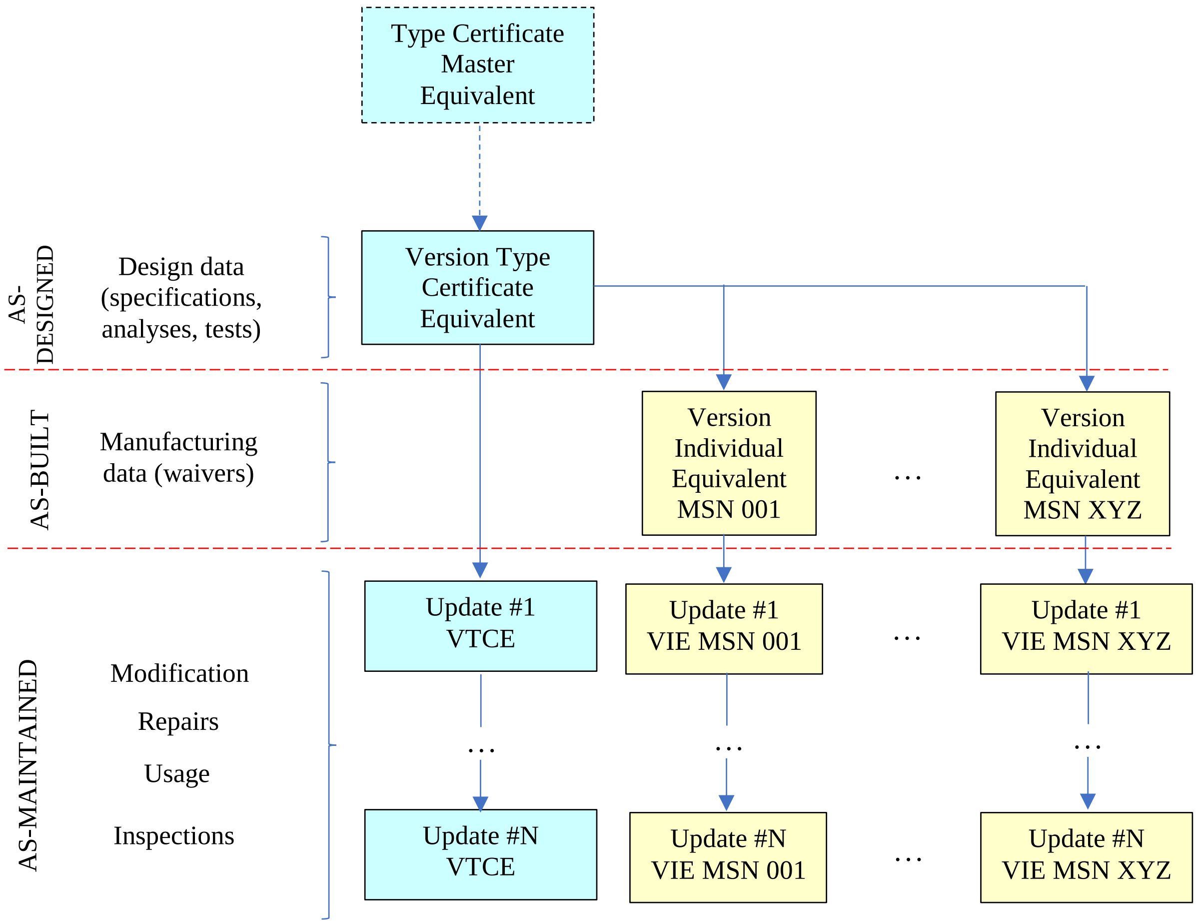


Figure 5: Hierarchy of FDE/FDE+ instances.

However, the traditional document-centric approach for continued airworthiness presents several issues to co-exist with a digital twin like the FDE/FDE+. First, by manually transferring the engineering information (e.g. from the analysis/simulation tools) into the documents, the data has become static. Second, it takes time for the information to work its way through the various documents, so there is a slow response to changes. Third, a myriad of formats can be used for the same purpose. Fourth, there is a natural tendency to work in silos, because the workflow for one activity can be significantly independently from another: as a result, almost every manufacturer has developed between five and ten different systems to identify zones or elements of the airframe, depending on the application.

In practice, these challenges mean that the information derived from the documents cannot be easily unified into one single repository, as the data contained on a document does not align with data on other documents or across the various information systems. In this context, the link between the document-centric approach of the traditional work in ageing platforms and the data-centric philosophy of the FDE/FDE+ has been established in two phases. Initially, a set of 'ad hoc' semi-manual procedures are deployed in order to convert the documents, forms, etc that comprise the input data needed by the virtual space. This activity includes also the extraction of useful metadata for the purpose of the FDE/FDE+ and, even more important, the standardization of the terminology used in each of the independent workflows. Although inefficient, this phase is a necessary intermediate step to launch the FDE/FDE+. During the second phase, these new standards are slowly propagated and converted into suitable automated data formats that are directly compatible with the FDE/FDE+.

Despite the FDE/FDE+ has been designed to work with data and, therefore, reduce the number of documents involved in the engineering processes, documents are still needed and will be needed for a long time, particularly in the output side. Since the models cannot be viewed directly by humans, documents as 'written reports on the models' remain part of the loop. This is particularly evident when communicating with external stakeholders, either operators or airworthiness authorities. Thus, most of the quality assurance processes of the traditional continued airworthiness is supported by document reviews and document signatures, and this framework is today an essential part of showing compliance with the applicable airworthiness requirements.

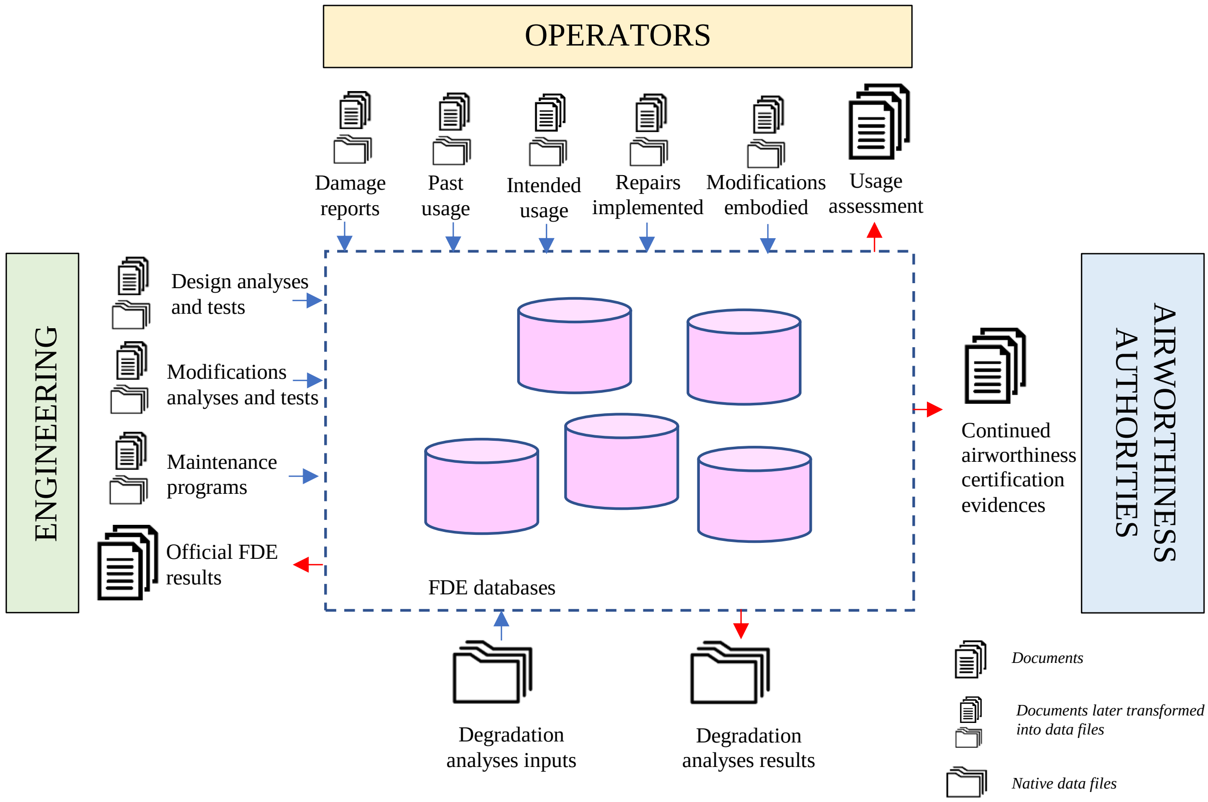


Figure 6: FDE/FDE+ data flows.

## CREDIBILITY

As any other engineering process, digital twins have the risk of including errors. The most common sources of potential errors and uncertainties that may appear in the FDE/FDE+ are data errors, modelling errors, integration errors and result interpretation errors [12].

Being the FDE/FDE+ a software-based element capable of processing vast amounts of data that cannot be reviewed individually, a comprehensive Verification, Validation and Uncertainty Quantification (VVUQ) process has to be adopted in order to ensure (and demonstrate to third parties) its credibility.

Probably the most pragmatic way to evaluate the performance of the VVUQ process is to implement a Credibility Assessment Framework (CAF), which is used to structure the credibility assessment into complementary elements that cover the different contributions to the accuracy, correctness and traceability of the results. General CAFs originally developed for simulations [13-15] were evaluated for this purpose. Among them, the Predictive Capability Maturity Model (PCMM) [14] was selected for the FDE, as was already being used successfully to assess the credibility of fatigue-related simulations and was considered that could be extended easily to a digital twin.

The credibility of the FDE is then based on an ecosystem of ‘PCMM evaluations’ at two levels: one PCMM evaluation for each of the Degradation Assessment Bots (DABs) (Figure 7b), and one overall evaluation for the FDE (Figure 7a). This arrangement efficiently addresses the different sources of errors mentioned earlier. Thus, PCMMs for numerical DABs and analytical DABs are mainly linked to the modelling errors and local data errors, while the PCMM at FDE/FDE+ level deals with global data errors, integration errors and result interpretation errors.

| PHYSICAL SPACE FIDELITY | PHYSICAL-VIRTUAL CONNECTION | VIRTUAL SPACE CODE VERIFICATION | VIRTUAL SPACE SOLUTION VERIFICATION | RESULTS INTERPRETATION VERIFICATION | UNCERTAINTY QUANTIFICATION AND SENSITIVITY ANALYSIS |
|---|---|---|---|---|---|
| What critical elements of the physical system are neglected? | Is the information exchanged between the physical and the virtual space reliable? Is it properly synchronized? | Are algorithm deficiencies, software errors, and poor software quality practices corrupting the simulation results? | Are human procedural errors corrupting the FDE results? | Is the outcome of the FDE unambiguous? Has the domain of application of those results been carefully determined? | How thoroughly are uncertainties and sensitivities characterized and propagated? |

(a)

| REPRESENTANTION AND GEOMETRIC FIDELITY | PHYSICS AND MATERIAL MODEL FIDELITY | CODE VERIFICATION | SOLUTION VERIFICATION | MODEL VERIFICATION | UNCERTAINTY QUANTIFICATION AND SENSITIVITY ANALYSIS |
|---|---|---|---|---|---|
| What features are neglected because of simplifications or stylizations? | How fundamental are the physics and material models and what is the level of model calibration? | Are algorithm deficiencies, software errors, and poor software quality practices corrupting the simulation results? | Are numerical solution errors and/or human procedural errors corrupting the simulation results? | How carefully is the accuracy of the simulation and experimental results assessed at various tiers in a validation hierarchy? | How thoroughly are uncertainties and sensitivities characterized and propagated? |

(b)

Figure 7: FDE/FDE+ PCMM elements per level: (a) digital twin level, (b) Degradation Assessment Bots level.

## APPLICATIONS

Once fully implemented, the FDE/FDE+ can play a central role to support better and faster decisions linked to continued airworthiness and in-service management optimization, including areas such as structural inspection and maintenance planning, evaluation of future operations or assessment of potential life extensions.

With advent of FDE/FDE+, it is possible to move towards a predictive management of the usage changes that optimizes maintenance cycle by reducing unscheduled maintenance and labour costs. The dense network of Degradation Assessment Locations (DALs) available in the FDE/FDE+ (Figure 8) provides a full-scale identification of potential maintenance hot spots up to a detail not achievable with conventional procedures. The associated Degradation Assessment Bots (DABs) can then perform quasi real-time evaluations of the damage accrual in many of the DALs with a reasonable computational cost, thus allowing the completion of sensitivity analyses to have a better knowledge of the behaviour of the structure.

For example, it is well known that military aircraft service usage typically changes during the life from that originally planned due to varying capability requirements. In many cases the real usage often produces fatigue damage at a greater rate than that predicted prior to acquisition, so the result is often an aircraft operating at either a higher than anticipated risk or with an increased operating cost, or both.

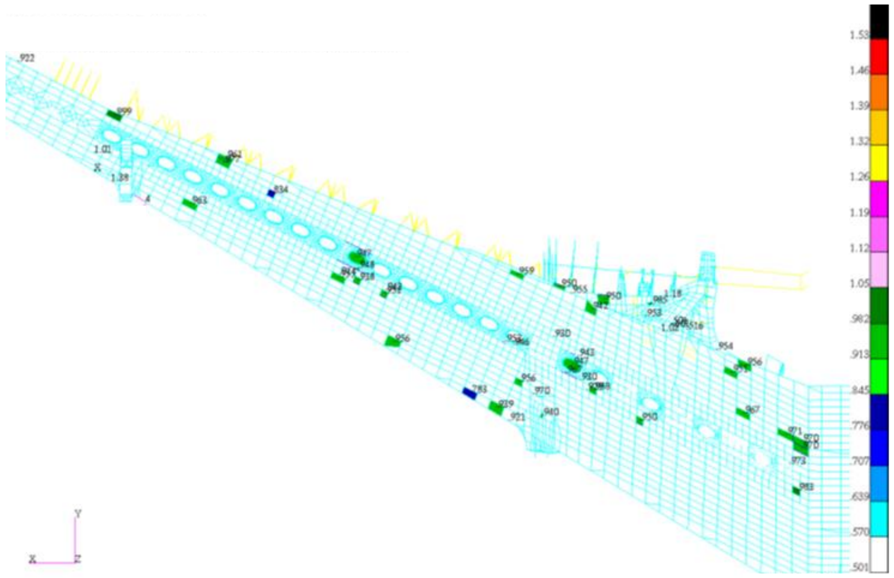

Figure 8: Degradation Assesment Locations mapping.

The collection, storage and reporting of aircraft usage when the aircraft enter in service implies that the degradation accrued during any past or future period can be evaluated. In particular, the FDE/FDE+ can extrapolate the future condition of each individual aircraft in case of expected changes in the operational scenarios, thus suggesting the appropriate targeted maintenance actions in advance. This evaluation is made for the whole airframe at the same time (Figure 9) in terms of severity relative to a given reference. At the same time, the combination of design data and the feedback from the fleet (crack findings, corrosion findings, accidental damage findings, etc), enables the identification or modification inspection areas more accurately.

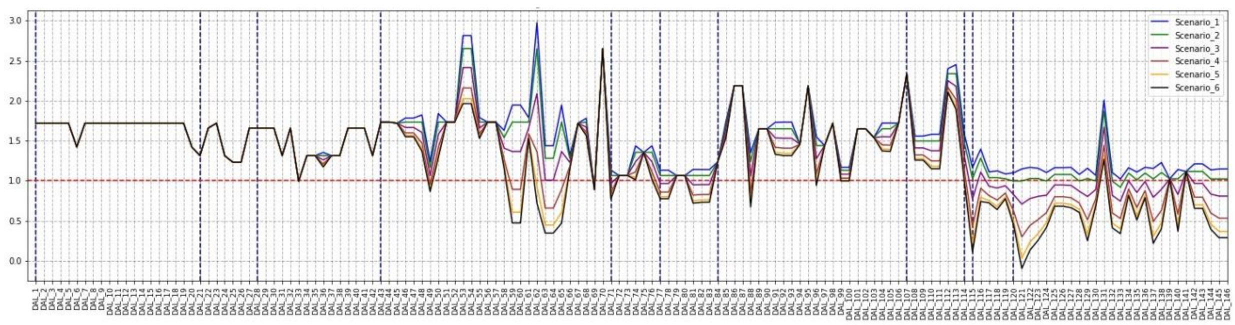


Figure 9: Airframe-wide sensitivity to usage for different projected scenarios.

Once the aircraft is ageing, the traditional approach for planning life extensions consists mainly on the evaluation of Remaining Useful Lives (RULs) based on the estimate of fatigue damage accrual only. However, this approach can be insufficient for airframes intensively exposed to aggressive environments, like in the case of maritime patrolling aircraft. In those situations, a holistic RUL determination is needed instead. The FDE+ version is able to integrate different degradation models in order to calculate the RUL, rather than focusing on just one aspect of the degradation of the materials. For this purpose, environmental spectra projections can be made for different Version Individual Equivalents (VIEs) of the same fleet (which will share a relatively uniform set of environmental conditions) or even for several Version Type Certificate Equivalents (VTCEs) with completely different environmental conditions (Figure 10).

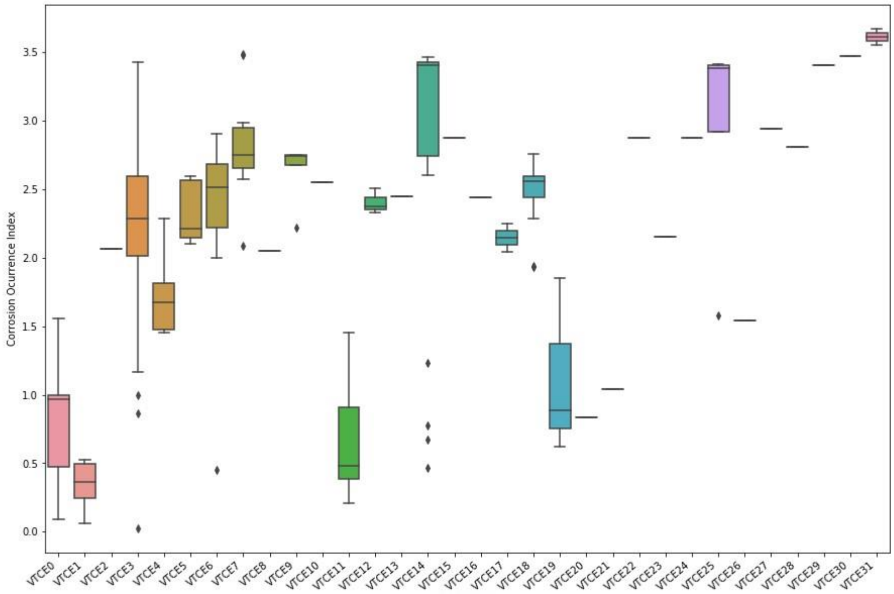


Figure 10: Environmental spectra simulations for different VTCEs.

In the simplest case, the starting point of the material degradation assessment may be a single corrosion pit, which is considered as the site where a corrosion fatigue crack nucleates. The growth of the corrosion pit may be typically described in terms of empirical models such as:

$$d = A \cdot t^n \quad (t>t_0) \tag{1}$$
$$w = B \cdot t^m \quad (t>t_0) \tag{2}$$

where $d$ is the pit depth, $w$ is the pit width, $A$, $B$, $n$ and $m$ are empirical in-house constants that depend on the material, the corrosive environment, the environmental spectrum applied and the previous experience in terms of reported findings, among other factors, and $t_0$ is the time needed for the failure of the protections considered in the design of the element. Once the size of the pit is enough as to develop a fatigue crack, the cycle-dependent crack growth is modelled considering in-house fracture mechanics formulations. The result, shown in Figure 11, allows a parametric determination of the total life of the structural detail, including the life fractions spent in corrosion pit growth and in fatigue crack, for each environmental spectra projection.

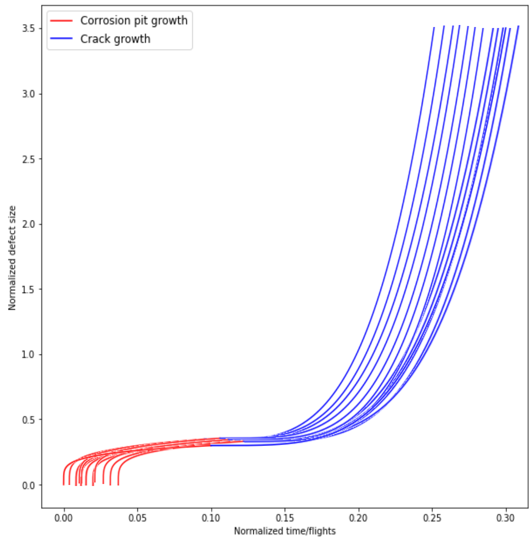


Figure 11: Pit evolution + crack growth simulation.

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