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DESIGN OF A TOOL FOR THE INTEGRATED LOGISTICS SUPPORT DEVELOPMENT OF AEROSPACE COMPLEX SYSTEMS : EMBRYO DIGITAL TWIN

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Talitha Cruz de Oliveira

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"In the midst of chaos, there is also opportunity"

— Sun Tzu

Resumo

A experiência da indústria mostra que, ao desenvolver as características de suporte de um novo sistema aeroespacial, as necessidades relacionadas à suportabilidade podem ser consideradas muito tarde no processo de desenvolvimento ou não ser adequadamente integradas às demais necessidades do sistema, levando a dificuldades, falta de inovação e uma série de restrições ao desempenho de suporte desses sistemas, principalmente quando estes entram em serviço e durante o restante de seus ciclos de vida. Portanto, o objetivo deste trabalho é definir e modelar, de forma gráfica e qualitativa, uma ferramenta para o desenvolvimento da suportabilidade envolvida na fase de preparação do ciclo de vida de novos sistemas aeroespaciais complexos. A fim de manter tal ferramenta relevante e considerando o contexto atual da indústria, estabeleceu-se a necessidade de que ela seja, desde a concepção, adequada e integrável ao paradigma da Indústria 4.0, assim como à novas tecnologias a serem desenvolvidas, sendo utilizada uma abordagem baseada em gêmeos digitais, em caráter embrionário. O procedimento seguido foi o de fornecer uma revisão das definições e classificações de gêmeos digitais observadas na literatura e compará-las com as características esperadas para a ferramenta, a fim de explicar os motivos pelos quais tal abordagem foi identificada como adequada para auxiliar na tomada de decisão no ciclo de vida do suporte de sistemas aerospaciais complexos. Portanto, devido a suas características inerentes esperadas, decidiu-se por denominá-la como Gêmeo Digital Embrionário do processo de desenvolvimento da suportabilidade na fase de preparação de um sistema aeroespacial complexo. Em seguida, foi estruturado o desenvolvimento conceitual da suportabilidade unificado ao processo geral de desenvolvimento de sistemas, com base em referenciais teóricos, objetivando apresentar a abordagem utilizada pela ferramenta, com especial destaque para a integração entre tais processos. Por fim, foi definida uma prova de conceito com estudos de caso, como meio de avaliar as características desta ferramenta na tomada de decisão. Como resultado e para afirmar a sua relevância, este trabalho apresenta um modelo de alto nível desta ferramenta, posicionando-a no contexto de desenvolvimento da suportabilidade de sistemas aeroespaciais complexos na era da Indústria 4.0.

Abstract

Experience from industry shows that, when developing the support characteristics of a new aerospace system, supportability needs may be considered too late in the process or not be properly integrated with other system needs, leading to difficulties, lack of innovation and a series of constraints to the supportability performance of these systems, particularly when they enter into service and throughout the rest of their life cycles. Therefore, the purpose of this work is to model, in a graphical and qualitative way, a tool for the development of the supportability involved in the preparation phase of the life cycle for new complex aerospace systems. In order to keep its relevance and considering the current context of the industry, it was established that the tool must be, from conceptualization, adequate and integrable to the Industry 4.0 paradigm, as well as to new technologies to be developed, using, therefore, an approach based on digital twins, in an embryo scheme. The procedure followed was 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 tool, in order to explain the reasons why this approach was chosen as suited to assist in decision making throughout the complex aerospace support system life cycle. Therefore, due to its inherent expected features, it was decided to be named as Embryo Digital Twin for the supportability development process in the preparation phase of a complex aerospace system. Then, a framework for the supportability conceptual development unified to the overall system development process was defined, based on theoretical references, aiming to present the approach used by the tool, with special emphasis on the integration between these processes. Finally, a proof of concept with case studies was defined, as a mean to assess the expected features of the tool on decision-making. As a result and to state its relevance, this work presents a high-level model of this tool, positioning it in the context of complex aerospace systems supportability development, in the Industry 4.0 era.

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List of Abbreviations and Acronyms

OEM	Original Equipment Manufacturer
IPS	Integrated Product Support
RAM	Reliability, Availability and Maintainability
LCC	Life-Cycle Cost
DT	Digital Twin
PHM	Prognosis and Health Management
SMRL	Supportability Maturity Readiness Level
CONOPS	Concept of Operations
PMI	Project Management Institute
MBSE	Model-Based Systems Engineering
CAD	Computer-Aided Design
MRO	Maintenance Repair and Overhaul
PHST	Package, Handling, Storage and Transportation
PLM	Product Life-Cycle Management
IDT	Intelligent Digital Twin
BPMN	Business Process Modeling Notation
LSA	Logistics Support Analysis
LORA	Level of Repair Analysis
FTA	Fault Tree Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
MTA	Maintenance Task Analysis
CM	Condition Monitoring
DPHM	Diagnosis, Prognosis and Health Management
FRACAS	Failure Reporting, Analysis and Corrective Action System

Contents

1 Introduction

The First Industrial Revolution on the XVIII century shifted the manner on which manufacturing processes were made, paving the way for increasing complex technologies to be developed on all societal sectors. Some of the key aspects defined by it were the use of coal and steam power, as well as the increase in iron production, which made possible the expansion of mechanized factory systems and the concept of mass production (WRIGLEY, 2018), effectively establishing the industry as known nowadays.

These allowed the occurrence of the Second Industrial Revolution or Technological Revolution, on XIX, which, in turn, focused on the application of the scientific method to understand why the things worked on a certain way, leading to improvements on the technologies and allowing the development and use of electricity, communications means (as the telegraph), large-scale steel production and assembly lines on the factory systems (MOKYR; STROTZ, 1998).

All of these made possible for humanity to master the challenge of producing artifacts heavier than air that were capable of powered flight, which first and foremost were applied on the military context during the Second World War (PETRESCU *et al.*, 2017). A lot of aerospace systems are still developed in this context, therefore aerospace and defense systems will be addressed together on the scope of this work.

After the War, the basis for aircraft's commercial operation were already in place, which lead to the increase on general aviation. It was the beginning of an era where transportation of humans and products would be substantially optimized in terms of speed and humanity would overcome the last boundary known: the space. As can be deduced, an aerospace system is, by definition, a complex system, since it is "an ensemble of many elements which are interacting in a disordered way, resulting in robust organization and memory" (LADYMAN *et al.*, 2013). Note that the disorder effect is undesired, and lots of engineering efforts consists in controlling this behavior and its effects.

In terms of aircraft operations, this complexity rises even more, considering that communication with control stations as well as procedures to identify failures on their subsystems beforehand are needed to enhance safety on civil and military contexts. These concerns were somehow addressed with the emergence of the Third Industrial Revolution or Digital Revolution, on the second half of the XX century, which, in essence, dealt with telecommunications (including internet) and electronics development, shifting from mechanical and analogical technologies to digital ones, which allowed the existence of computers and robots (FITZSIMMONS, 1994).

It was possible, by then, to catch and process much more information provided by the aerospace system, which allowed the global expansion of the supply chain involved, changing the role of the Original Equipment Manufactures (OEM) from a manufacturer to the systems integrator (BLOKLAND *et al.*, 2012). This means that this entity is now expected to not only design new systems, but to integrate data from all of the suppliers, effectively controlling the supply chain in terms of production, also being able to provide guidelines for operators in terms of the overall system operation and its maintenance needs all the way to its disposal.

Before proceeding further, it is important to note that the Fourth Industrial Revolution is ongoing 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 (VAIDYA *et al.*, 2018). The Industry 4.0, as its predecessors, is expected to provide a major shift on the way society interacts, and all of the proposed changes or new developments on the engineering context must take account of the trends defined by it, as a mean to not become obsolete quickly.

1.1 Scope

A system is defined as “a regularly interacting or interdependent group of items forming a unified whole” (MERRIAM-WEBSTER, 2021), whilst an engineered system is “a system designed or adapted to interact with an anticipated operational environment to achieve one or more intended purposes while complying with applicable constraints” (INCOSE, 2016). From this, it is already stipulated that all of the parts must work on an integrated manner, and, to be successful, it is necessary for the system to be as optimized as possible in terms of technical performance at minimal cost expenditure.

To guarantee an extended operating time with as little as possible decrease in performance, system needs some kind of maintenance support, because the components have different levels of criticality for the overall behavior and diverse failure rates from one another. This support could be as simple as an exchange of parts, but on the aerospace context, it becomes much more complicated due to the costs, the amount of integrated facilities involved on the supply chain and the safety requirements to be fulfilled.

An aerospace system is a human product designed to fly on the atmosphere or on the surrounding space. For their development, it is necessary to combine diverse kinds of science fields and technologies on a coupled manner.

A lot of time and effort is applied to develop such complex systems, and to facilitate the understanding of the process and its traceability, the developers tend to divide it on 5 phases, namely: Preparation, Development, Production, In-Service and Disposal (ASD/AIA, 2021c).

To be operable, this systems needs to interact with other entities, as the communication bases and all of the supporting system responsible for its operational readiness, herein referred as Integrated Product Support (IPS). IPS is composed of various related entities that have the primary goal to maintain the system operable, dealing primarily with the analysis regarding to Reliability, Availability and Maintainability (RAM), aiming to achieve the best cost-benefit ratio in terms of the related costs, safety needs and expected technical performance, which is composed of Precision, Situational Awareness and Control Capacity, respectively, as follows (ABRAHÃO, 2021):

- Precision and accuracy of the maintenance system to be sure that the information provided allows the correct diagnosis of the issues;
- Situational awareness so that the system consistently and up-to-date warns of any variations in the maintenance process that needs attention and/or intervention; and
- Ability to diagnose and act so that the system remains healthy from the point of view of its expected cost-benefit ratio.

If the IPS is addressed too late on the development, this may lead to unrealistic requirements, lack of priority on achieving reliability and maintainability and engineering process failures (DOD, 2005). Moreover, the In-Service Phase is when the system must achieve the capabilities it was designed to accomplish, also contributing to the largest portion of the Life-Cycle Cost (LCC), which exponentially increases the costs of design changes identified on this phase (INCOSE, 2015). Therefore, this approach leads to rising of issues on this phase (due to the lack of IPS testing), such as systems that are expensive to maintain, or that are not able to operate in accordance to the established specifications.

1.2 Motivation

The IPS is composed of several different elements that must work on a integrated manner to provide the best cost-benefit balance in terms of supportability performance for the system. This leads to the necessity for the design to be compliant with the capabilities expected by diverse stakeholders and for the communication among those elements on the operational context to be as effective as possible, which is a challenge generally managed with the use of systems engineering and project management.

Whatsoever, supportability problems continue to occur, which could be, as already stated, due to the support requirements being considered after the overall requirement's development, degrading the effectiveness of the cited approaches (since they rely on the correct requirements definition in the beginning of the project) and heavily impacting on life-cycle costs when the system enters into service (due to high maintenance costs or related intervals in which the system is non-operable).

The necessity for the support systems to be developed in compass with the aerospace system is sometimes addressed, but in general, it is still not a matter of fact in the industry (ABRAHÃO *et al.*, 2019). Aiming to change this mindset, this work's focus is to show a way of approaching the supportability aspects from the In-Service Phase as early as on the Preparation Phase of the system life-cycle, proposing to develop both systems on a simultaneous manner as a mean for them to become the most interconnected as possible.

On the Industry 4.0 context, the Digital Twin framework is outstanding, since it is a technology capable of connecting the as-built system to a virtual one and exchange information, providing opportunity to optimize the processes on a real-time basis. This type of technology is being implemented with success on manufacturing processes and on Product Health Management (PHM) during the In-Service phase, and some trends show that it must be integrated to the design of new products (TAO *et al.*, 2018).

Nonetheless, when considering the complexity and costs involved in the aerospace context, it becomes necessary to address its development since system conceptualization, a topic lacking on theoretical sources. It is also important to note that the use of this approach could assist on support development, specially considering the amount of trade-offs and integrations needed to achieve supportability readiness.

Notwithstanding, it is expected that the integration of a new technology on a system to be better accomplished if their development are performed on a jointly manner, so it can address correctly all of the system needs. In conclusion, this kind of framework will be discussed on this work as a tool to be developed in compass with the aerospace and its support systems, as a mean to assist the process.

1.3 Problem Statement

Complex aerospace systems reach the In-Service Phase with a low Supportability Maturity Readiness Level (SMRL), which increases overall costs and leads to operational issues. Since the literature generally focuses on specific aspects from IPS, Systems Engineering and Project Management approaches on separated ways, it is considered that one of the main gaps to be analyzed on this work is to integrate them on a single tool that assist both of these development cycles, therefore providing a holistic perspective on the system and aiming for the final product to be mature in terms of supportability readiness.

1.3.1 Primary objective

Development of a unified an integrated model that presents, on a coherent way, all elements of the Integrated Product Support connected to a Product Development Framework, for the Preparation Phase of the system's life-cycle.

1.3.2 Specific goals

This work aims to:

- Explore the logistics support problem;
- Identify and map all of the support related tasks to be held on the Preparation Phase of system life-cycle;
- Identify the gaps on the commonly used approaches to address the logistics support;
- Based on the identified tasks and gaps, define, on a high level view, a framework for the conceptual development of the Integrated Product Support in accordance to good practices defined by literature, on a graphical way;
- Integrate the framework with a system development process defined by literature;
- Develop case studies to evaluate the proposed framework; and
- Simulate the unified framework to access its expected features.

1.4 Relevance

As already stated, the cost of operation, safety and performance are the main drivers to account for the development of aerospace systems and all of them are ultimately connected on how well it is integrated to its supporting system (BLANCHARD, 2003). This work can be understood as an attempt to assist the development of those systems on the first phase of product life-cycle, specially on graphically stating the decision-making processes related to the balance of the necessary supportability cost-benefit analysis to be held, also filling the lack of a comprehensive work that clearly presents the interfaces between the system itself and its supporting elements, as well as proposing a standard process to be followed on this kind of development.

1.4.1 Delimitation of the research

The following items will not be addressed on this work:

- Detailed description of the activities to be performed for each of the elements shown: some literature sources will be provided on this behalf;
- The modeling process for the specific needs of other phases of the system's life-cycle.

1.5 Structure of the work

To assure that the problem is well defined, Chapter 2 will provide a broad review on the logistics support problem, including some common attempted solutions such as Systems Engineering and Product Management. It also brings a discussion on the Digital Twin framework, to justify the use of the concept on the tool to be developed.

Chapter 3 presents and explains the methodological approach perceived on the work, showing the definition of a Embryo Digital Twin and its expected features, development of a proof-of concept based on literature references for the Preparation Phase of system life-cycle and addressing the technical procedures utilized for simulation and evaluation of results, as a mean of achieving the defined goals.

Chapter 4 presents the developed framework, showing its expected features, as well as the expected sequence for the activities from the diverse Integrated Product Support elements to be performed, on an unified framework connected to the system's life-cycle. All of these are specified in terms of the first phase of development, concerning with the early design for operation rather than focusing solely on the In-Service Phase.

It also presents verifications on the model and discuss its utilization as a mean to enable the generation of a Digital Twin, and its capabilities as a tool to assist decision-making and knowledge management for the diverse stakeholders involved.

Chapter 5 concludes the work presenting a brief overview of the findings, and states the contributions in terms of the integration, in a single framework, of the diverse disciplines involved on supportability development and the usefulness of the model as a basis for Digital Twin development as well as its ability to assist knowledge management and decision-making on organizations, as discussed on the previous chapter. Finally, some prospects on future implementations are shown.

2 Literature Review and Theoretical Reference

An extensive literature research was made on the context of the problem, aiming to clearly identify the gaps on the existing approaches concerning product development, as well as establish arguments on the relevance of the work in terms of the costs involved. In addiction, the Digital Twin concept and current applications are presented, in conjunction with the Digital Thread concept and Knowledge Management, as a mean to explain the reasons for their use on the conceptualization of the proposed model.

2.1 Supportability Maturity Readiness Level

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, lead to the definition of the Supportability Maturity Readiness Level (SMRL) curve, which presents the consequences of the supportability activities established and accomplished on the early phases of the development of a complex aerospace system and how they affect the Deployment Phase (considered here as the time interval between the delivery of the first system to the first operator and the proceeding to mass production for that project) (ABRAHÃO *et al.*, 2019).

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.

However, a much more complicated scenario may happen. If, for any reason, almost no supportability requirements were engineered from the Concept of Operations and, only after the development of the first prototypes some maintenance requirements were taken into account, the SMRL may become way below the expected values. Without a good understanding of the supportability factors behavior, it is almost impossible to manage the readiness of the fleet within cost expectancy. Figure 2.1 presents two situations:

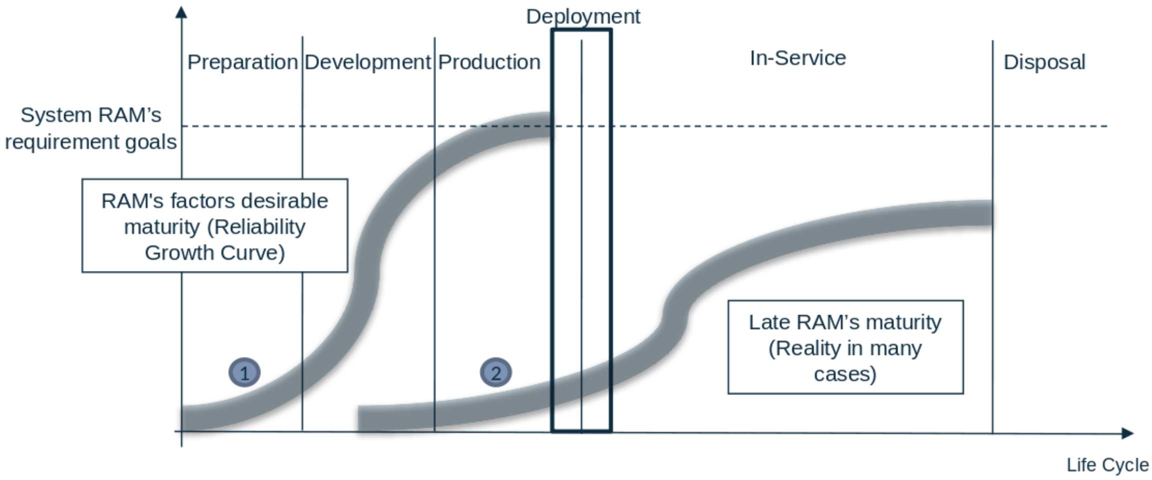

FIGURE 2.1 – Supportability Readiness Development - Adapted from (ABRAHÃO, 2021)

- In the first, supportability requirements are addressed early in system development (on the Preparation Phase), achieving deployment (first delivery for the first customer) with the expected maturity in terms of Reliability, Availability and Maintainability factors, i.e. is capable of providing the desired capabilities according to the expected operational scenarios;

- Whilst in the second, supportability requirements only begin to be addressed in the middle of the Development Phase, where some architectures of the system are already defined, which leads to the need for support aspects to be adapted accordingly and may cause system to achieve Reliability, Availability and Maintainability factors that are below the expected not only on deployment, but throughout all of the remaining system life-cycle.

The absence of supportability engineering at the conceptual 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 (GAO, 1987) and the Convair B-58 Hustler (RUSSELL, 2007) 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, which never reached the expected SMRL during its operational phase.

The primary problem related to this work is the need to make the system able to reach the expected SMRL curve, and to clearly specify the aspects to be taken into account for this expected behavior, it is important to understand the system life-cycle and the logistics support problem in details.

2.2 System Life-Cycle

A life-cycle is "the series of stages through which something (a system or manufactured product) passes" (INCOSE, 2015). As a matter of fact, it is necessary to map this process in order to maintain a certain level of traceability and to define milestones so that the stakeholders can have some control on the system. To do that, this process is, in general, divided on phases according to the level of detail available on the product and the objective of the specific phase.

There are several classifications systems, some define sub-phases for better specification, but all of them can be summarized on, at least, 5 primary phases: Preparation, Development, Production, In-Service and Disposal (ASD/AIA, 2021c).

The first phase is focused, initially, on prospecting the desired characteristics the system must have and what missions it should accomplish, formulating its concept of operations (CONOPS), which generates the Support Concept for the system that then leads to the development of the Maintenance Concept, all of them related to the top-level system requirements. As can be seen, this phase complies mostly with the business level, aiming to establish the feasibility and desirability of new systems.

Whatsoever, it starts to shift to the engineering level with the development of the system architecture and identification of technical risks and technological development needs, addressing the optimality aspects of the product to be developed, which is made by analyzing trade-offs in the effort to find the most cost-effective design (KAPURCH, 2010). This phase is referred here as the Preparation Phase.

The second phase deals with the development itself, how a system can achieve the features expected at the minimal cost and with the best performance possible. The focus initially is on the development of a functional architecture for the system, presenting all of the interfaces it must have and how they should work on a integrated way.

Once the logical architecture is established, the focus change to the development of the physical architecture of the system, refining the design and the analysis made to the subsystem or even component level, and finally defining the complete design, ready for prototype production and testing (KAPURCH, 2010). It is important to highlight that the related supportability must also be developed and pass through these steps in this phase, as a mean to fully address all the needs and requirements that the system must fulfill. This phase is classified as the Development Phase, and, as can be inferred, its basis is the engineering level.

The third phase complies the manufacturing of the product, the way it must be produced so the defective parts are kept to a minimum, the quality assurances that must be made so the reliability of the final product can be maintained on a high level and the integration or assemble of the diverse elements on the final product. Since the integration occurs on this phase, various verifications and validations also happens here, and only after the certification process the product is ready to full-rate production (DOD, 2005).

At this point, attention is paid on the optimization of the production process, as well as the supply chain involved to minimize the costs of these activities. This is often called the Production Phase, and is related to engineering, but also with the logistics processes to assemble all of the components for the final product. This is the last chance to access the logistics support maturity level before the delivery of the first product for the first customer (deployment phase), so the tests and verification process of the product and the support system should also be performed (ASD/AIA, 2021c).

The forth phase is the operation, it deals with the behavior of the system on its proposed environment, or, in other words, it is when the system fulfills its goal. Because it is, on a temporal basis, the longest phase, tons of information regarding the system are generated here and can be used for its modernization (aiming to enhance capabilities or extent its life) or as inputs for the development of new systems (INCOSE, 2015).

In addition, this phase is when the support for the system occurs, so the Integrated Product Support (IPS) must be ready to provide the activities demanded on the most effective way possible, minimizing the time out-of-operation for the aerospace system as well as the operational cost (BLANCHARD, 2003). It is named the In-Service Phase, being also related to the engineering process, but the focus is on the logistics processes for all of the parts to work together.

The fifth phase is the disposal, which states the way the system is going to be retired, which parts can be recycled or must be disposed of, decommissions that must be made, what strategies to follow regarding the overall process as well as the applicable regulations that must be taken into account (ASD/AIA, 2021c). As expected, it is named Disposal Phase and deals with logistics and business aspects.

2.2.1 Life-Cycle Costs

As can be inferred, each of the above-mentioned phases implies different costs needs. Four major cost categories are defined (DAU, 2021):

- Research and Development costs, related to the first and second phases of system life-cycle;
- Investment costs, related to procurement and production costs, therefore to the third phase of the life-cycle;
- Operation and Support costs, related to the In-Service phase; and

- Disposal costs, related to the last phase of the system life-cycle.

Nonetheless, as one can assume, the Investment, Operation and Support and Disposal costs are closely related to the logistics aspects of the project, the first dealing with the supply chain related to manufacturing, the second with the maintenance and operational needs and the last with the out-of-phase process for the product. The costs related to the cost categories for selected system types are shown on Figure 2.2 (DOD, 2020).

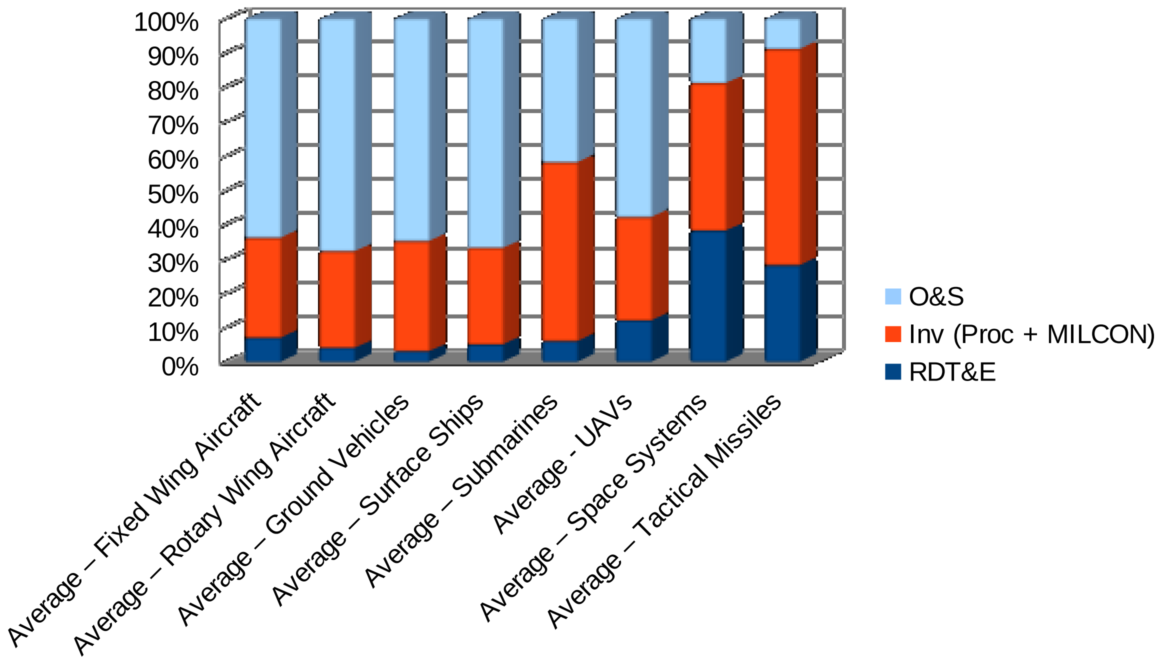

FIGURE 2.2 – Major Cost Categories as percentage of Total Life-Cycle Cost for Selected System Types - Adapted from (DOD, 2020)

On the scope of the present work, it can be seen that for the aircraft and UAV cases, the Operation and Support costs complies for more than 60 percent of the total costs retrieved on that analysis, whilst in the cases of tactical missiles and space systems it is the least cost category. This behavior can be explained because these latter systems are designed to rely on minimum to zero maintenance, due to their operational environment.

This constraint is also the reason why the investment costs in these cases rise, since it leads to the necessity for items that must have the highest possible reliability characteristics to prevent system failure. Since investments costs are derived on procurement and production costs, being the first directly related to the supply chain and the latter to the integration of the product, they are clearly related to supportability aspects. Also, reliability is a discipline pertaining to the logistics support, so it is clear that even for these cases, an approach regarding on logistics support is applicable.

Another important point to be analyzed refers to the costs of changes in design, since the development process is affected by variable conditions, especially when it comes to long-term projects as the aerospace ones. Figure 2.3 shows the impact of changes on the design in terms of costs (INCOSE, 2015).

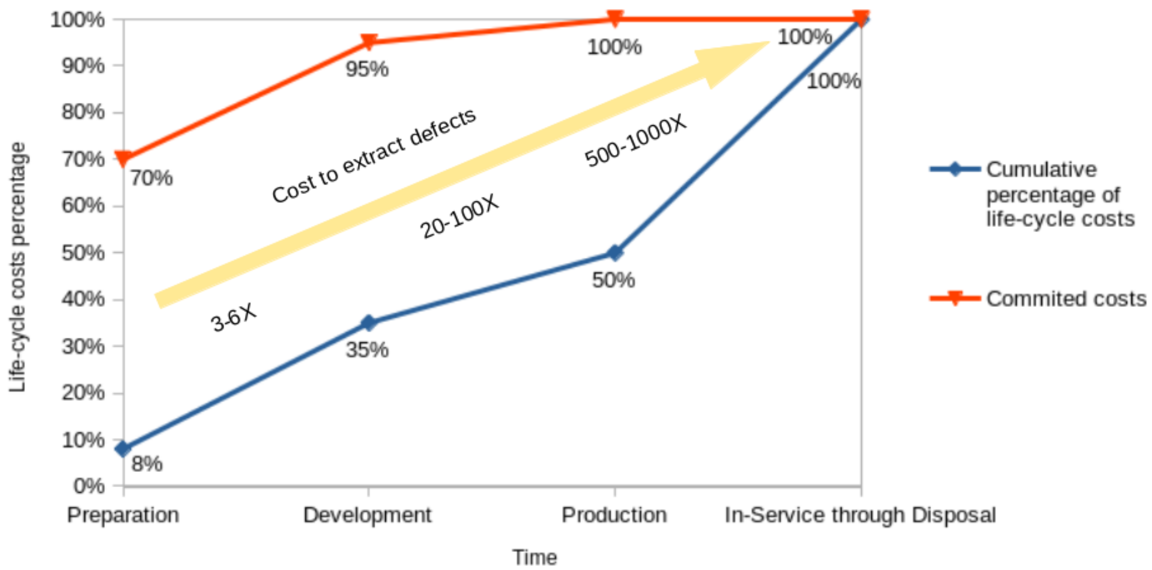

FIGURE 2.3 – Committed life-cycle cost against time - Adapted from (INCOSE, 2015)

As can be seen, changes performed on later phases amplify the costs to the extent that, in some cases, the system can become unfeasible.

Analyzing both of these data, one can infer that it is important to correctly establish the operational and support requirements as early as possible on the development process, due to the costs related to this phase and the huge impact caused by design changes that may occur if needed. Since operation and support are characterized by the interconnection between various organizations on a integrated manner, it is a logistics support problem.

2.2.2 Project Management

A project is defined as "a temporary endeavor undertaken to create a unique product, service, or result. The temporary nature of projects indicates a beginning and an end to the project work or a phase of the project work." (PMI, 2021). In general, system development follows some methodology on Project Management, for the sake of organization, primary in terms of scope, costs and time.

In this context, the most known and used methodology is the one defined by the Project Management Institute (PMI), which relies on ten knowledge areas (JOVANOVIC; BERIC, 2018):

- Project Scope Management: aiming to ensure that all of the work necessary to complete the project is addressed;

- Time Management: definition and management of the time intervals expected and effectively consumed by the project;
- Cost Management: analysis related to developing the project according to the approved budget;
- Human Resources Management: evaluations regarding to project team organization and management;
- Communication Management: collection and usage of the information associated to project execution;
- Risk Management: analysis of hazards related to the project, response planning and risk controlling;
- Quality Management: evaluation on the quality demanded for the project being developed to comply with its expected features;
- Project Integration Management: coordination on the various processes and activities to assure the project is being held according to the constrains on the diverse related domains;
- Negotiation in Procurement Management: relationship with suppliers to ensure all the materials are available when required on the development cycle; and
- Project Stakeholder Management: identification and engagement of the stakeholders on the project, seeking to guarantee that their needs are satisfied with the product being developed.

It can be understood that this approach relies on the business characteristics of the management, since it addresses the organizational perspective of the project, as identified by these knowledge areas. This means that the detail level is related to a broader context, in which project management would rather deal with team scheduling than with tests results evaluation as a mean to identify that further analysis are required to be done by the team for assurance that the system complies to a specified requirement.

As can be seen, this methodology is comprehensive and aims to serve as a standard and a guide (KARAMAN; KURT, 2015), proposing, also, five groups of processes to create a complete framework (WRIKE, 2020):

- Initiating Processes: includes identification of stakeholders and creation of the project charter, which is a description of the proposed project;

- Planning Processes: as can be inferred, is the group of processes related to the plan of project development;
- Executing Processes: is related to the management of activities and tasks required for the project to be carried out;
- Controlling and Monitoring Processes: aims to help identify and mitigate any potential issues, that may happen throughout the entire project as a mean to ensure there is sufficient oversight on it; and
- Closing Processes: ensures that the customer has accepted all final phase or project deliverables and that documentation is complete and stored.

It is interesting to note that this framework can be applied to any phase of the system life-cycle and this, on the other hand, can be thought of as a net of projects (as defined by this methodology) interconnected to each other. Nonetheless, the complexity grows exponentially when one consider that there are several enterprises connected on a supply chain, each one managing correlated projects that needs to be integrated on the final product, as happens on the case of aircraft development and operation.

2.2.2.1 Business Process Model and Notation

The term business model was first used on 1957 and is broadly seen as “an approach to the abstract representation of a company’s structure or architecture” (WIRTZ *et al.*, 2016). From this, it is readily related to the role of Project Management, on the managerial aspect it holds as a mean to analyze all of the processes occurring on the company (or to develop a product) and their interactions and interfaces. The main difference lies on the time aspect, since the project, as already said, is expected to have a clearly defined duration, whilst business processes can be updated according to the company’s needs and keep recurring.

Nonetheless, when a project is complex such as the ones on the aerospace context, they can, as already mentioned, last for so much time that the related process could be understood and evaluated in the same way as business processes, specially when it comes to the supportability aspects, since they deal, by default, with the interrelation between suppliers, manufactures, clients and other stakeholders that demand not only a engineering perspective, but also a logistics one. This leads to the necessity of an integrated approach to deal with supportability, since the cost-benefit analysis cannot be made based only on technical aspects.

As a mean to enhance business understanding of the internal procedures using a graphical notation, as well as communicating these in a standard way, the Business Process

Model and Notation (BPMN) was created (OMG, 2022). This helps the stakeholders to understand how the process is supposed to behave (thus documenting it), and could also be thought as a meaningful tool to assist on training people on their expected tasks across the organizations, due to the fact that people can understand the notation without prior knowledge about it (KOCBEK *et al.*, 2015).

Whatsoever, as can be inferred by the above-mentioned features, BPMN could be used to model any type of process, including the ones used for Project Management and related to system life-cycle phases.

2.2.3 Systems Engineering

Systems Engineering was developed as a field aiming to coordinate all of the diverse technical areas related to systems development, as a mean to guarantee that the product at development would comply with its requirements and, as a consequence, fulfill the needs for which it was conceived. The domain was formally recognized in 2002 with the introduction of the international standard ISO/IEC 15288 - System Life-Cycle Processes (HASKINS *et al.*, 2006).

As a matter of fact, there is not a specific definition on the term, since it is a novel area, but a representative one is "Systems engineering is an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system" (EISNER, 2008).

It is clear, then, that this approach heavily relies on the elicitation and definition of requirements based on the needs of the stakeholders for the systems, since those are the foundation for all of the following activities and integrations to be held during the development process.

On the other hand, this area must address and negotiate with the diverse engineering fields to provide the optimal solution for the system, ensuring that the design proceeds smoothly across diverse domains, which means that the development or changes made by one field do not degrade the performance of the others.

Systems Engineering is expected to be used on aerospace system's development, since these are complex systems and this field is designed to face the challenges proposed by them once the control on the constraints and interfaces is carried out throughout the entire life-cycle. Also, this methodology understands and is planned to deal with systems as a whole, considering them as bigger than their constitutive parts, with special attention to the emergent features envisioned (KOSSIAKOFF *et al.*, 2011).

In general, the process follow a top-down approach, in which the requirements are derived on system's specifications, which are further decomposed to subsystems and components level. Then, the components are developed, verified and validated against those specifications and integrated on subsystems, which pass by the same process and are finally assembled on the system, that is verified and validated by the stakeholders on terms of the expected features for the overall system. This approach is know as Vee-model (HASKINS *et al.*, 2006) and is represented on Figure 2.4.

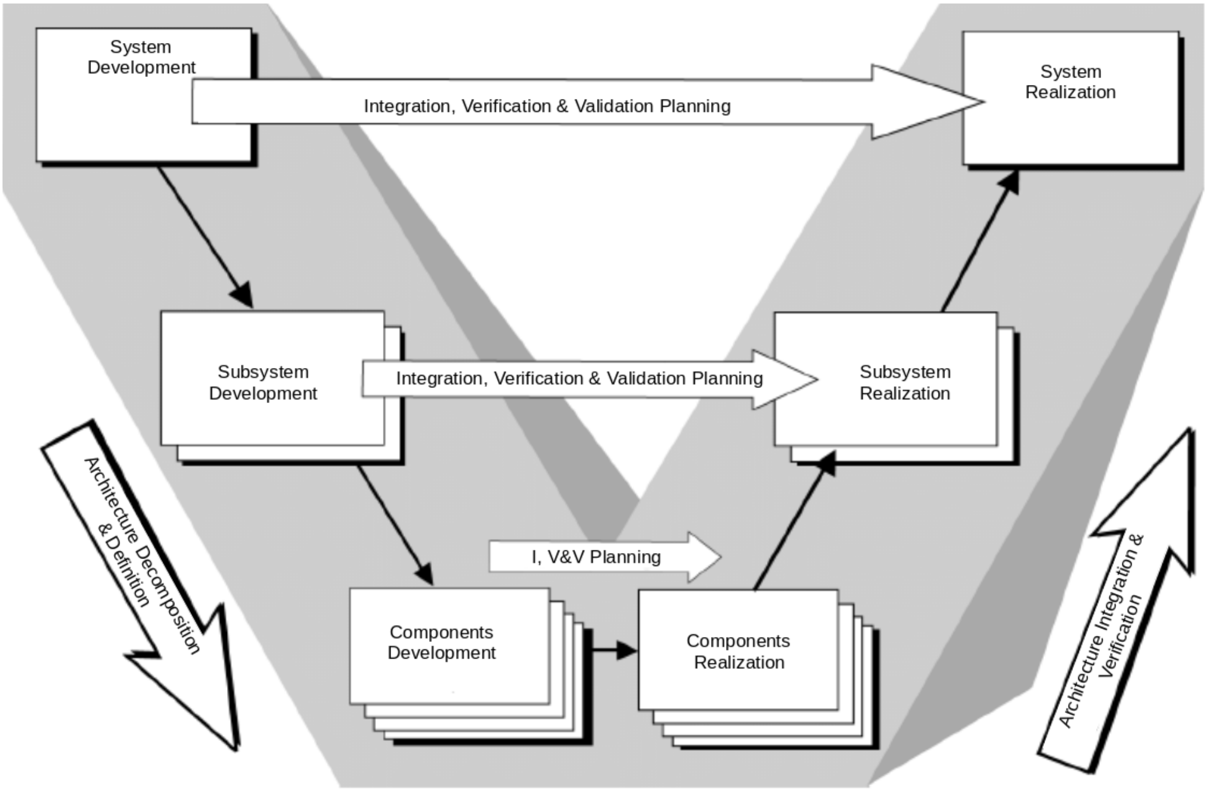

FIGURE 2.4 – Vee-model - Adapted from (HASKINS *et al.*, 2006)

It is important to note that this approach foresees the need for reviews on a regular basis to guarantee not only the verification and validation processes, which analyze the fulfillment to the requirements and constraints, but also to address operational risks and the aforementioned interface between the areas. Some of these reviews are held on predefined milestones, as the ones in which the system pass from one life-cycle phase to another (HASKINS *et al.*, 2006).

The focus on the requirements and the consequent holistic view of the system places Systems Engineering on the role of integrator for product development, but it is necessary to note that, although this approach can be very effective on guaranteeing the delivery of a product that complies with the requirements, if their elicitation lacks on some aspect, the final product will also carry those issues. This is another major argument on the need for supportability analysis to be held on the initial phases of product development, as a mean to assure that these aspects are considered and defined as requirements and constraints of the system to be created in a timely manner, helping to keep the SMRL curve aligned to its expected development.

2.2.3.1 Model-Based Systems Engineering

A model can be defined as “an abstraction of a system, aimed at understanding, communicating, explaining, or designing aspects of interest of that system” (DORI, 2011). This means that, on the context of systems engineering, a system can be translated into a model as an effort to specify, design, analyze and verify its features on a specified environment, as well as to share this information with other stakeholders.

On the other hand, system development needs to be extensively documented as a mean to maintain traceability, avoid repetition of mistakes and generate material for its proper understanding and operation. Due to the lack of technological development, this was initially performed on a paper-based approach, in which all system related data was stored and exchanged between the diverse entities when needed.

With the advent of computational tools, the creation of digital models was possible, and they were implemented on engineering since the 1960s, generally on specific and disconnected cases such as Computer Aided Design (CAD) or simulations on the diverse engineering domains (HART, 2015).

Systems engineering, although, continued to be performed and controlled on a document centric approach, in which the system was treated throughout the establishment of static baselines that were updated on a timely basis, in consonance to the Vee-model (HASKINS *et al.*, 2006). Even though these baselines where integrated to these digital models, they were not capable of presenting all of the advantages of the digital capabilities, since the tools were not integrated and the updates on the overall systems would still require a manual procedure to be performed.

To solve this issue, the Model-Based Systems Engineering was defined as “the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life-cycle phases” (HART, 2015).

An initiative on this behalf is being made by INCOSE, aiming to provide the following benefits on the area (FRIEDENTHAL *et al.*, 2007):

- Improve communication between the involved stakeholders;
- Enable the model to be viewed from multiple perspectives, increasing the ability to manage system complexity and to analyze the impact of changes;
- Improve quality through an unambiguous and precise model that can be evaluated for consistency, correctness, and completeness;
- Enhance reuse of information by the use of a standardized model and leveraging

built in abstraction mechanisms inherent in model driven approaches, which could lead to lower maintenance costs to modify the design; and

- Improve knowledge management in terms of capturing, teaching and learning, by providing a clear and unambiguous representation of the concepts.

There are tools applying the MBSE structure being development, and this is expected to be common place in the future, since it is lined up to the digitization trends on the industry 4.0 paradigm, that seeks to provide real-time monitoring and understanding of the systems being developed and operated, as will be further discussed. This leads to the need of the current proposed frameworks to be aligned to this expected behavior.

This concludes the overall understanding of the context in which the problem lies, presenting the management and system engineering views on system life-cycle together with the costs associated and expected features to be accounted. Next, the supportability aspect of the problem will be discussed, in general terms.

2.3 The logistics support problem

The In-Service phase is, as already cited, the longest one of the system life-cycle and, as a mean for a product to be operational, one would expect that it must be maintained, or, in other words, some activities must be held to assure its operational readiness. This translates in calculations on the time to failure for the diverse components of the system, as well as the abilities necessary to operate and change its parts, along with equipments and training needs.

Initially, these activities were controlled and performed by one single enterprise, but, with globalization, this was pulverized across several entities, such as airlines, suppliers and Maintenance, Repair and Operations (MRO), even though the Original Equipment Manufactures (OEM) still holds a major function as the integrator for these activities, since it is the one responsible for system development (BLOKLAND *et al.*, 2012).

Complex systems rely on advanced logistics support structures aiming to minimize the downtime (when the system is passing through maintenance tasks and, therefore, is not operating), since this means financial losses.

It should be noted that there are constraints derived of these structures that must be imposed on system development and it is possible to upgrade the activities to be performed using information on this existing environment, which means that one can develop a system that is easier to maintain based on pre-determined conditions. Also, during development, the manufacturer can design additional services that could facilitate operation or provide innovation, which is another reason for the logistics support development to occur together and aligned with the system's development, as presented on the first situation shown on the SMRL curve (ABRAHÃO *et al.*, 2019).

2.3.1 Reliability, Availability and Maintainability - RAM factors

Operational readiness can be attained when a conjunction of factors are considered and modeled to guarantee the supportability of a system. These are know as the RAM factors, concerning Reliability, Availability and Maintainability, which refers to some features expected for the system to have in order to minimize its downtime (when the system is passing through maintenance or correcting some unexpected failure).

Reliability is related to the probability of failure occurrence, or, in other words: "Reliability measures the probability that the system will perform without failure over a specified interval under specified conditions" (DOD, 2009). This means that it is a feature intrinsic to the project of the system, derived from its physical aspects and interfaces. It can be estimated by the manufacturer to a precise value and, if the production process occurs according to the specifications, the parts are expected to degrade in consonance to a pre-defined behavior for each operational environment envisioned when developing the system (DOD, 2005).

On the other hand, maintainability is "a characteristic of design and installation which is expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time, when maintenance is performed in accordance with prescribed procedures and resources" (BLANCHARD *et al.*, 1995). It can be inferred that this is related to how the system is conceived in terms of the needed maintenance actions, concerning their easiness, accuracy, safety and related economic factors.

There are two main types of maintenance actions, being the ones that occur when the failure already happened called corrective maintenance. Since the degradation of components can be tracked and occurs according to a specified behavior, the failure can be avoided with preventive maintenance tasks, which are conceived to restore the part's reliability to a previous level, being the second type of maintenance mentioned. These maintenance frequencies and their respective elapsed times can be measured and accounted as the maintainability for a determined system.

Availability is "a measure of the degree to which an item is in an operable state and can be committed at the start of a mission when the mission is called for at an unknown (random) point in time" (DOD, 2005). It can be understood as the concatenation of the aforementioned factors, due to the fact that those are complementary in the sense that they must balance each other, since the occurrence of more failures (poor reliability) ideally implies on better maintainability to attain the same availability.

This can be exemplified as follows: if a system was perfectly reliable, which means that a failure would never occur since the part would not degrade, it would not matter its maintainability characteristics (the time to perform maintenance could be very long) and it would still be always available. Conversely, if it was perfectly maintainable (zero time to perform any maintenance action), it would not matter its reliability characteristics, failures could constantly occur, but the system would also be always available for use.

It is important to note that these are not the only factors that affect availability, since maintenance actions relies not only on the frequency and times demanded, but on a support system to occur. Personnel, equipments, spare parts, etc are finite resources that must be allocated for these activities to take place and can not be pre-defined as a project parameter. This leads to the need of understanding the product support structure.

2.3.2 Integrated Product Support

To provide support for system's operation, and due to the complexity involved, the Integrated Product Support approach was developed aiming to address all the supportability for the desired system to be planned, acquired, implemented, tested and provided in a timely and cost-effective way, based on the definition of twelve interconnected elements to be integrated systematically, as presented on Figure 2.5 (DAU, 2021). A brief introduction on all of these elements is necessary to understand the problem at hand.

2.3.2.1 Product Support Management

This element is responsible for the management of all the other elements throughout the life-cycle, which means that it must develop and implement strategies to ensure supportability is considered throughout the system life-cycle and that the RAM factors are optimized. It is responsible for the development of the IPS plan, which is a living document that contains the links between activities to be performed by the other elements, that must include the support strategy and identification of key milestones and decision points for the current phase and plans for the succeeding stages concerning logistic support (ASD/AIA, 2021c).

This can be correlated to Project Management, due to the management aspect required and the business relationships derived from the need for negotiations with suppliers and other entities related.

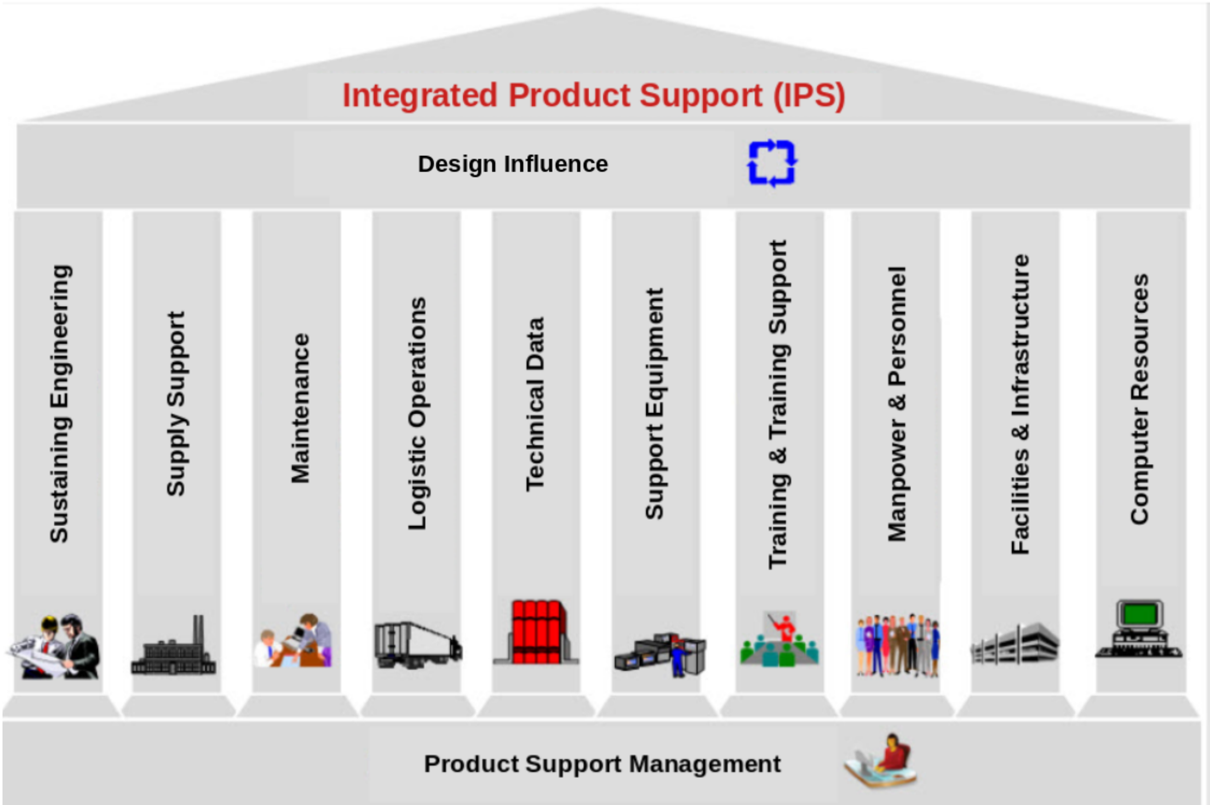

FIGURE 2.5 – Integrated Product Support elements - Adapted from (DAU, 2021) and (ASD/AIA, 2021c)

2.3.2.2 Design Influence

As suggested by the name, this element concerns for the integration of the quantitative design represented by the RAM factors with the functional ILS elements. This means that it represents the interface between the system development and the logistics support needs that can affect the design, reflecting the relationship between design parameters and support requirements (DAU, 2021).

The activities performed on this element relate to the Support Engineering Analysis (previously called RAM analysis) which seeks to define and design the overall supportability for the system, since it is expected that, if the development does not comply to the supportability requirements then it must be changed, from where the name of the element is derived. Also, the Life-Cycle Cost Analysis is performed as part of this element, as a mean to guarantee that the project is aligned to the expected budget (ASD/AIA, 2021c).

As can be inferred, this can be connected to the System Engineering aspect, since it needs to be able to define supportability requirements and negotiate with the other domains to assure system compliment to them.

2.3.2.3 Maintenance

As can be deduced, it was the first element and is the most prominent one, since all of the others could be seen as included on it, due to the fact that the product itself effectively only deals with the maintenance activities, it is not concerned with the background needed for them to occur. It states the activities to be performed aiming to bring the system back to a desired operational level, at the lowest possible cost.

On a formal definition, it has the goal “to identify, plan, resource, and implement maintenance concepts and requirements as well as to execute the maintenance to ensure the best possible equipment/capability is available at an affordable cost” (ASD/AIA, 2021c).

Activities such as the definition of the Maintenance Concept and Preventive Maintenance Plan occurs here and seek to describe the approach chosen for system development in terms of supportability. Also, Maintenance Task Analysis and Level of Repair Analysis deals with the actual estimation of maintainability for the system, while Supportability Safety Analysis and Diagnosis, Prognosis and Health Management relates to the identification of hazards and the monitoring of components’ degradation, respectively.

These three elements will be further detailed on the work, since the aforementioned activities related to them can be performed readily on the first phase of system life-cycle, while the next ones needs the project to be a bit more advanced to be evaluated, since they rely on decisions to be performed on later phases.

2.3.2.4 Manpower and Personnel

Maintenance actions have been historically treated as a intrinsic human-related activity, due to the amount of details that have to be dealt with, as well as the safety requirements constraints on the aerospace environment. It brings the need to evaluate the skills and qualifications desired for someone to perform the necessary tasks and the derived ergonomic requirements that must appear on the design. Manpower refers to the number of individuals required to perform a specified task whilst personnel indicates the human skills, knowledge, abilities and experience levels needed to properly perform those tasks (DAU, 2021)

2.3.2.5 Facilities and Infrastructure

This elements focuses on the required infrastructure for the maintenance actions to be performed. It deals specially with permanent (or semi-permanent) assets, that often needs long lead times to be on a operational status, so it must be considered as early as possible on the design. As a formal description: “consists of the permanent and semi-permanent real property assets required to support a system, including studies to define types of facilities or facility improvements, location, space needs, environmental and security requirements, and equipment” (DAU, 2021).

2.3.2.6 Computer Resources

As the system’s dependence on hardware and software is increasing continuously, this element specifically address these critical systems, covering “all computers, associated software, interfaces and the networks necessary to support scheduled and unscheduled activities at each level of maintenance” (BLANCHARD, 2003). It also identifies the necessary improvements or new features to be implemented as a mean to improve the supportability, and includes condition monitoring programs.

2.3.2.7 Supply Support

Its responsibility is to design an optimized supply support structure, dealing, for example, with the repair parts and spares subcontractors to foresee the expected deadlines and costs, as well as those assets needs for initial operation and the necessary storage for the minimal logistics delay (inventory management). A proper management of this element should result on all classes of supplies (such as spares and repair parts) available in the right quantities and at the right place, time and price (DAU, 2021).

2.3.2.8 Logistic Operations

Formally, this element is defined as “the combination of resources, processes, procedures, design, considerations, and methods to ensure that all system, equipment, and support items are preserved, packaged, handled, and transported properly, including environmental considerations, equipment preservation for the short and long storage, and transportability” (DAU, 2021). This means that the main purpose is to clearly identify the needs for special handling, in terms of the integration to the human resources, as a safety aspect. The other analysis to be made focuses on maintaining the assets on the expected operational level (packaging and storage) and minimizing the logistics delays (transportation) related.

2.3.2.9 Support Equipment

This element focuses on the necessary equipment (mobile or fixed) that needs to be available as a mean to maintain the system’s operational readiness on pre-defined desired level and at the lowest possible cost. To do that, it is important to consider the legate equipments already available on the inventory, minimizing the development of new ones (ASD/AIA, 2021c).

2.3.2.10 Technical Data

It contains all the data recorded from the development of the system, including specifications, manuals, drawing and other information needed to support and operate the system. When it comes to knowledge management, this element is of great concern, since the development and operation of a system often lasts for years, and a large amount of information is lost due to human resources changes, which can lead to rises on terms of costs. It does not include computer software or financial/management data. (DAU, 2021)

2.3.2.11 Training and Training Support

To guarantee the human resources are ready to handle the diverse features for the system at hand on the most effective way, it is necessary to provide training on the expected operation and support activities, so this elements deals with the associated resources needed to perform these activities, including initial and replenishment training (BLANCHARD, 2003).

2.3.2.12 Sustaining Engineering

This element is the main focus on the Operational phase, since it deals with the engineering and logistics analysis concerning the data acquired on the field. It relies on technical tasks aiming to ensure continued operation for the system until its disposal and includes implementation of corrective actions on it and the monitoring of its health management (ASD/AIA, 2021c).

The functional division on the twelve elements has the goal to help one understand the many factors related to an effective support management and its relation to the overall system operation, but the readiness is also related to the capacity of doing the necessary analysis and developments on a time basis consonant to the development, which is not always the case, as presented by the second situation shown on the SMRL curve.

2.4 Industry 4.0 and digitization trend

Industry 4.0 refers to the Fourth Industrial Revolution focusing on automation and digitization of the industrial practices to provide interconnection, digitization of products and services as well as technical assistance from the systems on their own behavior

(VAIDYA *et al.*, 2018).

It is the result of technological improvements that enabled to connect the real and virtual worlds, aiming to improve the overall performance and maintenance management of the machines, according to their surrounding environments. In other words, “the idea of Industry 4.0 is to focus on the end-to-end digitization of all physical assets and their integration into digital ecosystems with value chain partners.” (LELE, 2019).

This trend is based on nine pillars (RÜSSMANN *et al.*, 2015):

- Big Data and Analytics: collection and evaluation of data from many sources as a mean to assist decision-making;
- Autonomous Robots: interconnected robots that can automatically adjust their actions and work together;
- Simulation: ability to leverage real-time data to mirror the physical world in a virtual model;
- Horizontal and Vertical System Integration: universal data-integration networks that enable truly automated value chains;
- The Industrial Internet of Things: devices that can communicate and interact both with one another and with centralized controllers, enabling real-time responses with the use of embedded computing;
- Cyber security: development of secure and reliable communications means as well as sophisticated identity and access management of machines and users;
- The cloud: increased data sharing across sites and company boundaries;
- Additive manufacturing: technologies such as 3-D printing that allows creating customized products that offer construction advantages, such as complex and lightweight designs; and
- Augmented reality: ability to provide workers with real-time information to improve decision making and work procedures as well as virtual training.

As can be seen, this new paradigm aims to ensure interoperability, decentralization, real time analysis and flexible services, all based on the digitization of systems by using sensors and providing the information acquired to the internet, where analysis are made as a mean to assist decision-making by human beings.

It must be noted that the data interconnection is one of the main requirements for all of this integrated environment to work together and achieve the goals described above.

2.4.1 Digital Twin (DT)

As a result of Industry 4.0 new technologies, 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 (TAO *et al.*, 2018).

The Digital Twin (DT) is defined as the conjunction of three elements: the digital entity, the physical entity and the exchange of information between them (GRIEVES, 2014), as shown on Figure 2.6.

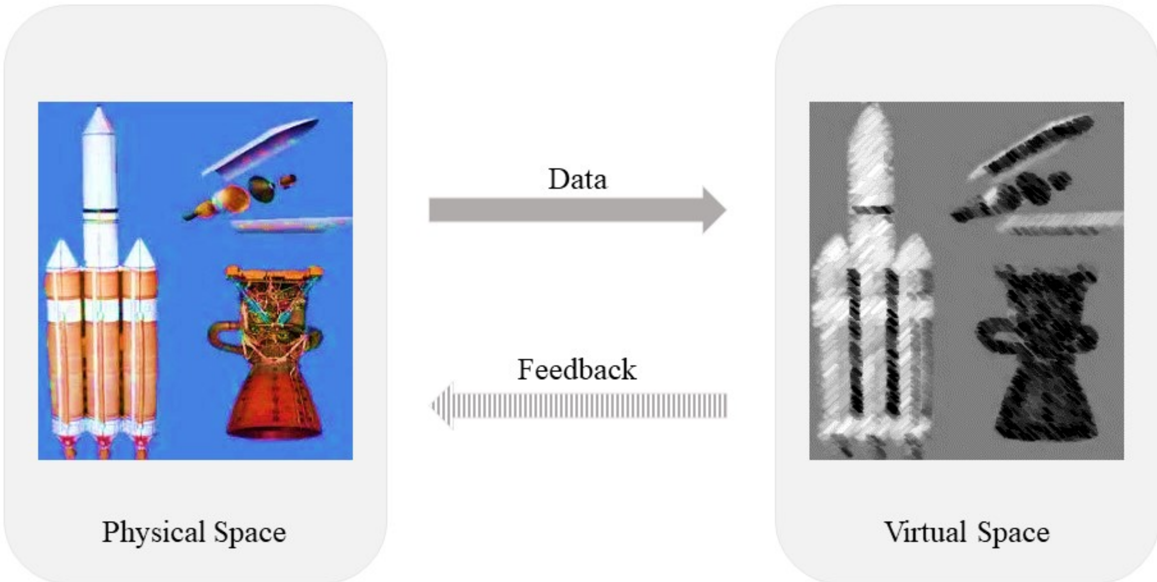

FIGURE 2.6 – Parts of a Digital Twin - Adapted from (GRIEVES, 2014)

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 Figure 2.6 is the as-built rocket, containing all of the subsystems and physical components, while the digital model has all of 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.

It is clear that this type of technology demands high computational efforts to be able to process and analyze the big amount of data provided by the real system. In this context, the evolution of technology towards Industry 4.0 paradigm, especially with the development of internet of things, cloud computing and artificial intelligence, made it possible for Digital Twins to become one of the most promising tools for the design and control of complex systems, due to its integrated nature (SCHLUSE; ROSSMANN, 2016).

It was conceived as a part of the Product Life-Cycle Management (PLM) concept, having plenty of work on its application on manufacturing processes concerning factory optimization and on Product Health Management (PHM), where the most challenging task is to link the two entities (TAO *et al.*, 2018), as already stated. There is, although, little development about its application on the other phases of the life-cycle and most of these concern with the clear definition of the concept on different types of applications rather than on the implementation itself (KRITZINGER *et al.*, 2018).

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 (GLAESSGEN; STARGEL, 2012) : "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 and/or electrical) of the system. The Digital Twin, on the other hand, is an integrated model of all the characteristics of the system. It can be thought that the Digital Twin 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.

The most complete and consensus definition found about the Digital Twin defines it as composed of five parts (TAO *et al.*, 2018): physical entity (PE), virtual entity (VE), connection (CN), data (DD) and service (Ss), as shown in Figure 2.7 (GRIEVES, 2014) and (TAO *et al.*, 2018).

The service entity was established on this definition, and the data interconnection was split into two separated ones. A possible explanation for this is that service can be

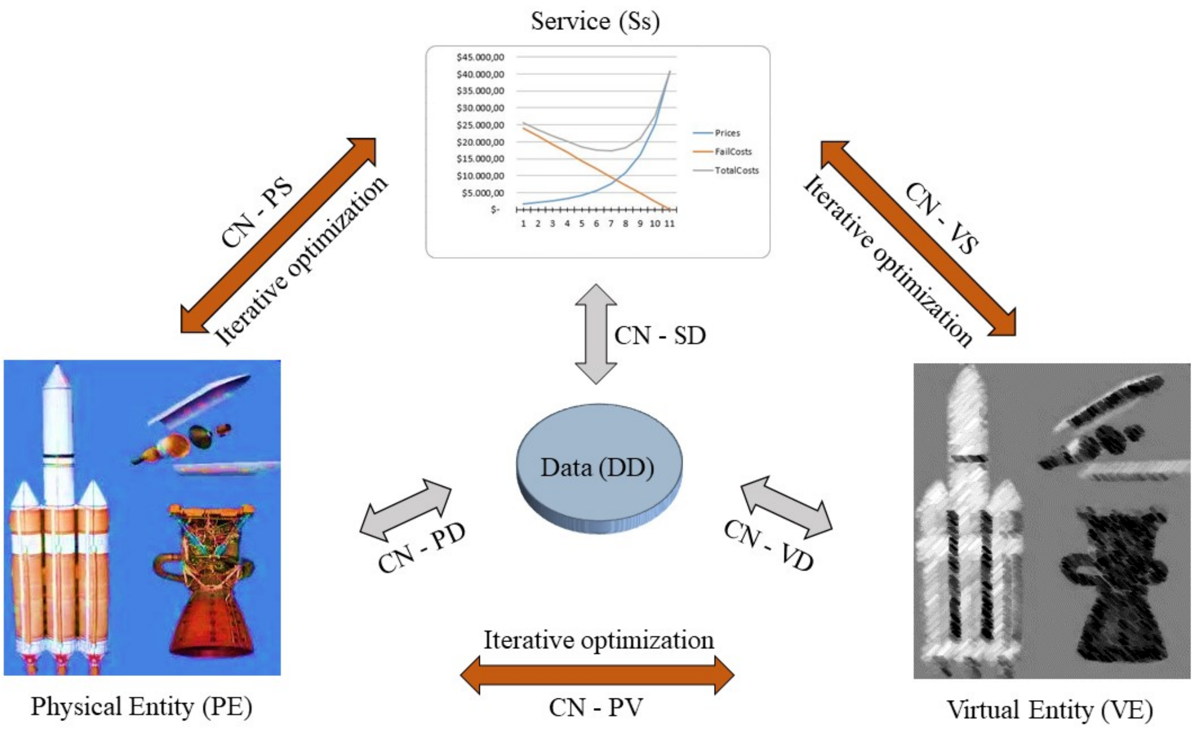

FIGURE 2.7 – Five components of a Digital Twin - Adapted from (GRIEVES, 2014) and (TAO *et al.*, 2018)

understood as the new features provided upon analyzing the system operation as well as the gaps for optimization found, which is a key characteristic on the industrial context in terms of innovation.

It is important to state that the optimization can occur directly on the interface between physical and virtual entity, as shown in the figure, being this type of optimization the focus on the initial development of a Digital Twin.

The second change concerns the data and connection separation and can be addressed on highlighting the influence of the Industry 4.0 context on this definition, due to the needs derived from the first on terms of its analysis and evaluation that can be accomplished with big data analysis, for example. The connection is the both way link between the other elements, which can be achieved using 4.0 technologies such as internet of things.

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

On this behalf, the level of integration of the proposed Digital Twin up to date can be categorized on three categories (KRITZINGER *et al.*, 2018):

- 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 of the parts are integrated and the information flows on both ways.

It is important to note that, when one have a full Digital Twin as established above, they will be able to provide new and/or personalized services.

There is, although, another type of classification, based on the level of maturity (MADNI *et al.*, 2019), 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; and
- Intelligent Digital Twin, where the system is capable of machine learning, so it can discern patterns on the operational environment and prepare the system accordingly.

Based on this, it can be assumed that a Pre-Digital Twin 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.

As such, there are some works dealing with the development and application of Digital Twin itself, on a bicycle design modernization using it. This approach is based on the evaluation of customers on a bicycle-sharing app and the data obtained from each serial number, so it can be used to improve future redesigns of the product (TAO *et al.*, 2019).

Another example suggests a new paradigm for controlling and optimizing a shaft manufacturing process, as follows: firstly, the raw materials and machining equipment are allocated according to the production task. Then, the virtual twin simulates the production to find out potential conflicts so the service system can make corrections and generate a new optimized plan. Lastly, the physical twin receives the revised plans and feedbacks the virtual twin with the former real-time state data so the latter can provide any needed adjustments on the process control (FEI *et al.*, 2018).

As can be seen, both approaches are based on the previous existence of the physical twin to provide the necessary information, so they are only applicable on the In-Service (operational) phase of the product life-cycle.

On the other hand, the need for development of digital twins in compass with early phases of the life-cycle is already being discussed, as presented for the Pre-Digital Twins, which leads to the concept of Digital Thread.

2.4.2 Digital Thread

Digital thread can be defined as an improvement of the Model Based Systems Engineering (MBSE), bringing some quantitative and analytical rigor to the design. In other words, it can be defined as “a framework for merging the conceptual models of the system (the traditional focus of MBSE) with the discipline-specific engineering models of various system elements” (WEST; PYSTER, 2015).

To do that, it is necessary for the data to be mapped through the diverse tools used and to be capable of being captured, stored, transferred, checked for completeness and consistency, and changed under change control management, so that the physical model can correctly and timely update the digital one, providing all of the people involved on the development with the same information, as a mean to work as a digital twin and assist decision-making (BONE *et al.*, 2018).

As can be seen, the Digital Thread is a key enabler for Digital Twin development, since it is necessary to develop this framework prior to the implementation of the digital entity, to ensure that all the relevant aspects are being addressed and analyzed with no gaps concerning the interfaces or emergent features of the system.

Finally, the development of a Digital Thread is intimately related to the Knowledge Management approach, which is shown next.

2.4.3 Knowledge Management

Knowledge Management deals with the need to maintain knowledge within the organization with minimal dependency on individuals, as a way to increase opportunities for innovation and decrease risks and rework. It is based on four aspects (ROWLEY, 1999):

- Creation of knowledge repositories: includes external (benchmarking), structured internal (reports) and tacit knowledge (discussion databases), as a mean to store both knowledge and information;
- Improvement of knowledge access: use of connectivity and transfer technologies to provide access to knowledge or to facilitate its transfer among individuals;
- Enhancement of knowledge environment: preparation of a environment that is effective on knowledge creation, transfer and use; and

- Management of knowledge as an asset: since value can be assigned to assets, the recognition of knowledge as one is a mean to identify their potential value, for example, on the case of customer databases and detailed parts catalogs.

Since it depends on organizational culture, it can be a real challenge to provide an effective knowledge management, but the advantages on a costly development environment such as the aerospace one is clear, since all of the system life-cycle process relies on the need to minimize rework.

It can be readily deduced that if, during the development of a new system, a repository with all of its digital thread is created, including the reasons for the decisions made during the process, the next projects could use this information as a mean to make reliable decisions on less time or to avoid rework when some path taken was found ineffective.

As a mean to provide an explanation of this perspective in the supportability context presented on this work, a set of four digital twins can be imagined, as presented on Figure 2.8. For the Conceptual and Development phases, the Embryo Digital Twin, as will be defined on this work is fed with the supportability requirements and incrementally provides an updated Integrated Logistics Support Plan, whilst also assists on promoting the integration between product and support system.

Then, the Digital Thread created with the data that was fed to, analyzed and stored on this Digital Twin can be used as a Knowledge Management repository tool to upgrade the Digital Twin to be used on the Production phase of the life-cycle development, either as and Embryo Prototype/Acquisition/Certification Digital Twin or as a Manufacturing Digital Twin. The difference between them lies on their purpose, since the first aims to deliver the Prototype Integrated Logistics Support Plan, and, as so, focuses on the product being produced and its support requirements, whilst the other aspires to work together with the manufacturing line, enhancing the production rates and minimizing administrative and logistics delays that may impact on this phase.

Lastly, when the aerospace product is deployed, this Knowledge Management repository is used again to integrate and upgrade the existing Digital Twins to the Operational Digital Twin, which should be capable of dealing with the the system as a whole, as well as the entire fleet, since it was fed up with data on all of the other phases that could point out needs for improvement on supportability aspects that were not addressed earlier due to some kind of misguiding or even changes on requirements. Since all the decision-making process is stored and could be readily connected to the actual features of the product, it should be easier to identify the impacts introduced on the supportability performance by the change of requirements and how this would affect the operation, for example.

It is important to note that all of the Digital Twins are connected and capable of sharing information to one another, since the Embryo Digital Twin as proposed here will,

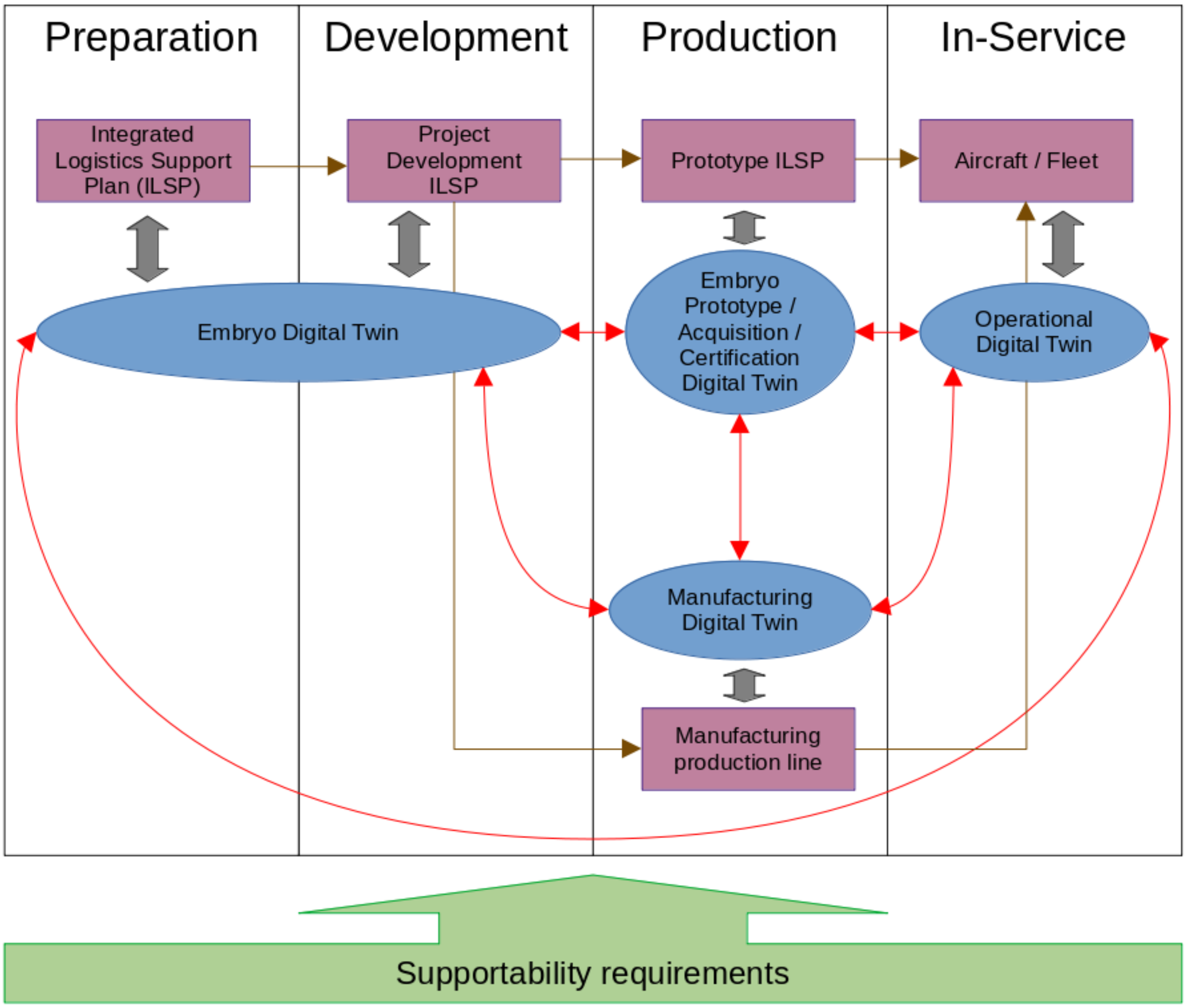

FIGURE 2.8 – Supportability Development of a Digital Twin Conceptual Framework - Adapted from (ABRAHÃO, 2021)

by design, be fed up the organizational data available, which, after the first successful implementation of the other Digital Twins should also encompass the data stored on these systems. Therefore, the approach is designed to be cyclical as a mean to help the developers to avoid problems that were already addressed on other projects and be capable of deciding based on data, as already stated.

2.5 Hipothesis

Based on this bibliographical review and aiming to start an actual description on the potential use of the Embryo Digital Twin as a tool to assist on supportability development, as a knowledge management tool and as a basis for the Integrated Digital Twin development, a hypothesis was created to address the supportability problem on nowadays Industry 4.0 environment.

Since none of the studied approaches (Systems Engineering and Project Management) consider the integrated development of supportability in consonance with system development and the references that deal specially with supportability do not provide a visualization of the activities to be performed on each phase of system life-cycle to access the desired support maturity, it is expected to define a Digital Twin-based framework that concatenates all of the Integrated Product Support development activities and is suitable for assisting on the decrease of the Supportability Maturity Readiness Level (SMRL) gap.

The Digital Twin framework is a way of reaching the digitization needs on the Industry 4.0 paradigm, but also is a mean to propose that the development data is stored and reused as a knowledge management tool within the organizations. The approach proposed by this work is aligned to the graphical representations that underline the use of BPMN and MBSE, aiming to be useful for better understating to the involved stakeholders.

Nonetheless, as a proof-of-concept, the actual problem evaluated on this work lies on the development of a high-level integrated digital tool that presents all of the support related activities to be held on the Preparation Phase of the system life-cycle as a mean to evaluate its capability of decreasing the integration issues related and being used to assist supportability decision-making processes early and throughout all of the design.

3 Methodology

The main goal of this work is to define the Embryo Digital Twin, a tool suited for assisting the supportability development and connecting it to product development since the early phases of system life-cycle.

Aiming to present some expected features and their use as a tool to assist on decision-making processes, a proof-of-concept for the Embryo DT was defined and simulated for the Preparation Phase of the System Life-Cycle.

Figure 3.1 presents the main steps executed on the work:

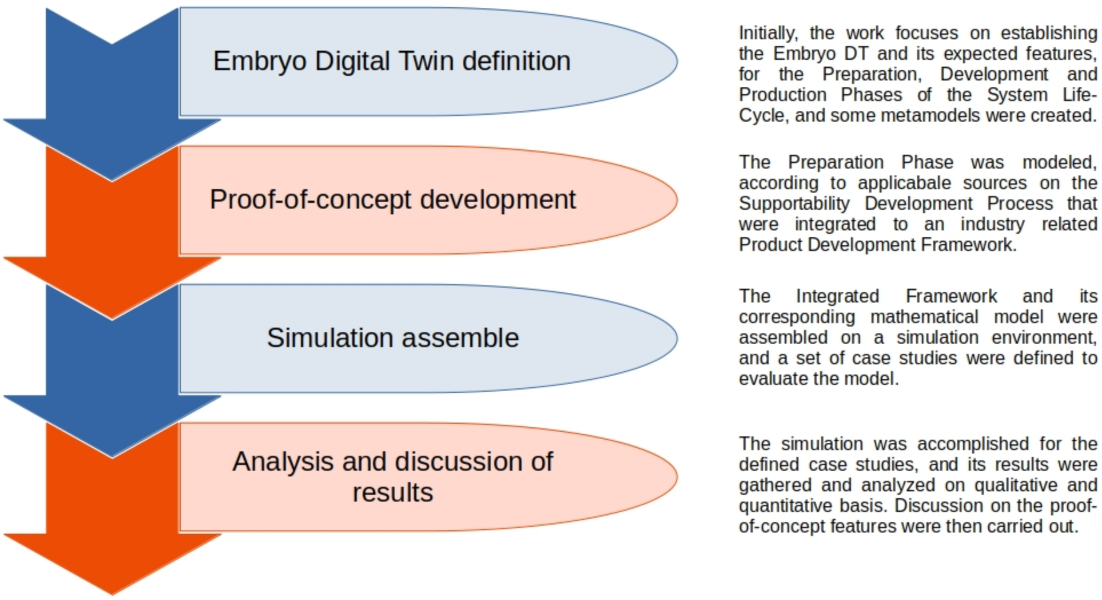

FIGURE 3.1 – Methodology Definition - Created by the author

Embryo Digital Twin was defined on terms of a meta-model for the Preparation, Development and Production Phases, presenting its essential features and aspects, as well as needs for future integration according to its expected utilization.

Once the features expected for the Embryo DT were defined, a proof-of-concept for the tool was established, as a mean to provide some insight on the actual capabilities of this approach.

The Preparation Phase was chosen to be modeled since it is the first phase of the system life-cycle and the one which decisions impact most on development. For this modeling, three major sources on the supportability processes were consulted (ASD/AIA, 2021c), (BLANCHARD, 2003), (DAU, 2021), aiming to clearly understand the expected activities to be performed with the inputs and outputs demanded on each of them.

Then, these activities were integrated on an industry overall system development process for the Preparation Phase (EPPINGER *et al.*, 2019), creating an integrated framework. For this framework design, Business Process Modeling Notation (BPMN) was used, on the online tool BPMN.iO, which was chosen due to its graphical approach that simplifies the presentation of the amount of information necessary to be addressed.

To provide a proof-of-concept on the Embryo DT expected capabilities, it was settled to use the already presented diagrams on a discrete event-simulation tool as a mean to evaluate which activities could be of concern on the development of new projects, assisting decisions for the ILS element Product Support Management on the planning and negotiation with other areas (such as Systems Engineering and Project Management). To do that, the open-source Jaamsim (JaamSim Development Team, 2016) tool was chosen to analyze the capabilities of the proposed framework in regards of decision-making assistance.

Finally, the results were compiled and analyzed, leading to the discussion of possible implementations for the tool and some other features to be integrated on it.

4 Methodology Application, Results and Discussion

As a mean to provide a proof-of-concept, a detailed framework for the development process of the Integrated Product Support on the Preparation Phase was modeled on Business Process Notation, aiming to present a graphical representation of the proposed Embryo Digital Twin, showing the relation between the IPS elements and their development process integrating them to the system's. This model was later applied on a simulation environment, along with mathematical modeling and the results were discussed.

4.1 Embryo Digital Twin Conceptualization

The proposed Embryo Digital Twin uses a preconceived mathematical model to simulate all of 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 logistics support development, allows the engineers to perform analysis and is expected to prevent the separation of the desired SMRL curve from the actual one, as discussed in Chapter 2.

As already discussed, system life-cycle can be divided into five phases (ASD/AIA, 2021c): Preparation, Development, Production, In Service and Disposal. Figure 4.1 summarizes the expected activities to be performed on the first three phases on the ambit of logistics support engineering (ASD/AIA, 2021c).

PREPARATION PHASE	DEVELOPMENT PHASE	PRODUCTION PHASE
- Identify user needs; - Develop product requirements; - Assess potential material solution; - Identify and reduce technology risks through studies, experiments and engineering models; - Establish a business case including analysis of alternatives, cost estimate (Life Cycle Cost) for the launch of the development phase.	- Develop a product that meets user requirements and can be produced, tested, evaluated, operated, supported and retired; - Develop an affordable and executable manufacturing process; - Ensure operational supportability with particular attention to minimizing the logistics footprint.	- Produce or manufacture the product; - Test the product; - Conduct product acceptance to confirm that the product satisfies the requirements.

FIGURE 4.1 – SX000i life-cycle phases - Adapted from (ASD/AIA, 2021c)

As can be seen, the overall process of development for IPS is similar to the one of the product itself, applied to various integrated and interconnected parts that demands different approaches (the 12 IPS elements cited on Chapter 2).

Supportability is mainly composed of the following interconnected parts: Reliability, Availability and Maintainability, the RAM factors. All of them have some measures that are used to predict the expected system behavior on terms of product support.

Embryo Digital Twin is a tool to model and integrate all of those data throughout a mathematical model and with other logistics support development tools. This allows the Embryo DT to perform trade-off studies to choose the best product support concept and, at the same time, simulate what-if scenarios on this context.

Another feature of the Embryo Digital Twin is to provide guidelines and milestones for the expected activities to be performed on the logistics support development at each life-cycle phase. Figure 4.2 shows a qualitative model of the Embryo DT, with its inputs and outputs.

As can be seen, the Embryo Digital Twin requires some inputs that must come from knowledge of the involved engineers and available data on the phase of the life-cycle the development is in, and can be upgraded as the project evolves. It must be connected to other logistics support development tools so it can give them the necessary data to operate and, at the same time, aggregate data from them on its internal mathematical models. Its outputs feedbacks the database so it can become more robust and generate an integrated product support plan based on the available historical data (since the physical

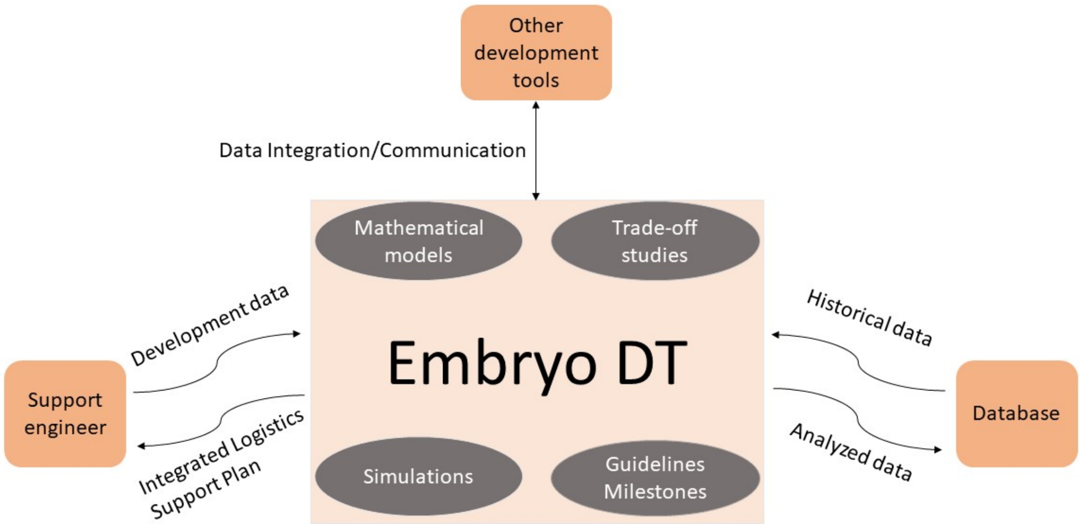

FIGURE 4.2 – Embryo Digital Twin definition - Created by the author

system still does not exist) and safety requirements.

The aim of the Embryo DT is to be a Digital Model on the shape of a Pre-Digital Twin but fed with historical data on the scope of logistics support development of the complex system, so it can help to optimize its performance on later phases. Then, as design evolves, the model must be updated and integrated, so ultimately it can become an Intelligent Digital Twin of the final product.

It is important to point out that the Embryo Digital Twin is intended to help the trade offs and decision making on Preparation, Development and Production Phases, presenting quantitative values for the planned support of the product, even if at that specific phase it presents only a generic model of supportability. This is another difference between it and the common concept of Pre-Digital Twin since the latter refers to a specific virtual model of one desired system, and, as can be seen, the Embryo DT includes not only the physical system, but all of its Integrated Product Support (IPS).

On the other hand, (SCHLUSE; ROSSMANN, 2016) defined the so-called Experimental Digital Twin, which aims to integrate the DT technology with Virtual Testbeds to provide simulations, so the Embryo Digital Twin proposed here can be seen as a type of Experimental Digital Twin that concerns factors beside the system itself, since it focuses on the logistics support scope, as already discussed.

Another difference is that the Embryo DT is designed to compare the obtained data for the system under development to the data provided for similar systems, allowing the engineers to make decisions with broader level of confidence. Normally, they would evaluate the data obtained against expected values previously defined by themselves, which can lead to errors if the documentation were not consistent in terms of traceability.

As presented, system life-cycle is divided in 5 phases (ASD/AIA, 2021c), and it is clear that each of these have specific tasks to be performed in the scope of IPS, so Figure 4.3 presents the proposed use of Embryo Digital Twin as a tool for these tasks on the Preparation Phase.

	SX000i activities (Preparation Phase)				
	Identify user needs	Develop Product Requirements	Assess potential material solution	Identify and reduce technology risks through studies, experiments and engineering models	Establish a business case including analysis of alternatives, cost estimate (Life Cycle Cost for the launch of the Development phase
Embryo DT use throughout system lifecycle	• Using databases and new experiences, develop use case diagrams for the complete product support as defined by MBSE standards.	• Using databases and new experiences, develop requirements diagrams for the complete product support as defined by MBSE standards.	• Storage historical data from similar systems provided by engineers. • Perform trade-off studies concerning RAMS factors with this data, to the appropriate level of detail so that the analysis is reliable.	• Provide historical data comparison based on mathematical models of RAMS factors and compare them to the new ones generated by trade-off studies.	• Consolidate a support concept for the new system. • Provide a milestone goal to certify readiness to the next phase. • Receive feedback from the product development to upgrade the Embryo DT.

FIGURE 4.3 – Embryo DT activities during Preparation Phase - Created by the author

It is important to note that the concept of Embryo DT is to be an interconnected tool with other development features, and, as such, it is proposed that Model-Based System Engineering models and diagrams are used whenever is possible. This approach guaranties both the traceability throughout life-cycle phases and readiness of the product for digitization in the scope of Industry 4.0 (MADNI *et al.*, 2019).

Following the system life-cycle development, Figure 4.4 shows activities to be performed by the Embryo Digital Twin on Development Phase.

It is clear that, in this phase, the models defined on the previous phase will be used and refined to the level of the available data, so the outputs can be compared and the process of inference for the data can be upgraded with the empirical results.

Another feature of Embryo DT is its ability to be used as a tutorial on the process of development for supportability, on the sense that it presents guidelines and checklists to guide the engineers on the process, which guaranties that product's attributes are being addressed on time (the SMRL curve is evolving as it is supposed to).

It is important to note that, on this phase, the Embryo DT must be integrated to the

	SX000i activities (Development Phase)		
	Develop a Product that meets user requirements and can be produced, tested, evaluated, operated, supported and retired	Develop an affordable and executable manufacturing process	Ensure operational supportability with particular attention to minimizing the logistics footprint
Embryo DT use throughout system lifecycle	• Model trade off studies for supportability based on the mathematical model and on MBSE diagrams standards such as block definition, package and others. • Provide guidelines to the development of the supportability referring to the required goals, requirements and milestones.	• Integrate, communicate and receive feedback from the Manufacturing Process, if possible by another Digital Twin so both of them can be upgraded.	• Model trade off studies for supportability based on the mathematical model and on MBSE diagrams standards such as block definition, package and others. • Provide a milestone goal (checklist) to certify readiness to the next phase. • Receive feedback from the product development to upgrade the Embryo DT.

FIGURE 4.4 – Embryo Digital Twin activities during Development Phase - Created by the author

manufacturing DT on the "Develop an affordable and executable manufacturing process" activity, since DTs for manufacturing already exist and there are some models that deal with them, as already presented.

The last phase to be fully addressed by the Embryo DT is the Production Phase, since the other ones will need an integration between it and the Intelligent Digital Twin (IDT), which is out the scope of this work. In Embryo DT context, Figure 4.5 shows activities that it can perform on Production Phase.

The most prominent activity here is "Test the product", which will verify and validate that the system is on the desired product support maturity level and can be serialized. To do that, the Embryo DT must be capable of receiving and comparing all the data obtained on test flights to the calculated ones. The biggest feature here, although, is its ability to simulate the logistical aspects, such as supply chain and RAM factors for the entire in-service phase of the product.

As a way to further explore the concept, some Business Process Models showing the expected behavior for the Embryo DT on each life-cycle phase were developed. These models aim to provide an understanding on the business procedures in a graphical and structured manner, stating clearly the system's flow of activities and decision nodes.

Therefore, this representation can be seen as a meta model of system operation, indicating its high level functions and their interactions. To demonstrate this capacity, a standard notation called Business Process Model Notation (BPMN) was used (OMG,

	SX000i activities (Production Phase)		
	Produce or manufacture the product	Test the Product	Conduct product acceptance to confirm that the Product satisfies the requirements
Embryo DT use throughout system lifecycle	• Integrate, communicate and receive feedback from the Manufacturing Process, if possible by another Digital Twin so both of them can be upgraded.	• Test from the logistics maturity point of view by means of: ✓ Trade-off studies; ✓ Simulation of the supply chain or other necessary parameters; ✓ Comparison of tests results (mainly flight tests) to the data received from the furnishers, and, if necessary, require more tests.	• Furnish acceptation features. • Deliver interface with the system's operator to give information and receive feedback about the logistics maturity of the product. • Provide a milestone goal (checklist) to certify readiness to the next phase. • Receive feedback from the product development to upgrade the Embryo DT.

FIGURE 4.5 – Embryo DT activities during Production Phase - Created by the author

2011). The tool used was the free license of Bizagi Modeler©.

For the aim of this work, there have been developed three simplified diagrams, one for each phase addressed by the Embryo DT: Preparation, Development and Production, containing the expected features for the system identified so far.

Figure 4.6 presents the diagram for Preparation Phase, the first activity is a database research on similar systems, aiming to help the product development initiation. Another important activity on the beginning of the process "Aggregate new data provided by engineers" is expected to provide robustness for the Embryo DT, based on experience from the related development engineers.

The process them goes to an integration with MBSE tools, which aim to provide a structured model for the system support, as already discussed. Then, the Embryo DT uses the various models provided by the engineers along with the mathematical models on its storage to help perform initial trade studies, acting as a development tool. After comparison with data from similar systems, the engineers can decide to go further with the design, to work on a different proposition, or even to change the entire support concept, going back to the start of the process, as shown by the decision node "Acceptable results?".

Lastly, if the milestones provided by the Embryo DT (it must also work as a guide tool, as already discussed) were satisfied, the system can go to the next phase of development, but before it proceeds, the system will request for feedback from the development team, as a way to improve its capacities and become more user friendly.

Figure 4.7 defines the diagram for the Development Phase, and the first activity is

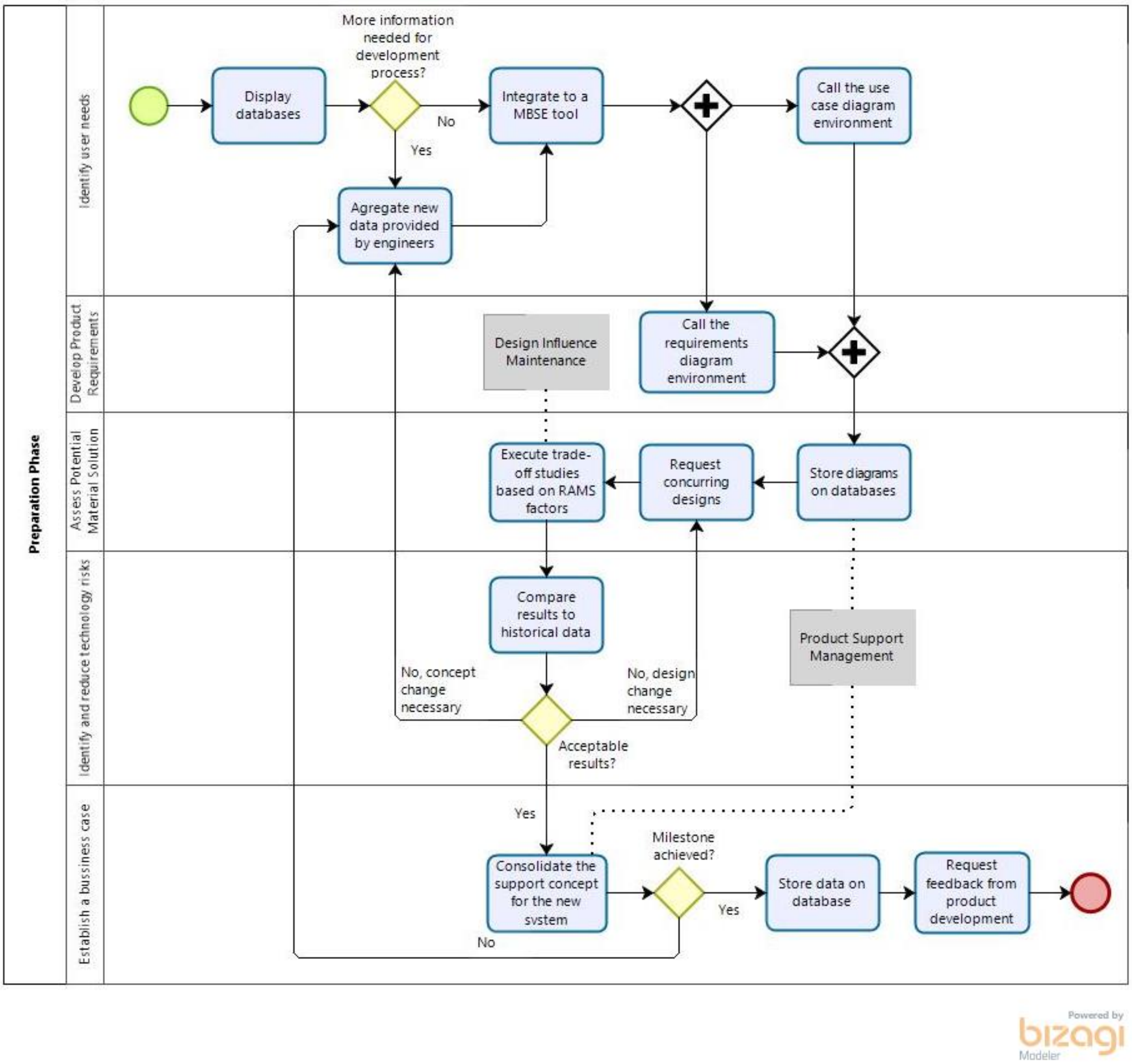

FIGURE 4.6 – Preparation Phase Business Process Model - Created by the author

connected to the guide feature of the Embryo DT, since it relies on guidelines for the product support development that can be obtained from lessons learned from other previous developments. Then, the system should integrate again to MBSE tools, perform trade studies and compare the results obtained to the ones available on the database for similar systems. All of these activities will now be on a new level of abstraction, since the system is, at this time, on an advanced stage of development and, as such, is able to provide more detailed data.

The greatest difference expected on this phase is the integration of the Digital Twin proposed here to a manufacturing digital twin. At the end of the phase, once more, the system will request feedback from the user.

The Production Phase diagram is shown on Figure 4.8, in which the first activity is related to the manufacturing digital twin, since the system is on the life-cycle phase where

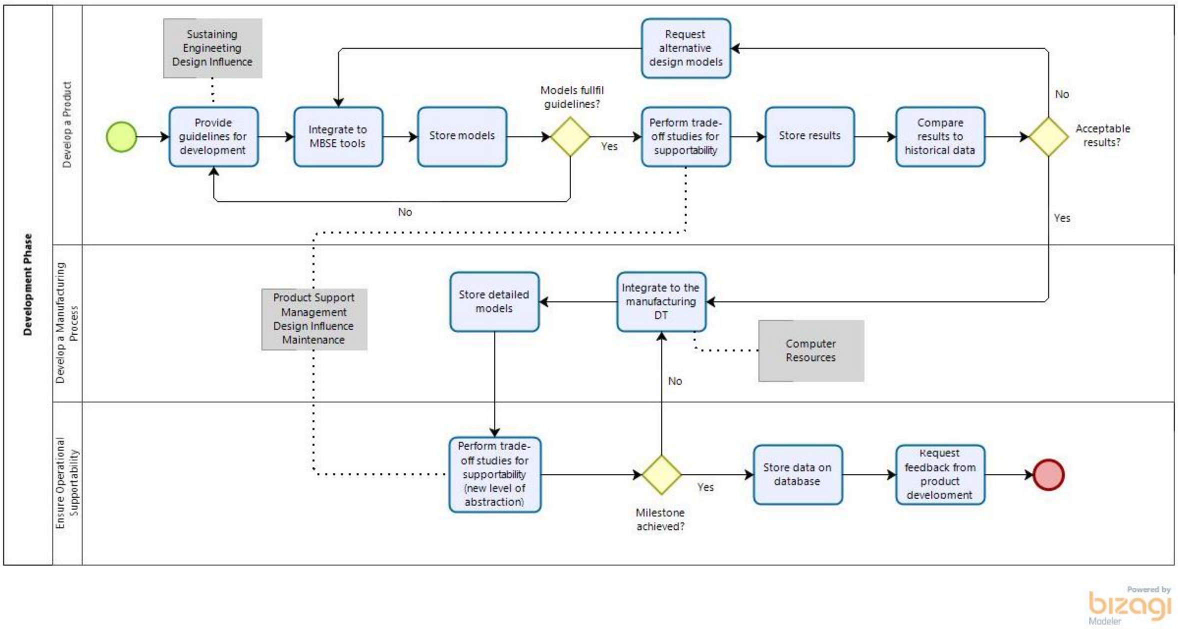

FIGURE 4.7 – Development Phase Business Process Model - Created by the author

it is mostly dependent on the information provided by this process. For the activities related to "Test the product" more complete trade-off analysis must be achieved, as well as simulations and the tests themselves, to a level where it is possible to evaluate the need for more tests or attest the system logistics support maturity.

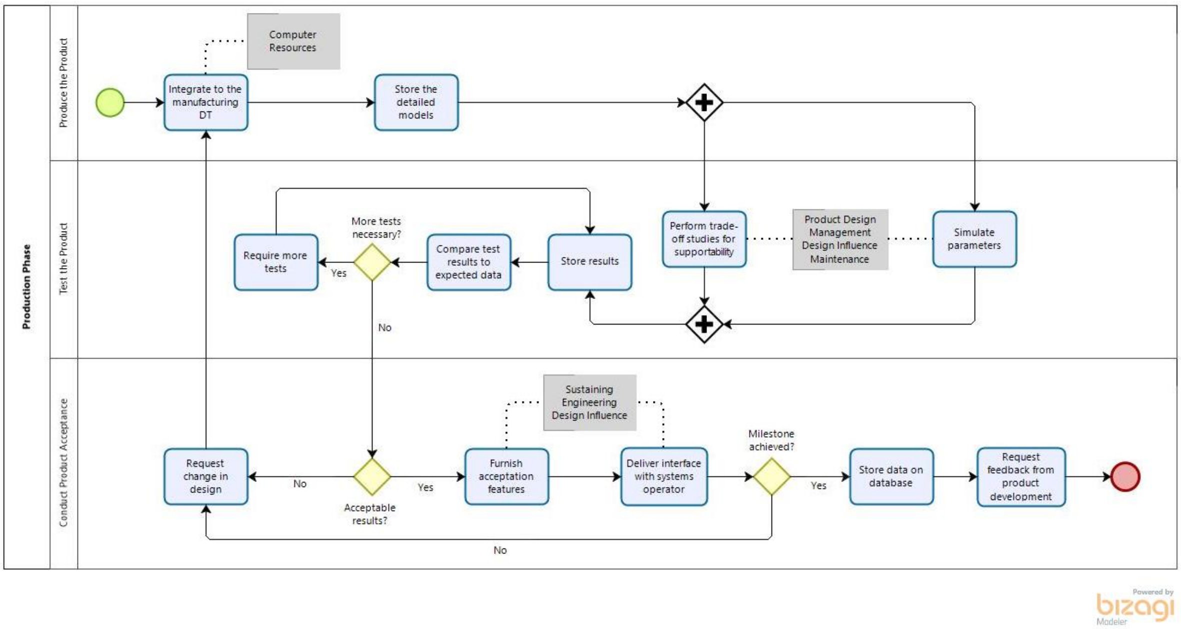

FIGURE 4.8 – Production Phase Business Process Model - Created by the author

The activities on "Conduct Product Acceptance" must prepare the Embryo DT to deal with the product operators directly, being the major link between this Digital Twin to the Intelligent Digital Twin that is expected to be developed based on it. Again, the last activities aim to upgrade the system based on feedback from the users.

To demonstrate which activities are closest related to some of the IPS elements, some notes (gray squares) were added to the model, also as a way to guide the development of these activities.

It is important to address that all of the activities represented here are on a high-level basis, so they are going to be refined into sub processes for the implementation of the Embryo DT. As such, each of them can become a new extensive work, one example is that the expected future work directly derived from this one is to detail how the connection to the other development tools must work as well as the interconnection of the Embryo DT to the IPS elements for all life-cycle phases.

The Embryo DT would be a tool to apply a digital twin-driven product design methodology based on the following aspects (FEI *et al.*, 2018):

- 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 reliability, availability and maintainability (RAM) 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 the supportability is addressed only on the detailed design phase, so the Embryo DT aims to develop a way of simulating most of the logistics support aspects early, a problem that is not modeled by the common used frameworks and simulation tools.

4.2 Framework development

Upon to this research process, it was noted that supportability is taken as an feature apart of the product development process and the activities are not clearly defined on a timely basis for each phase of development, which results on each industry carrying them out according to experience and not on a integrated framework.

This lack was believed to be the most prominent issue for the supportability development, due to its impacts on both project management and systems engineering processes and to the fact that the three literature sources used in this work i.e. (ASD/AIA, 2021c), (BLANCHARD, 2003), (DAU, 2021), provide a broad knowledge on the activities to be performed as well as techniques to achieve them, so the shift on the SMRL curve was believed, in this context, to rely mostly on the mismatch of the time to accomplish those tasks from the system life-cycle perspective.

As a way to address this issue, an industry overall system development process for the Preparation Phase (EPPINGER *et al.*, 2019) was selected, and the activities to be done according to the supportability sources were merged on this process to create an integrated framework, clearly positioning each of the tasks to be accomplished according to their expected inputs and outputs.

The goal was to identify when the supportability related activities could be addressed on this phase as a way to 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.

Figure 4.9 shows the BPMN 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 convey the supportability related tasks to be done.

This diagram also presents which activities are related to each of the chapters of the Standard Concept of Operations (CONOPS) Document (IEEE, 1998), as a mean to assist engineers on its fulfillment, which already presents a contribution of this work on terms of assistance for the knowledge management, since it provides a structured view that can be integrated with the systems engineering and project management practices.

It is important to note that the activities “Perform support engineering analysis (RAMT)” and “Perform Life-Cycle Cost analysis” are addressed two times on this Phase, due to the need to perform them on two levels of detail, one on a high conceptual basis when the product does not even have a technical model yet and the other when the concept is being specified, so there are more information on regards of the expected product.

Another feature to be highlighted is the existence of the last decision gateway called “Further analysis necessary? (Progressive level of detail)” which provides a decision for the engineers to prevent an immature conceptual system from going to the Development Phase, having, although, a different role than the previous gateways, since this decision relies on a broader view rather than only on the supportability aspects.

Activities to be performed to develop a preventive maintenance plan and to establish the logistics support analysis (LSA) database were out of the scope of this work,

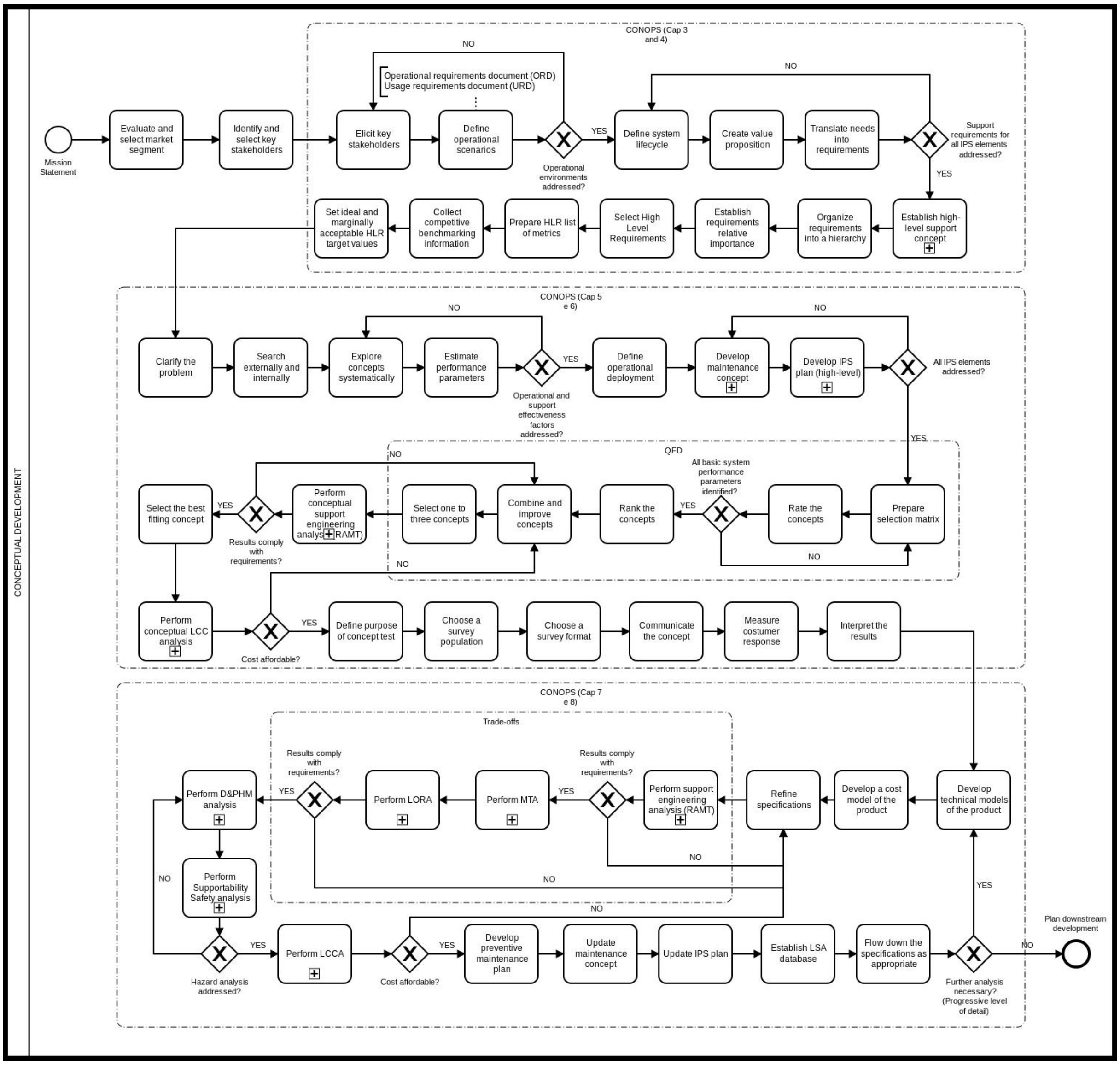

FIGURE 4.9 – Embryo Digital Twin (Preparation Phase BPMN Diagram) - Created by the author

since there are already standards which deals with those processes, as the International procedure specification for Logistics Support Analysis (LSA) (ASD/AIA, 2021a) and the International specification for developing and continuously improving preventive maintenance (ASD/AIA, 2021b). In terms of the last, there is also a current used methodology in industry, the Maintenance Steering Group-3 (MSG-3) (AMERICA, 2007).

Since the primary goal of this work was to present a holistic view of the processes to be done in terms of the IPS elements organized on a chronological manner, the detailing of such processes were out of the scope and are expected to be done on future works.

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.

4.2.1 Second level processes

To further understand the necessary activities to be achieved as a mean to attain a higher supportability maturity level, all of the second level processes that were indicated with the + sign on the overall diagram were developed and are presented, on chronological order in Figures 4.10 to 4.21.

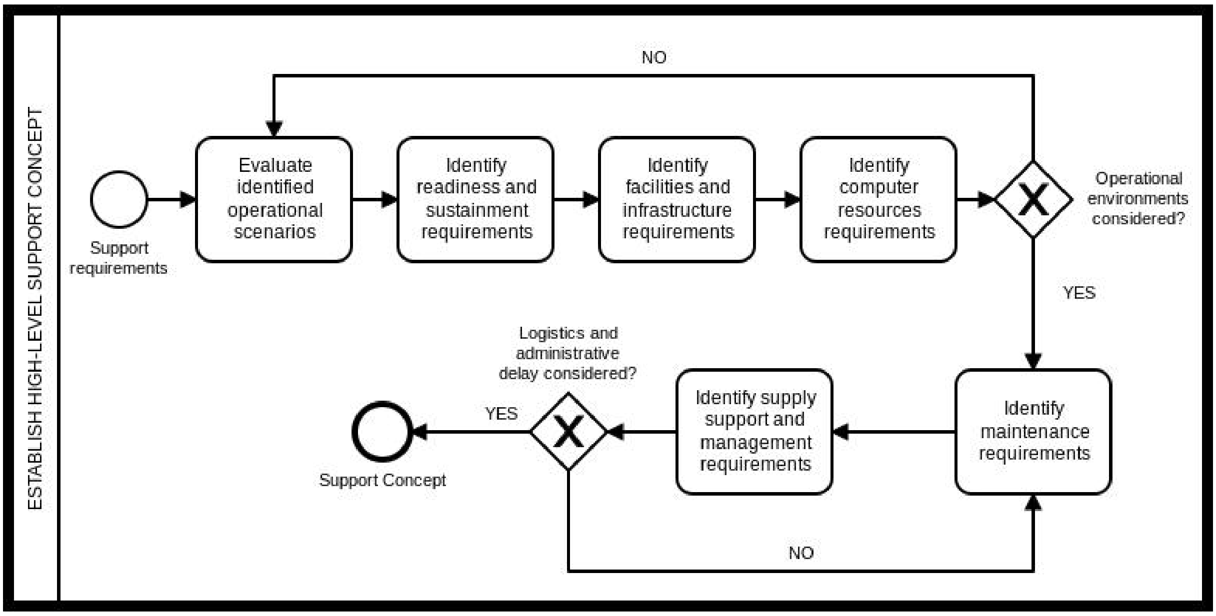

FIGURE 4.10 – Support Concept (Preparation Phase BPMN Diagram) - Created by the author

Figure 4.10 refers to the Support Concept, which is the first embedded process to be done, and is the first approach to the supportability development.

Some highlights of this process relate to the consideration of operational scenarios and delays (both administrative and logistics) that must be addressed, even on this high abstraction level.

Figure 4.11 refers to the Maintenance Concept, and the activities to be done here demands feedback from legate systems as a mean to establish some of the maintainability quantitative parameters to guide product development.

It also generates inputs for the Level of Repair Analysis (LORA) that is going to be performed later on the process and begins the actual integration to the IPS elements, clearly addressing some of their requirements and constraints.

It is important to note that this concept is expected to be updated before the system proceeds to the Development Phase, so the configuration control can be accurately

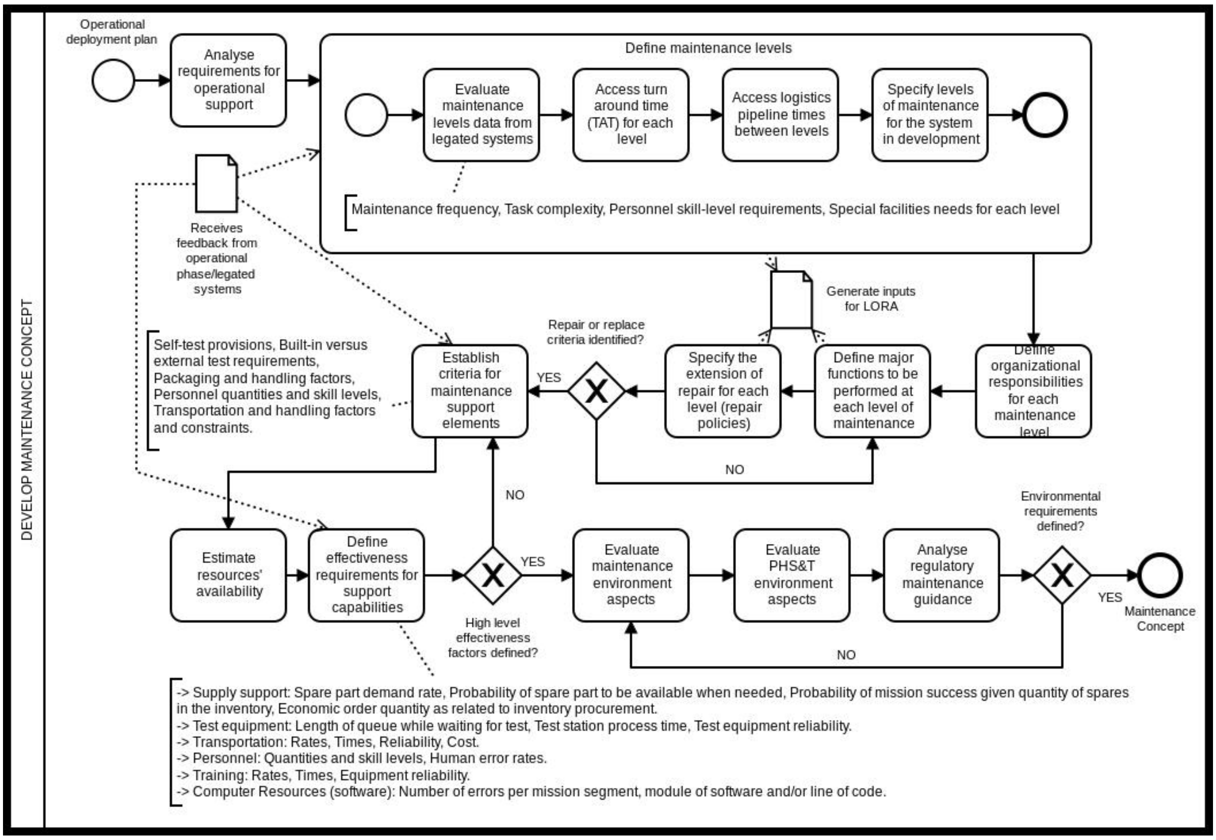

FIGURE 4.11 – Maintenance Concept (Preparation Phase BPMN Diagram) - Created by the author

accessed with the decisions made on the next steps.

Figure 4.12 address the first interaction of Integrated Product Support Plan (IPS Plan), which is the main output for the Embryo Digital Twin, since it is expected to be updated along with product development and must address all of the support aspects of the system on an integrated manner.

Nonetheless, it receives inputs from both the Maintenance and Support Concepts, as well as from legate systems and includes a Work Breakdown Structure as a mean to provide the expected traceability on the development of all of the IPS elements.

Figures 4.13 to 4.16 refers to only one sub-process: Support Engineering Analysis (RAMT). This occurs because this is the most exhaustive sub-process, since it deals with feasibility and functional analysis, requirements allocation, alternatives evaluations and validation/verification planning.

It is important to explain a feature presented on this sub-process: it refers to the Support Engineering Analysis to comply with the standard presented at (ASD/AIA, 2021c), but its activities are also refered as Reliability, Availability, Maintainability and Testability (RAMT) Analysis or even Supportability Analysis on other sources. Since RAMT is the most known name for this process, the name chosen was a merge of it and the one presented

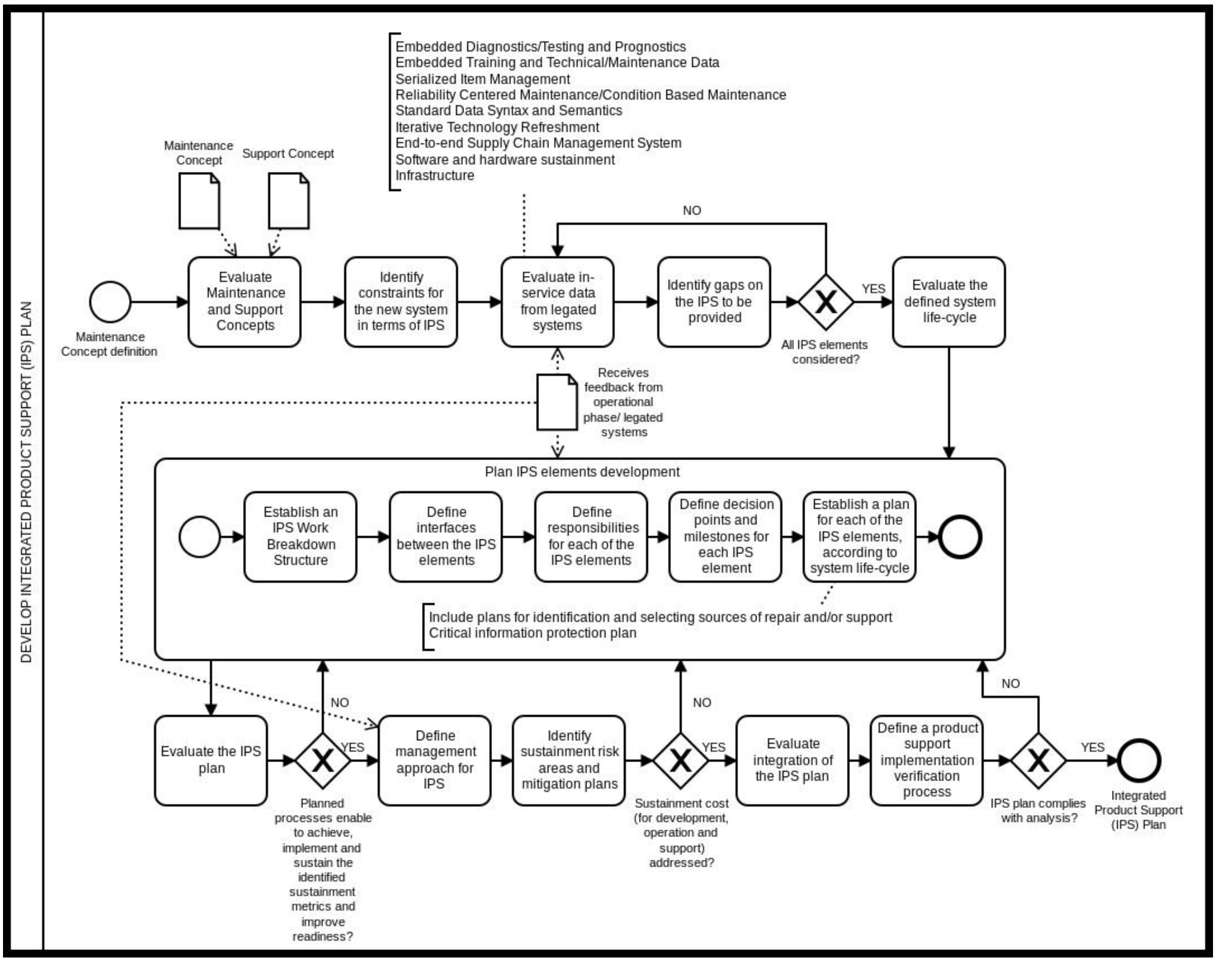

FIGURE 4.12 – Integrated Product Support Plan (Preparation Phase BPMN Diagram) - Created by the author

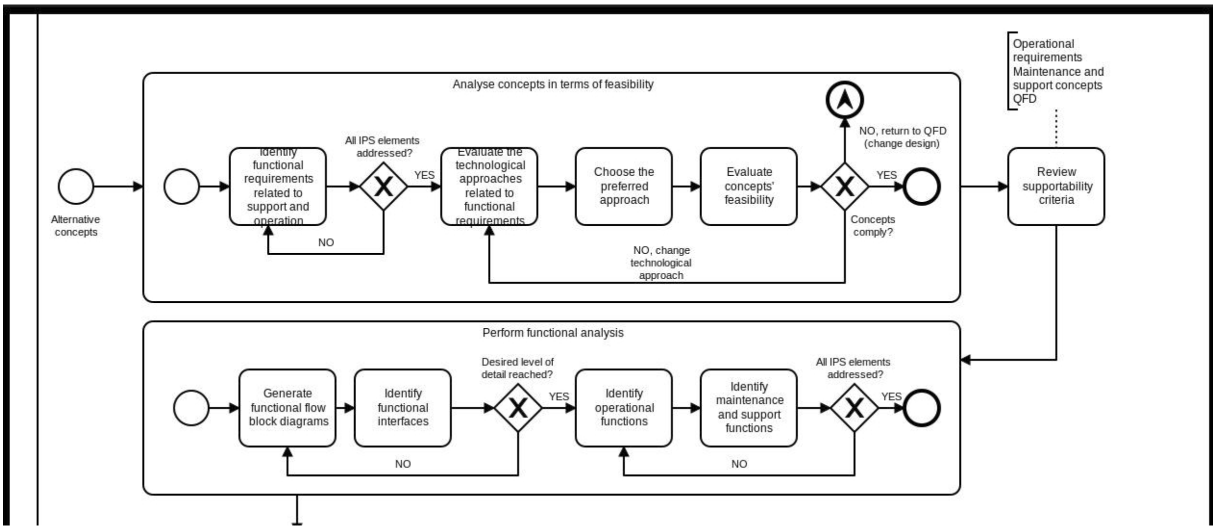

FIGURE 4.13 – Support Engineering Analysis (RAMT) Part 1 (Preparation Phase BPMN Diagram) - Created by the author

on the standard, to facilitate knowledge management and application of the framework.

Figure 4.13 shows the activities related to feasibility and functional analysis related to supportability development.

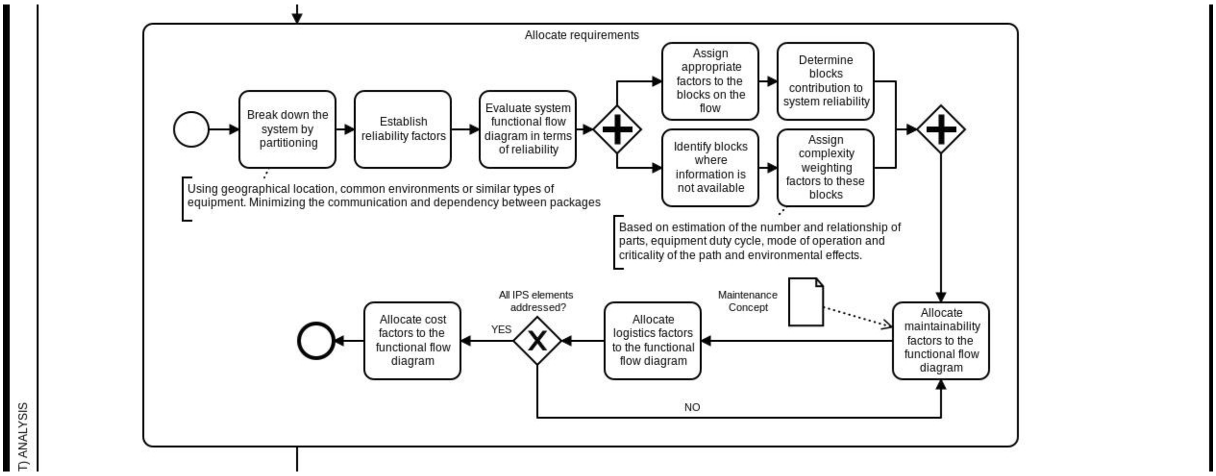

FIGURE 4.14 – Support Engineering Analysis (RAMT) Part 2 (Preparation Phase BPMN Diagram) - Created by the author

Figure 4.14, on the other hand, deals with requirements allocation and is the first diagram to present activities occurring in parallel arrangement, or, in other words, activities that are expected to be performed in conjunction.

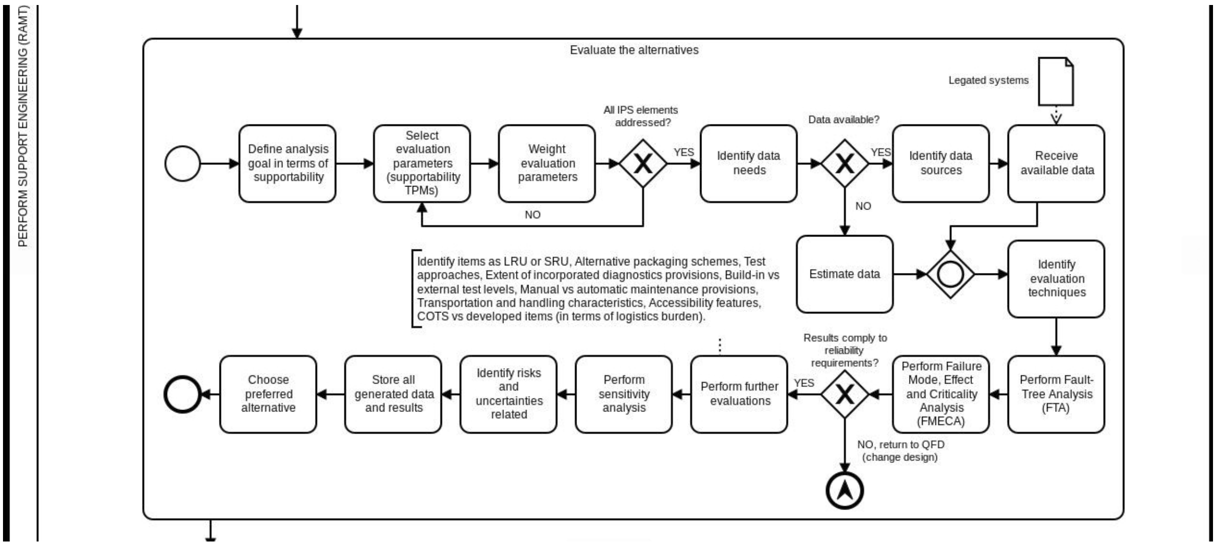

FIGURE 4.15 – Support Engineering Analysis (RAMT) Part 3 (Preparation Phase BPMN Diagram) - Created by the author

Figure 4.15 shows the activities related to alternatives evaluation and presents two common analysis associated to supportability: Fault-Tree Analysis (FTA) and Failure Mode, Effect and Criticality Analysis (FMECA), both of them correlated to the reliability aspects of the system in development. Explanations on both of these analysis are presented on (BLANCHARD, 2003). FTA is further detailed in (ERICSON; LL, 1999) and FMECA in (LAWSON, 1983). Also, an interesting approach integrating both of these analysis is presented on (PEETERS *et al.*, 2018).

Here, it is clearly shown the contribution of this work in terms of concatenation of the knowledge, since it presents, on a temporal basis, even commonly known analysis made on the ambit of supportability, guaranteeing that they are made on the system before it proceeds further on the development, which is a way to prevent the SMRL curve from shifting to the right.

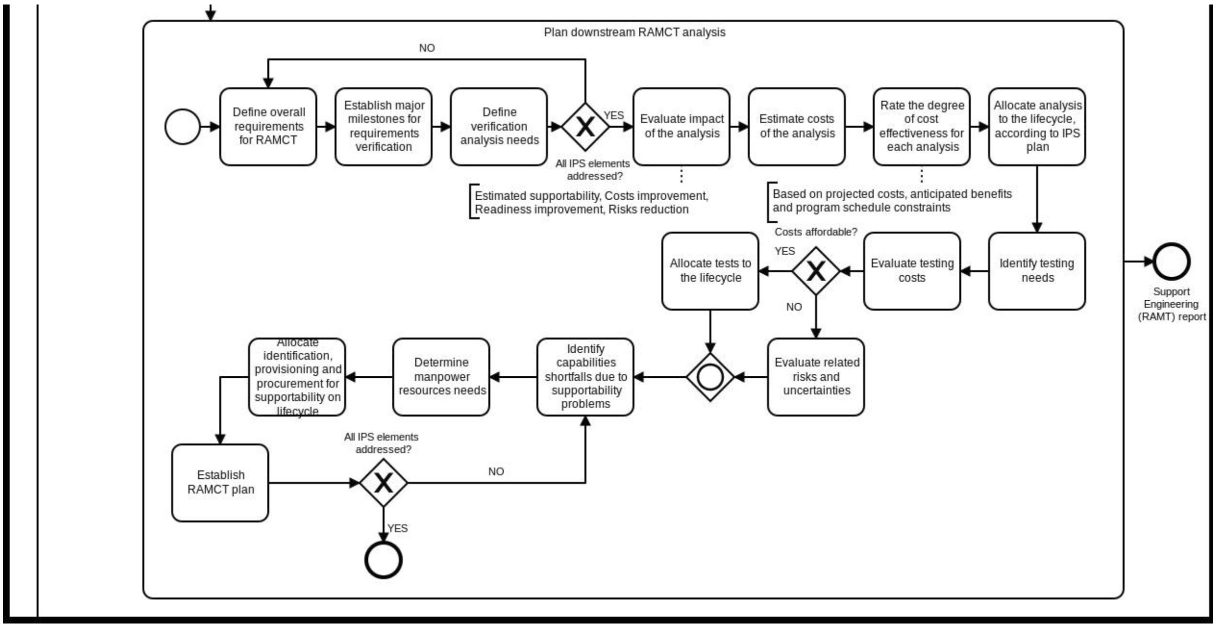

FIGURE 4.16 – Support Engineering Analysis (RAMT) Part 4 (Preparation Phase BPMN Diagram) - Created by the author

Figure 4.16 presents the verification planning for the engineering analysis made, allocating them on the system life-cycle, according to the IPS Plan.

Figure 4.17 deals with the Life-Cycle Cost Analysis (LCCA), developing a cost breakdown structure and dividing the system life-cycle on the cost categories specified on Chapter 2, as a mean to correctly evaluate the cost and related risks.

Figure 4.18 refers to the Maintenance Task Analysis (MTA), which primally deals with the maintainability aspects of the system. It is mostly related to the operational aspects, evaluating the tasks required for maintenance to succeed.

Nonetheless, Figure 4.19 presents the Level of Repair Analysis (LORA), which is mostly related to the logistics aspects of maintainability, analyzing the levels on which the maintenance tasks must occur according to availability and cost requirements.

Figure 4.20 refers to the first analysis related to planning the Condition Monitoring (CM) for the system and was based on (TSUI *et al.*, 2015) and (KHORASANI, 2018) since the source materials used on this part of the research do not present detailed analysis on this sub-process, even though they specify they should be made on this phase of development.

This can be explained because Diagnosis, Prognosis and Health Management (DPHM)

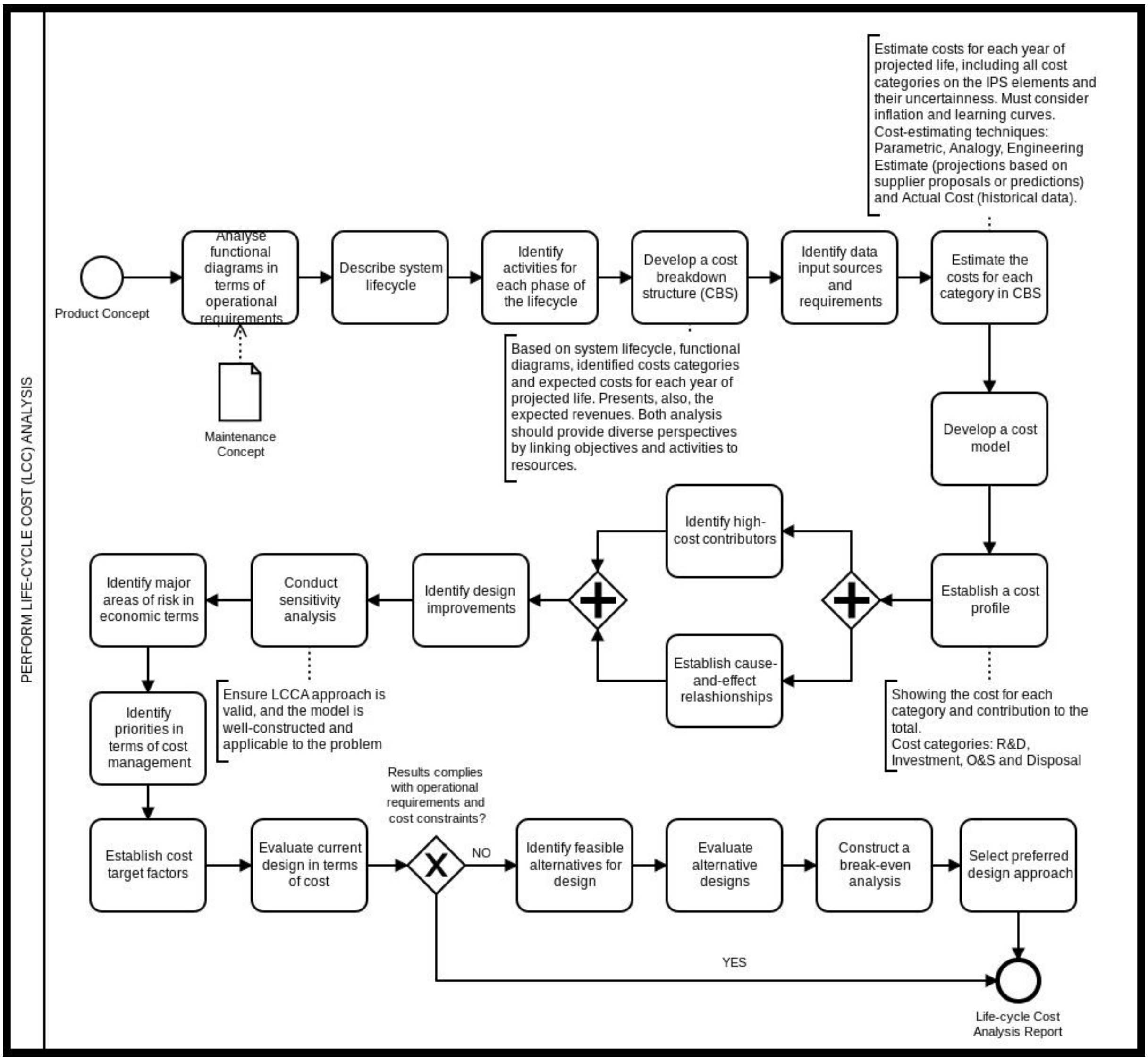

FIGURE 4.17 – Life-Cycle Cost Analysis (Preparation Phase BPMN Diagram) - Created by the author

is the most affected subject on terms of Industry 4.0 technologies, with Digital Twin and other tools being developed and applied to assist these tasks on operating systems already in use, so frameworks to be applied on this sub-process are still being developed, and are not yet presented on broader materials as the ones this work relies on.

Nonetheless, since this work intends to be the most comprehensive possible, a simple approach based on the aforementioned references was made.

Finally, Figure 4.21 refers to the Safety Analysis, analyzing hazards and their preventive and corrective actions, as well as defining a Failure Reporting, Analysis, and Corrective Action System (FRACAS) approach, which relates to the quality control of the system. A standard regarding this type of implementation is found at (GROUP, 2009).

It is important to note that when a design change request is made, the development is

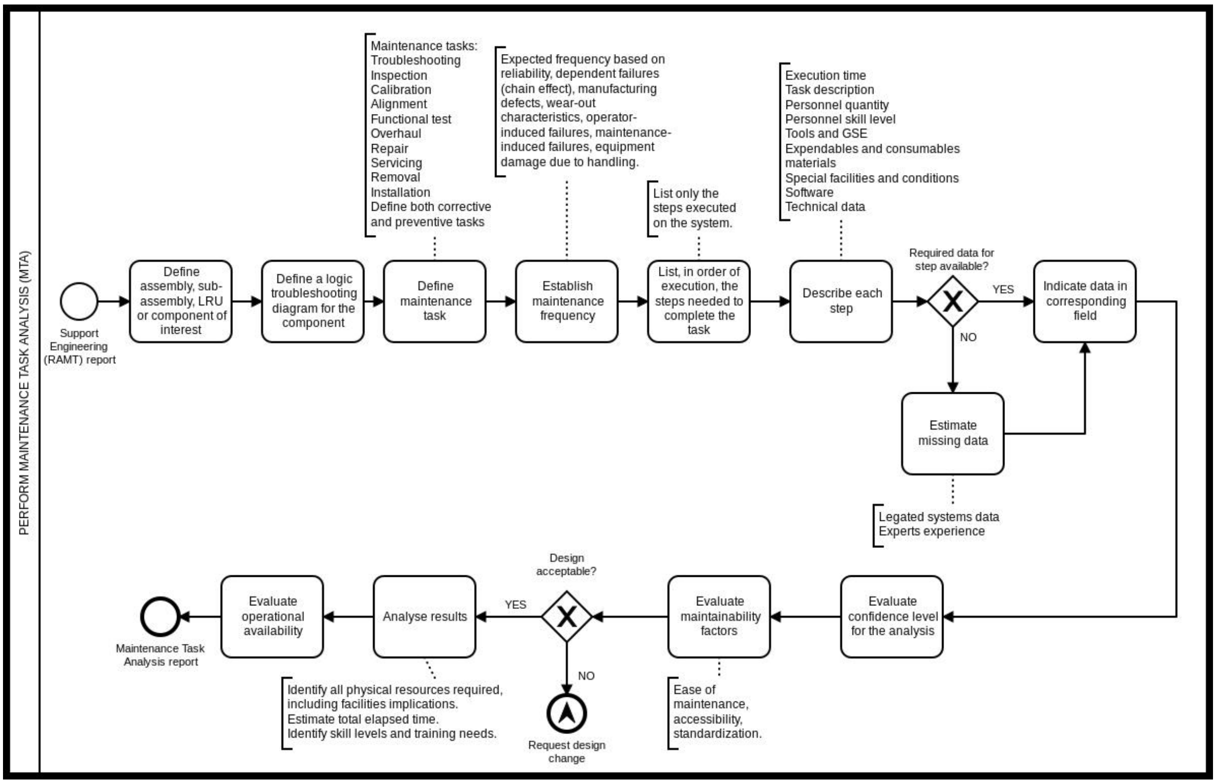

FIGURE 4.18 – Maintenance Task Analysis (Preparation Phase BPMN Diagram) - Created by the author

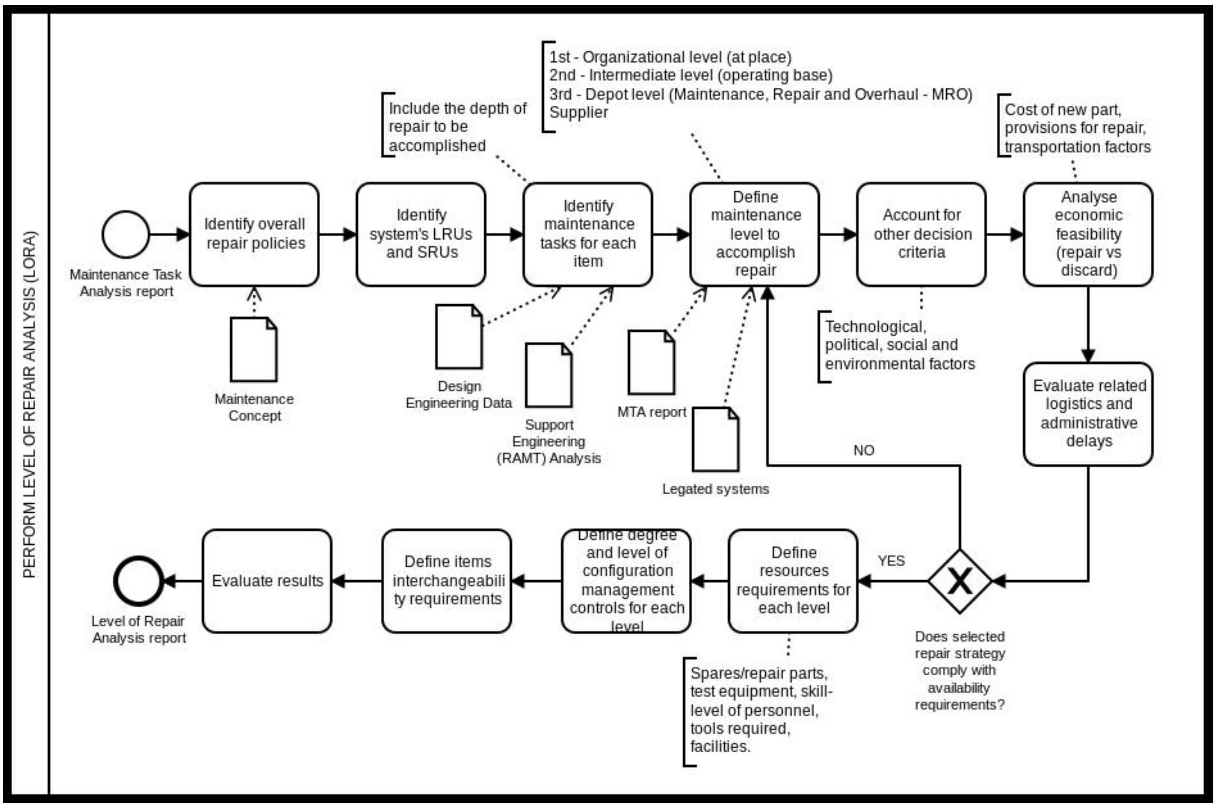

FIGURE 4.19 – Level of Repair Analysis (Preparation Phase BPMN Diagram) - Created by the author

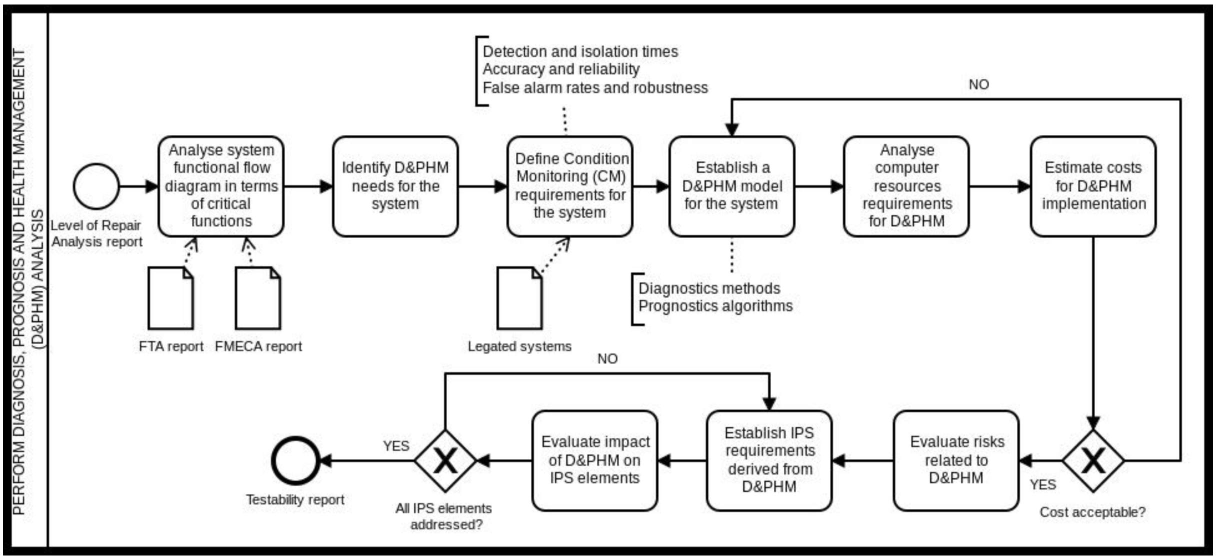

FIGURE 4.20 – Diagnosis, Prognosis and Health Management (Preparation Phase BPMN Diagram) - Created by the author

expected to return to either the "Combine and improve concepts" activity or the "Refine specifications" activity on the main flow, depending on the one that is closest to the activity at hand.

It must be stated that, as the system is still on a conceptual basis, the foremost IPS elements analyzed on these activities are (ASD/AIA, 2021c):

- Product Support Management, to which pertains the sub-processes "Establish high-level support concept" and "Develop Integrated Product Support (IPS) Plan";
- Design Influence, to which pertains the sub-processes "Perform support engineering (RAMT) analysis" and "Perform Life-Cycle Cost (LCC) Analysis" and the activity "Establish LSA database"; and
- Maintenance, to which pertains the sub-processes "Develop maintenance concept", "Perform maintenance task analysis (MTA)", "Perform level of repair analysis (LORA)", "Perform Prognosis, Diagnosis and Health Management (DPHM) Analysis", "Perform supportability safety analysis", and the activity "Develop preventive maintenance plan".

Lastly, it must be acknowledged that these diagrams can be further detailed on new levels of abstraction, but, as this work focuses on the initial development for the Embryo Digital Twin, this was not accomplished here, since it was believed that the level of detail attained is sufficient for the understanding as a proof-of-concept of the planned tool.

This concludes the qualitative aspect of the research. Some highlights concerning the limitations of the approach are:

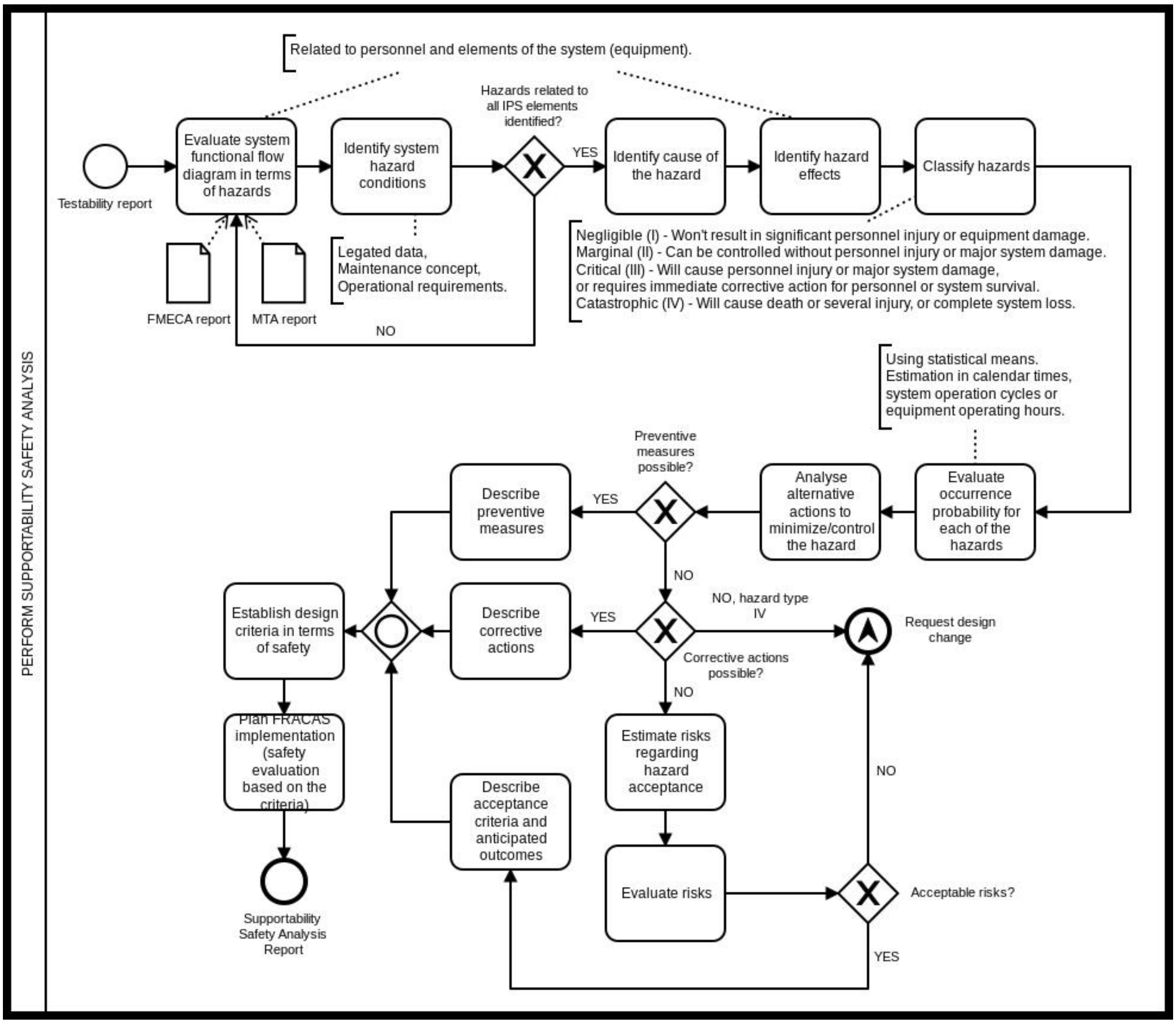

FIGURE 4.21 – Safety Analysis (Preparation Phase BPMN Diagram) - Created by the author

- Although the work was conducted based on three established sources on the ambit of supportability and logistics engineering (ASD/AIA, 2021c), (BLANCHARD, 2003) and (DAU, 2021), it was not submitted to a validation with industry experts, which could provide some insights on activities lacking or changes on the way the fluxograms were organized, for example; and

- As this work is intended to be public and the modeling was made on a phase in which the system is highly conceptual, it mainly presents a processional perspective, instead of a data-based approach (that could present the need for it to become confidential due to copyright industrial factors), which affect its practical application assessment, as will be further discussed.

The processional approach presented was then submitted to a simulation modeling aiming to show an advantage of the proposed framework in regards of decision-making assistance.

4.3 Simulation environment

Discrete event-simulation is widely used on manufacturing system design and operation (SMITH, 2003), since it is “suitable for problems in which variables change in discrete times and by discrete steps” (ÖZGÜN; BARLAS, 2009). This means that when the focus relies on estimating parameters from processes, such as quantity of units processed or mean time to finish determined activity, this type of simulation can be used to perform those analyses.

To clarify the concept, suppose a factory responsible for two processes: Sand and Paint the assembled parts it receives. The sanding process duration is 7 minutes whilst the painting one is 9 minutes and the factory receives one part each 5 minutes. If the goal is to know how many painted parts are delivered on 60 minutes, or which process could be optimized for the overall operation to be faster (adding a second machine capable of making that process, for example), a discrete event-simulation tool could be used.

The Jaamsim (JaamSim Development Team, 2016) tool is Java-based and was chosen due to its graphical representation and fast assimilation, as well as the existence of a resource library that facilitates the knowledge management and educational purposes of this work. Also, the open-source characteristics is desired for possible future developments and integrations, since they shall not require negotiations of contracts.

To present the major features covered on the tool, the example above was reproduced, as shown in Figure 4.22. For this case, the entities are presented as the black dots, and the Figure shows that, at 60 minutes, 3 parts wait to be sanded and 2 parts are already sanded and wait to be painted. Also, on the “Output Viewer” for the “Release-Finished-Part” it is shown that 5 parts were completed on 52 minutes. It is possible to analyze each of the tokens presented on the image, but, as a way to not become exhaustive, this will not be addressed in this work. Some presentation on the tool can be found at (KING; HARRISON, 2013).

4.3.1 Mathematical model

A hypothetical scenario was created as a mean to evaluate the proposed framework as a tool to assist decision-making. The main features of this approach were that:

- All the activities described on Figures 4.9 to 4.21 and their relationships are modeled and preceded by a queue counter to evaluate overall development effectiveness;
- The decision points are modeled with three options based on the maturity of the company being simulated to develop that type of system; and
- The time-frame to perform each activity is based on the complexity of the system

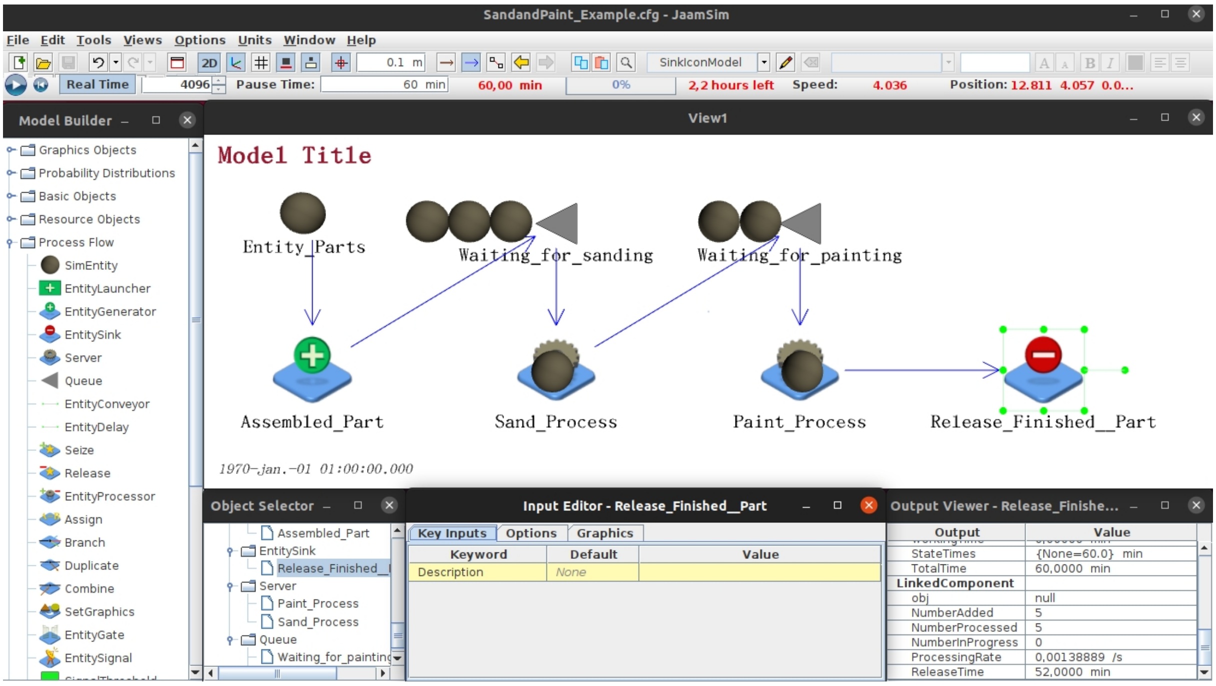

FIGURE 4.22 – Factory Discrete Event Simulation Example at Jaamsim - Created by the author

to be developed and on the maturity of the company.

It should be noted that this approach permits the simulation to be customized to various contexts according to the calculated parameters for each type of project or company.

Whatsoever, two major inputs are evaluated: the maturity that the development company presents for that kind of system, for which the higher the better, and the complexity of the system, analyzed here as the minimum interval of time needed to perform each activity. For a determined complexity evaluated, all of the activities had the same minimal interval time.

The inputs applied to the problem are presented in Equation 4.1:

$$\begin{aligned} \text{Maturity} &= \{1, 2, 3, 4, 5\} \\ \text{Activity Minimal Time (days)} &= \{3, 5, 7\} \end{aligned} \tag{4.1}$$

The expected results are measured on the quantity of systems that pass to the Development Phase on a determined simulation time and the price per unit for the Preparation Phase for the five maturity levels and three complexity degrees, as shown on Equation 4.1. Therefore, the outputs are shown in Equation 4.2:

$$\begin{aligned} \text{Final Cost (for Preparation Phase)} \\ \text{Final Quantity (for Preparation Phase)} \end{aligned} \tag{4.2}$$

Furthermore, it is necessary to explain the three options presented on the decision gates, which were based on experience of past projects on the area:

- The development shall return to a previous defined point of the flux, as presented on the Figures beforehand;
- The development should return, but the managers choose to go ahead even if supportability aspects were not considered. For this case, a punition cost was implemented to indicate future expected issues; and
- The development can go ahead with no observations.

For these decisions, the Equation 4.3 is applied:

$$\begin{aligned}
{}'\mathrm{indexOfNearest}(0.175 - (\log(\mathrm{Maturity})/7) \\
0.55 - (\log(\mathrm{Maturity})/2) \\
0.875 - (\log(\mathrm{Maturity})/2.8), \\
\mathrm{DecisionSeed})'
\end{aligned} \tag{4.3}$$

In Equation 4.3, the Decision Seed is a Uniform Probability function varying from 0 to 1, and the Index of Nearest function chooses the option which contains the nearest value to the one generated by the probability function. The values obtained by the function and the respective probabilities are shown in Tables 4.1 and 4.2:

TABLE 4.1 – Maturity Levels vs Function Values for the decision gates

Maturity Level	**1**	**2**	**3**	**4**	**5**
Return Value	0,175	0,132	0,107	0,089	0,075
Punition Value	0,55	0,4	0,311	0,249	0,2
Go Ahead Value	0,875	0,767	0,705	0,66	0,625

TABLE 4.2 – Maturity Levels vs Probabilities for the decision gates

Maturity Level	**1**	**2**	**3**	**4**	**5**
Return Probability	35%	26,4%	21,4%	17,8%	15%
Punition Probability	40%	27%	19,6%	14,2%	10%
Go Ahead Probability	25%	46,6%	59%	68%	75%

These choices were modeled according to the expected behavior based on the maturity level, in which companies with low maturity levels tend to have more rework or decide to go ahead with no regards to supportability than the ones with higher levels of maturity.

For the time interval required to complete the activities, an Uniform Probability function was also defined, as a mean to enhance the analysis with maturity considerations for variability on this parameter. The lower and upper bounds for this probability function are based on the maturity levels and the time to perform the activity is calculated based on the generated value and the Activity Minimal Time in days, as shown in Equation 4.4:

$$\begin{aligned} \text{Activity seed lower bound} &= (1.55 - (\log(\text{Maturity})/2.5)) \\ \text{Activity seed upper bound} &= (1.75 - (\log(\text{Maturity})/2.5)) \\ \text{Activity Time (days)} &= \text{Activity Seed} * \text{Activity Minimal Time (days)} \end{aligned} \tag{4.4}$$

For each complexity degree and maturity level, the minimal and maximal values possible for the activities times are shown in Table 4.3:

TABLE 4.3 – Activities minimal and maximal time (days) based on maturity level and complexity degrees

Maturity	**1**		**2**		**3**		**4**		**5**	
Complexity	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Low (3 d)	4,65	5,25	4,29	4,89	4,08	4,68	3,93	4,53	3,81	4,41
Medium (5 d)	7,75	8,75	7,15	8,15	6,8	7,8	6,55	7,55	6,35	7,35
High (7 d)	10,85	12,25	10,01	11,41	9,51	10,91	9,16	10,56	8,89	10,29

There are, also, cases in which there is a decision gate that does not imply on returning to previous activities, but opening two different paths that can be followed based on the amount of information a company possesses. This behavior was also modeled according to probabilities based on the maturity level, since it is more likely that a mature company have developed a lessons learned capability that assists the engineers with information on legate systems that are similar to the one being developed. The following Equation 4.5 was applied for these cases:

$$\begin{aligned} &{}'\text{indexOfNearest}(0.275(\log(\text{Maturity})/13.9) \\ &0.775(\log(\text{Maturity})/13.9) \\ &\text{DecisionSeed})' \end{aligned} \tag{4.5}$$

The Primary Path refers to the straightforward one, in which less analysis are necessary since the organization already has enough information to go ahead with development, whilst the Secondary Path is when more analysis are needed. At some point of the development, these paths come back together, as one could expect. Equation 4.5 follows the same logic as Equation 4.3, whilst the values obtained by the function and the respective probabilities for the Primary and Secondary paths are shown in Tables 4.4 and 4.5:

TABLE 4.4 – Maturity Levels vs Function Values for each path

Maturity Level	**1**	**2**	**3**	**4**	**5**
Primary Path Value	0,275	0,297	0,309	0,318	0,325
Secondary Path Value	0,775	0,797	0,809	0,818	0,825

TABLE 4.5 – Maturity Levels vs Probabilities for each path

Maturity Level	**1**	**2**	**3**	**4**	**5**
Primary Path Probability	55%	59,4%	61,8%	63,6%	65%
Secondary Path Probability	45%	40,6%	38,2%	36,4%	35%

Finally, the cost parameters are defined on Equation 4.6:

$$\begin{aligned} \text{Cost per time} &= 100 \text{ Dollars/day} \\ \text{Punition Cost} &= 150 \text{ Dollars} \end{aligned} \tag{4.6}$$

And the Final Cost for each project is calculated as shown in Equation 4.7:

$$\begin{aligned} &\text{Final Cost (Dollars)} = ((\text{Total Time (days)} * \text{Cost per time (Dollars/days)}+ \\ &\sum_{\text{First DG}}^{\text{Last DG}} \text{Activities to redo} * \text{Punition Cost (Dollars)} * \text{Quantity of punitions})/ \\ &\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{Projects completed}) \end{aligned} \tag{4.7}$$

This equation presents a mean cost for the Preparation Phase, based on the Total Time elapsed in days for all of the activities to be performed, a constant cost per day elapsed and the total of projects that were approved to go to the Development Phase.

Nonetheless, the Punition Cost was also considered, and for each decision gate it was parametrized by the number of activities that should be redone and the quantity of times that it was decided to follow with a immature project on logistics support terms.

4.3.2 Case Studies definition

To evaluate the developed model, a simulation time of 12500 days (25 years) and two scenarios were defined:

- New projects being added to the system on a biannual basis (500 days between each project);
- New projects being added to the system on a mensal basis (20 days between each project).

These situations aim to show how the system would behave on a normal scenario (biannual basis), evaluating the costs and number of products that reached the end of the Preparation Phase and, on the other hand, its behavior on a overloaded environment, as a mean to evaluate which activities should be of concern when a effort to upgrade the system is being considered.

It is important to state that, for the biannual basis, a total of 25 new projects are added to the environment being simulated, whilst, for the mensal basis, the number of projects added is 625.

A constraint on the tool utilized is that the probabilities are always calculated based on a specified seed, and, aiming to provide an accurate result, 11 seeds were evaluated, from 0 to 10, and the result presented is the calculated mean for this analysis.

4.4 Results and Discussion

The results for the first scenario (biannual basis) are shown on Table 4.6:

TABLE 4.6 – Quantity of projects approved and price per unit for each maturity level and complexity degree for the biannual scenario

Complexity	Low (Act = 3d)		Medium (Act = 5d)		High (Act = 7d)	
Maturity	**Quantity**	**Price ($)**	**Quantity**	**Price ($)**	**Quantity**	**Price ($)**
1	11	376229,00	6	527807,31	2	1010688,39
2	19	162370,89	14	211560,13	10	270976,02
3	20	134522,02	17	149711,40	14	177043,23
4	22	113698,23	19	126792,58	16	142259,75
5	22	106080,54	19	115834,44	17	125367,04

As expected, for lower maturity levels, the quantity of systems approved tend to drop while the price per unit tend to rise. The same occurs when the complexity is increased. It is interesting to note, although, that the number of systems approved do not increase for low and medium complexity when it comes to maturity levels 4 and 5.

As for the second scenario (mensal basis), Table 4.7 presents the values for quantity and price per unit. For this case, the same analysis can be made, and the difference in the quantity of projects approved for maturity levels 4 and 5 in all cases shows that the concern for the modeling is not a big issue since they can be clearly separated, and the previous result can be explained by the reduced quantity of inputs.

In terms of cost, it was noted that for both analysis, the difference in unit prices does not follow a defined pattern, as shown is Table 4.8, but for the maturity level 5 in all cases the price for the mensal scenario reaches almost half of the price for the biannual one.

TABLE 4.7 – Quantity of projects approved and price per unit for each maturity level and complexity degree for the mensal scenario

Complexity	Low (Act = 3d)		Medium (Act = 5d)		High (Act = 7d)	
Maturity	**Quantity**	**Price ($)**	**Quantity**	**Price ($)**	**Quantity**	**Price ($)**
1	57	356766,46	26	470688,95	15	651715,32
2	188	147103,11	103	169237,23	62	204757,17
3	359	83108,56	197	103640,79	125	118254,70
4	475	61719,83	297	73656,51	195	82266,14
5	536	51232,21	388	57102,70	257	63825,29

TABLE 4.8 – Ratio between unit prices for mensal and biannual scenarios

Complexity	Low (Act = 3d)	Medium (Act = 5d)	High (Act = 7d)
Maturity	**Price (Mensal/Biannual)**		
1	0,95	0,89	0,64
2	0,91	0,80	0,76
3	0,62	0,69	0,67
4	0,54	0,58	0,58
5	0,48	0,49	0,51

Since the mensal scenario seeks to present which activities could be of concern on the development, Table 4.9 presents the activities that had most queues and the respective quantity of entities parked on them at the end of simulation time.

These results can be interpreted as the first activities that require more resources for the development process to be optimized, and, as can be seen, for lower maturity levels this behavior tend to happen on the beginning of the development, when the IPS plan is being defined, whilst for higher maturity levels they tend to be on the second support engineering (RAMT) analysis.

The maturity level influences since different activities return to the same point on the flux, as it is to be expected for changes in design. As can be analyzed for the results, when the maturity grows (i.e. when the development tend to go ahead without problems on the decision points), this effect tends to be minimized, since less entities shall return on the development process.

On the other hand, the complexity on some cases only implies on the quantity of entities parked on each activity, it does not change the position of the activity of concern on the flux. This can be explained due to the time necessary to perform each activity. Once this time is longer, there must be more entities parked on the point of concern.

It could be thought that applying more resources only on the activities with more queues would solve the issue, but this would only increase the queues for the next activities, due to the processional behavior of the system.

This implies that, to optimize the overall performance, it would be necessary to apply

TABLE 4.9 – Activities with most queues and their respective quantity of entities for each maturity level and complexity degree for the mensal scenario

Complexity	Low (Act = 3d)		Medium (Act = 5d)		High (Act = 7d)	
Maturity	**Activity**	**Entities**	**Activity**	**Entities**	**Activity**	**Entities**
1	Establish IPS Work Breakdown Structure (IPS Plan)	192	Establish IPS Work Breakdown Structure (IPS Plan)	344	Establish IPS Work Breakdown Structure (IPS Plan)	324
2	Identify functional requirements related to support and operation (RAMT2)	201	Establish IPS Work Breakdown Structure (IPS Plan)	146	Establish IPS Work Breakdown Structure (IPS Plan)	255
3	Estimate data (RAMT2)	118	Identify functional requirements related to support and operation (RAMT2)	127	Establish IPS Work Breakdown Structure (IPS Plan)	127
4	Estimate data (RAMT2)	49	Estimate data (RAMT2)	98	Define analysis goal in terms of supportability (RAMT1)	113
5	Estimate data (RAMT2)	5	Estimate data (RAMT2)	80	Define analysis goal in terms of supportability (RAMT1)	148

more resources on all subsequent activities that follows the ones identified here (as a mean to be able to perform the desired activities on less time) or to invest on experienced personnel on the supportability field to perform these activities (aiming to improve the maturity level).

The quantitative aspect of the work is concluded here. It is considered that the proof of concept addresses its goal, since it was possible to evaluate some scenarios regarding the integration of supportability to the overall development process and to evaluate needs of improvement for the simulated environments, presenting a contribution to the decision-making process to be carried out on aerospace projects.

It is important to note, however, that the mathematical model used on the work only had the goal of evaluating the response of the system, and it is necessary to obtain data from the industry in order to provide robustness for the model. In addition, it would be relevant to analyze the activities proposed on the framework in greater detail to estimate their real duration times. Also, other expected characteristics of the Embryo Digital Twin should be addressed, such as its integration with other development tools to guarantee its use as a repository and auxiliary tool in decision making.

As discussed on Chapter 2, the logistics support problem is a relevant issue when it comes to aerospace systems, due to the costs related. As a mean to optimize system operation and decrease its costs, several approaches are developed, but some of them do not fulfill all of their potential on assessing the problem due to the lack of alignment in terms of time they should be applied, because this association is not clearly defined.

On the other hand, the current paradigm shift due to the Industry 4.0 leads to the need to provide solutions that are already prepared to integrate and work with these new technologies, which inspired the use of a digital twin logic in this work.

To define a comprehensive framework, a qualitative and quantitative research were carried out, the first dealing with the features expected for the tool on a high level of abstraction for the first three phases of product development and with the creation of a framework for the Preparation Phase, whilst the second dealing with the establishment of a proof of concept and simulation scenarios, to evaluate the proposed framework.

One may question the practical use of the proposed framework, since it presents a processional view of the development rather the a data-based approach, as already cited. It is believed that some contributions of this work relies specifically on this holistic view, since lots of efforts are being made on development of new optimization methods and analysis (using data obtained from the systems) with good results on the specific domains they are applied, but incapable of solving the overall supportability problem due to its integrated (and thus emergent) inherent feature.

The results for both the qualitative and quantitative aspects shows that this type of integrated framework may present a new approach for the problem that could be explored, since it was possible to create and obtain results for the proof of concept as a tool to assist decision-making based on estimations for the expected environments.

Finally, the educational aspect of the work, presenting a graphical visualization for the activities and a broad view for the supportability features and needs is underlined here as another contribution, due to the complexity of the subject and need for integration to the common known development processes such as Systems Engineering, which leads to an explanation for the other engineering domains on the reasons for the development of supportability requirements and related activities, as well as provides a path to be followed or integrated on the existing frameworks aiming to enhance product support maturity.

5 Conclusion

The goal of this work is to present the logistics support problem and develop an approach capable of assisting on the decrease of the Supportability Maturity Readiness Level (SMRL) gap. This concept was presented, to clearly state the problem and the reasons the current approaches are incapable of solving it, i.e. due to the lack of alignment on the assessment of supportability requirements for the systems being developed.

To explore the logistics support problem and identify the gaps on the commonly used approaches to address it, a broad literature review on the theme was carried out, presenting the impacts in terms of costs to the system life-cycle, the definitions of Reliability, Availability and Maintainability factors and the Integrated Product Support approach.

Then, the digital twin framework was presented and its use was justified due to the Industry 4.0 paradigm that leads to the need for systems to be ready for integration to the new technologies used or in development. With this, the features expected for the Embryo Digital Twin were defined, and a high level meta model was created for the first three phases of product development.

To enhance the analysis, a framework for the conceptual development (Preparation Phase) of the Integrated Product Support unified to the overall System development process was defined on a graphical way, based on some theoretical references.

Finally, a proof of concept was carried out for this phase, analyzing its potential use for assisting decision-making on some case studies developed, achieving results such as the identification of activities in which more resources should be applied to decrease the time demanded for its fulfillment.

Based on this, it can be concluded that the work achieved the defined objectives and contributes with a holistic view of the problem at hand and similarly a systemic approach for its assessment, clearly presenting the time in which the analysis should be made, which was identified as the primary issue related to the supportability problem. This approach is also designed to be integrated on the Industry 4.0 context and to Systems Engineering practices, which can be described as another contribution.

It can be stated that, with the approach presented in this work, engineers using it will be able to have a clearer view of supportability development integrated to system life-cycle, so the dependencies derived from those requirements can be taken into account as early as on the Preparation Phase, which would also help to advocate for supportability friendly decisions, since most of the features to be evaluated in this scope are not testable yet on this phase.

By adapting the framework to different contexts, high level estimations on the overall process can also be done, which could help on creating supportability related databases to be used in future developments.

When comparing to the common approaches, the perspective presented here represents advances on a way to reach lower SMRL gaps, by connecting supportability analysis on a structured and graphical way to the life-cycle, specially to the Preparation Phase, that impacts the most on overall design aspects.

Nonetheless, some limitations were identified, as discussed throughout the work, as well as opportunities for improvement of the concept and further developments to be made. To address these, some future works were defined and are presented next.

5.1 Future works

Some of the derived future works that were identified are:

- Validation with industry experts on the Embryo Digital Twin framework for Preparation Phase presented on this work;
- Development of Embryo Digital Twin frameworks for the Development and Production Phases of System Life-Cycle;
- Development and simulation of other features expected from the Embryo DT;
- Technical specification of the Embryo DT;
- Acquirement of data and population of mathematical models on the Embryo DT with posterior simulation of its behavior and evaluation against the expected;
- Integration of the Embryo Digital Twin to other development tools;
- Application of the Embryo Digital Twin on a development environment;
- Development of an Intelligent Digital Twin based on the Embryo Digital Twin.

Nonetheless, this list is not intended to be extensive and present all of the possible applications or developments, it a guide for the expected next steps for this new approach.

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Appendix A - Appendix

A.1 Simulation code developed for the Jaamsim tool

It was not possible to provide the entire code in text format.

A secondary archive on the digital version of this document (CD-ROM) presents it.

Nonetheless, it can also be accessed with the following link:

https://drive.google.com/file/d/1Qamz8sd0Ci4EIpM1ISKKQb7hYg1bcDca/view?usp=sharing

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11. RESUMO:

Experience from industry shows that, when developing the support characteristics of a new aerospace system, supportability needs may be considered too late in the process or not be properly integrated with other system needs, leading to difficulties, lack of innovation and a series of constraints to the supportability performance of these systems, particularly when they enter into service and throughout the rest of their life cycles. Therefore, the purpose of this work is to model, in a graphical and qualitative way, a tool for the development of the supportability involved in the preparation phase of the life cycle for new complex aerospace systems. In order to keep its relevance and considering the current context of the industry, it was established that the tool must be, from conceptualization, adequate and integrable to the Industry 4.0 paradigm, as well as to new technologies to be developed, using, therefore, an approach based on digital twins, in an embryo scheme. The procedure followed was 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 tool, in order to explain the reasons why this approach was chosen as suited to assist in decision making throughout the complex aerospace support system life cycle. Therefore, due to its inherent expected features, it was decided to be named as Embryo Digital Twin for the supportability development process in the preparation phase of a complex aerospace system. Then, a framework for the supportability conceptual development unified to the overall system development process was defined, based on theoretical references, aiming to present the approach used by the tool, with special emphasis on the integration between these processes. Finally, a proof of concept with case studies was defined, as a mean to assess the expected features of the tool on decision-making. As a result and to state its relevance, this work presents a high-level model of this tool, positioning it in the context of complex aerospace systems supportability development, in the Industry 4.0 era.

12. GRAU DE SIGILO:

(X) OSTENSIVO **( ) RESERVADO** **( ) SECRETO**