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The Embryo Digital Twin: A tool for the development of aerospace robust support systems

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Abstract— **Experience from industry shows that, when developing the support characteristics of a new aerospace system, supportability needs may enter the process too late, leading to difficulties, lack of innovation and a series of constraints to the supportability performance of these systems, mostly when they enter into service and throughout the rest of their life cycles. Therefore, the purpose of this work is to define the Embryo Digital Twin, which is a tool specially designed for the development of all supportability involved in new complex aerospace systems. The procedure followed on this study is to provide a review of the definitions and classifications of digital twins observed in the literature and compare them to the features expected for the Embryo Digital Twin. As a result and to state its relevance, this work presents a high-level model of this tool, clearly positioning it in this context of development.**

Keywords— **Supportability, Digital Twin, Aerospace Systems.**

I. Introduction

The way society interacts is changing due to the advent of the Industry 4.0 paradigm and its focus is on the automation and digitization of the industrial practices, using technologies such as the Internet of Things, Big Data Analysis and Machine Learning to provide interconnection, digitization of products and services and technical assistance from the systems on their own behavior [1].

As a result of this approach, the Digital Twin Framework is being spread, with special attention on the manufacturing processes and Product Health Management (PHM), where its application is straightforward, since all the data is available and the changes made on the system can be readily tested [2].

The Digital Twin is defined as the conjunction of three elements: the digital entity, the physical entity and the exchange of information between them [3], as shown on Fig. 1.

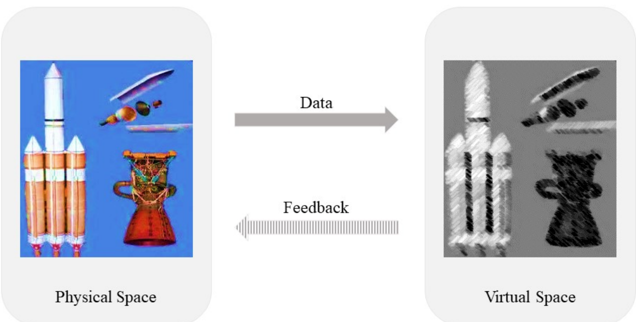

Fig. 1. Parts of a Digital Twin - Adapted from [3]

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By definition, the digital model is a copy of the physical system that receives data from sensors installed on the latter and is capable of processing this information and giving feedback. To clarify the concept, it can be thought that the physical system presented on the figure is the as-built rocket, containing all the subsystems and physical components, while the digital model has all the development data stored and receives the environmental data on a real-time basis from the sensors installed on the system. The digital model must then be capable of analyzing all of this data and provide optimization evaluations aiming to upgrade the performance of the physical asset, furnishing it with these decisions, which is represented by the feedback arrow.

This paper aims to revise some works on the subject and clearly define a type of Digital Twin (named Embryo Digital Twin) suited for the preparation, development and production phases of the life cycle of a complex system. The focus is on the aerospace industry, on the context of the Integrated Product Support (IPS) concept, so that the Embryo Digital Twin will evolve together with the system's supportability until its entry into service as a full Intelligent Digital Twin. It is expected that this early development would provide most accurate trade-off analysis and achieve better supportability planning for the In-Service (Operational) Phase.

The research is organized as follows: Section 2 provides a review of the supportability problem for complex aerospace systems, showing the gap observed on industry concerning the expected supportability maturity upon deployment and the actual achieved one. Section 3 provides a review on Digital Twins with its definitions and classifications, especially in the terms of level of integration between the physical system and the digital model and in terms of the level of maturity for its use. Section 4 describes the Embryo Digital Twin in general terms, including a high-level model for its expected behavior. Section 5 presents the methodology used on the qualitative framework development and the results obtained, whilst Section 6 concludes this paper.

II. The Supportability Problem for Aerospace Systems

The major constraints on supporting complex aerospace systems comprise more than just one dimension of the problem. If we consider a system's approach to the issue, at least three main perspectives would guide the development of solutions, innovation or improvements in the area.

One dimension is the time and phasing required when creating such systems. Complex aerospace systems creation management demands the division of its activities in at least five consecutive and integrated phases to succeed [4]: Preparation, Development, Production, In-Service and Disposal. The Life Cycle perspective emphasizes that the optimal chance to explore supportability precision and coherency throughout a complex aerospace system operational life cycle phase is to act on the early phases of a product's life cycle [5].

This is crucial to concept, design, develop, manufacture, and to test and verify, if the entire helm of supportability is ready and robust for the first operator to utilize the system with no supportability problems and following its expected operational concept. The Life Cycle perspective implies that some supportability considerations are specific, better suited, or convenient to be taken into account on each phase of the development of the supportability of a complex system.

Another supportability perspective is the need for integrated development of a set of activities that assures completeness in terms of what is necessary to support a complex aerospace system. Supportability demands the precise and integrated development of twelve supportability elements to guarantee the required readiness and service levels for the complex system on its In-Service phase [4]: Product Support Management, Design Influence, Maintenance, Human Resources, Facilities and Infrastructure, Computer Resources, Supply Support, Logistics Related Operations, Support Equipment, Technical Data, Training and Training Support, and Sustaining Engineering.

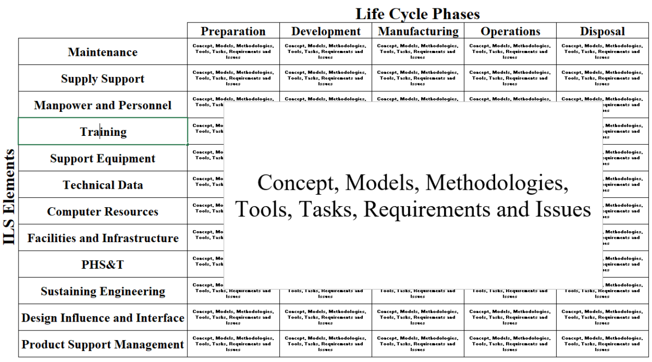

Fig. 2. IPS Elements x Life Cycle Phases Matrix - Adapted from [5]

Academically, it becomes more didactic and self-explanatory to divide the development of the supportability according to the map suggested in Fig. 2, which presents the development of each IPS element when they are required in each life cycle phase. For each cell of the matrix, a series of concept, models, methodologies, tools, tasks, requirements and lessons learned to apply. The figure suggests a huge amount of work to achieve supportability excellence and to coordinate the engineering efforts to accomplish everything expected for each cell related to each IPS element and the correspondent Life Cycle Phase. The IPS approach is necessary to [4]:

- Insert and accommodate supportability considerations early in project development (Preparation and Design phases);
- Develop supportability requirements compatible and integrated with the operational goals of the system;
- Acquire and deploy supportability assets;
- Provide the necessary supportability throughout the entire Life Cycle of the system at achievable economic costs.

The last perspective is the Systems Engineering approach to the problem. It is necessary to develop all the requirements and implement engineering techniques to address the Life Cycle phases with the best set of injections, aiming, with that, to provide the system with the best supportability solution. From an engineering point of view, modeling such systems follows what systems engineering suggests and recommends from developing requirements until becoming marketable products.

The final topic in this section describes the problem faced by many operators that is vital for the purpose of this research. The definition comes from the experience dealing with commercial, defense and some other major complex systems throughout their life cycles, but especially on the deployment or commissioning phase of the first hull or tail numbers delivered. Fig. 3 presents what happens when project management does not properly address supportability requirements. The Supportability Maturity Readiness Level (SMRL) on the Deployment phase is a consequence of the supportability activities established and accomplished on the early phases of the development of a complex aerospace system. Actually, it should be part of the Concept of Operations (CONOPS) and management should take it seriously during the early phases. Since the complexity of the engineering effort may be vast, some minor gaps may occur for the first deliveries. These potential gaps are a function of the complexity involved and should be part of the maturity growth program with shared risks among users and suppliers during the deployment phase.

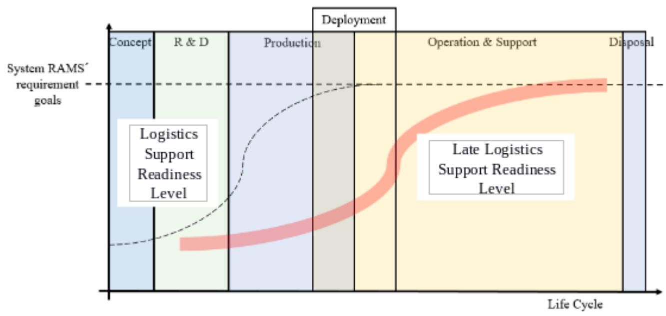

Fig. 3. Supportability Readiness Development - Adapted from [5]

However, a much more complicated scenario may develop. Suppose, for any given reason, that almost no supportability requirements were engineered from the Concept of Operations and, only after the development of the first prototypes, some maintenance requirements are really taken into account. In this case, the SMRL may become way below the expected values. Without a good understanding of the supportability factors behaviors, it is almost impossible to manage the readiness of the fleet within cost expectancy.

Fig. 3 presents this condition. The absence of supportability engineering at the concept phase and the lack of understanding by other engineers of supportability requirements may cause the SMRL curve to shift to the right. The Rockwell B-1B [6] and the Convair B-58 Hustler [7] are examples of systems with such behavior. The first with Reliability and Maintainability problems, resulting in low Availability and vast amount of maintenance person-hours per Flight Hour until it became mature. The second, a quite complex aerospace system in terms of support, never reaching the expected SMRL during its operational phase.

III. Review on Digital Twins

Whereas the technology is still being developed, there are plenty of definitions on the term Digital Twin, although only the most prominent ones on the field of complex systems will be addressed on this work.

The first one comes from [8] : *A Digital Twin is an integrated multi-physics, multi-scale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.*

From this, one can already differentiate the concept of a Digital Twin model from the traditional CAD/CAE models because the latter are generic models focusing on determined characteristics (mostly mechanical or electrical) of the system. The DT, on the other hand, is an integrated model of all the characteristics of the system. It can be thought that the DT is a tool to:

- Concatenate all the design data of the product (including the CAD/CAE models) together with the environmental data provided by each system; and
- Use these data to simulate the expected behavior of the specific system, based on the feedback received from each one of them (this means one can have a tail number control on the aeronautics context).

On the ambit of maintenance and service for the aircraft example, this specific control is desired (if not mandatory) since it enables operators to plan their work according to the environment and type of mission that system operates, instead of ordinary duties designed for an entire production line.

As can be seen, data and connection are the center of the DT, which is expected, considering that the information flow is what enables their existence.

On this behalf, the level of integration of the proposed DT up to date can be categorized on three categories [9]:

- Digital Model, where the connection and exchange of data and service between the physical and virtual parts is manually made;
- Digital Shadow, where the connection starts to be automatic, so the physical part feeds its data and service to the virtual one but cannot import data from it; and
- Digital Twin, where all the parts are integrated, and the information flows on both ways.

There is, although, another type of classification, based on the level of maturity [10], as follows:

- Pre-Digital Twin, a virtual prototype that supports decision-making on concept and preliminary design;
- Digital Twin, the virtual system model is capable of acquiring data from the physical system on its operational phase;
- Adaptive Digital Twin, which provides a user interface that is adaptive and sensitive to the preferences of the operator, so it can be used on modernization and new versions of the physical system; and
- Intelligent Digital Twin, where the system is capable of machine learning, so it can discern patterns on the operational environment and change system behavior accordingly.

Based on this, it can be assumed that a Pre-DT is, by definition, a Digital Model on the Preparation and Development Phases of the system life cycle and can be upgraded to a Digital Shadow on Production Phase and first models delivery, finally reaching the level of Digital Twin when it is serialized and enters the In-Service Phase. The Intelligent Digital Twin level of maturity is only possible when the product is already developed, since it require data from the physical part.

Whatsoever, Embryo DT is conceived to address the problem of developing a Pre-DT model for supportability that can be applied to new products based on knowledge and historical data from similar ones and, most importantly, provides supportability definitions and trade-offs early in the supportability development of the systems.

It is important to clearly differentiate the Embryo DT from the Pre-DT, since the first must have some data available from legatee systems on its database or to be provided by the working engineers. It occurs because of the characteristics involved on the development of products on the aerospace context that are somewhat strict in terms of huge changes in design due to the harsh standards applied in vision of safety.

IV. Embryo Digital Twin

The proposed Embryo Digital Twin uses a preconceived mathematical model to simulate all the supportability behavior of the new system to be developed or under development. To do that, it models the main measures of supportability to be verified throughout the system's life cycle while, at the same time, describes their behavior and how the integration between them happens.

It works as a complete system with all the components of a generic aircraft, each of them modeled in terms of Reliability, Availability, Maintainability, Safety, and cost performances, which are systematically integrated in a mathematical model. The initial inputs are set based on historical data and checked in terms of consistency. As the development process evolve, the Embryo DT (and consequently the mathematical model) must evolve together. This behavior, allied with other tools for the supportability development, allows the engineers to perform analysis and is expected to prevent the separation of the desired maturity curve from the actual one.

Supportability is mainly composed of the following interconnected parts: Reliability, Availability, Maintainability, and Safety, commonly called the RAMS factors. All of them have some measures that are used to predict the expected system behavior in terms of supportability.

Embryo DT is a tool to model and integrate all of those data throughout a mathematical model and with other supportability development tools. This allows the Embryo DT to perform trade-off studies to choose the best supportability concept and, at the same time, simulate what-if scenarios in this context. Another feature of the Embryo DT is to provide guidelines and milestones for the expected activities to be performed on the supportability development on each life cycle phase. Fig. 4 shows a qualitative model of the Embryo DT, with its inputs and outputs.

The Embryo DT would be a tool to apply a digital twin-driven product design methodology based on the following aspects [11]:

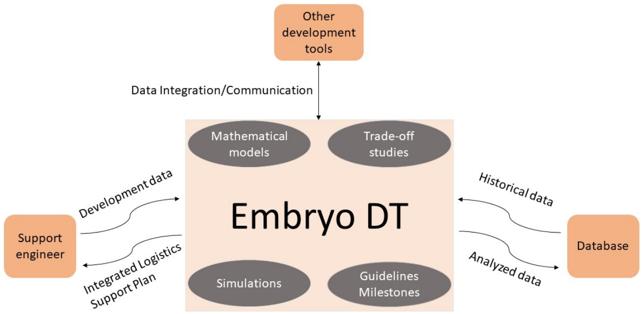

Fig. 4. Embryo Digital Twin definition - Created by the authors

- Task clarification: common known logistics and support information are fed to the Embryo DT to help designers formulate functional requirements;
- Conceptual design: historical data of alike products and simulations of what-if scenarios based on RAMS factors are made on Embryo DT to provide applicable solutions; and
- Virtual verification: when product passes to detailed design and production, the models applied on the Embryo DT can be used with real-time data collected from the physical prototypes to improve the tool itself as well as the operation, support and maintenance plans.

Rather than the development of performance prototypes, which is a well-known area on this kind of system, generally supportability is addressed only on the detailed design phase, so the Embryo DT aims to develop a way of simulating most of the supportability aspects early, a problem that is not modeled by the common frameworks and simulation tools.

V. Framework development

The approach chosen to start the tool development was to review the supportability processes as defined by three major sources [4], [12], [13] and to link those to a selected overall system development process [14] using a high-level modeling approach known as Business Process Modeling Notation (BPMN), for the Preparation (Conceptual) Phase of the system life-cycle. The goal was to identify when the supportability related activities could be addressed on this phase as a way to firstly present this data on a schematic way for future developments (providing knowledge for the involved engineers) and, secondly, to evaluate the supportability maturity on the process, preventing the SMRL curve from shifting to the right as presented on Fig. 3.

Fig. 5 shows the diagram obtained for this phase. As can be seen, due to the complexity involved, some activities where further detailed on a second level (which is represented by the + symbol on the bottom), as a mean to fully address the supportability related tasks to be done.

As already stated, the Digital Twin aspect is addressed as the empiric data from developments with use of the tool become available, refining the embedded mathematical model to estimate accurately the maturity attained on each activity and predict the expected future behavior, as a mean to assist decision-making.

VI. Conclusion and future works

Industry 4.0 is shifting the paradigm of development and operation of complex systems, and Digital Twins are a growing technology in this context, although they are still not fully defined and academy is only starting to develop models and applications for them.

This work focused on briefly introducing the concept and classifications that already exist and to define a new kind of DT, whose major focus is on supportability, but is applicable to the early stages of the Life Cycle, rather than only on the In-Service phase.

The qualitative aspect of the ongoing research is presented in this article, consisting of the identification of the gap for a maturity measurement and the connection of the overall system development with the logistics aspects and defining a model to connect these approaches for the Preparation Phase of the system life cycle.

The planned future development to complete the framework consists of developing the mathematical model and providing simulations on its expected behavior as a Proof of Concept for the proposed tool.

Future works consist of:

- Integration of a RAMS and a preventive maintenance model on the Embryo DT framework and application on the Conceptual phase development of a new system; and
- Development of an Embryo DT framework for the Development and Production phases.

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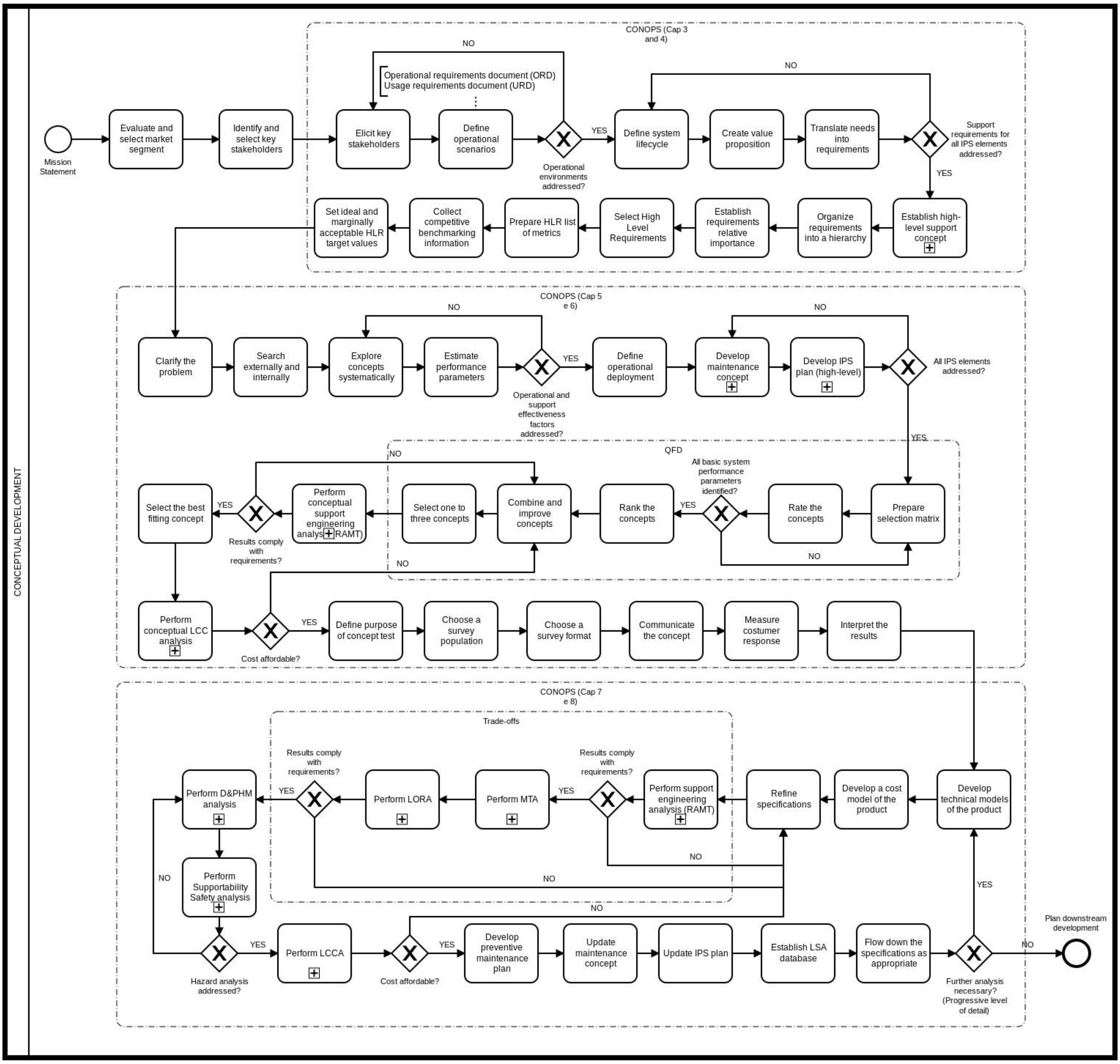

Fig. 5. Embryo Digital Twin (Preparation Phase BPMN Diagram) - Created by the authors