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Fins Module Conception of the Microsatellite Launch Vehicle Based on Design for Manufacture and Assembly Method

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ABSTRACT: This paper presents the application of the Design for Manufacture and Assembly method (DFMA) during the conception of a space product. This approach enables to capture manufacture and assembly requirements in early phases of development. DFMA guides the manufacture processes and materials that rule the Fins Module interface to the Microsatellite Launch Vehicle (VLM-1) main structure. The results of this process are the requirements captured in the beginning of the project development, allowing avoiding problems that generally occur in the manufacture stage and in assembly, integration and test (AIT) phase. Rework, material loss, wasting time to assembly and integration, over engineering and unnecessary engineering are problems that the method intends to reduce in the physical implementation phase.

KEYWORDS: Design for manufacture, Design for assembly, Concurrent engineering.

INTRODUCTION

The Microsatellite Launch Vehicle (VLM-1) is a project under development at *Instituto de Aeronáutica e Espaço* (IAE) in Brazil and aims at carrying small satellites and small payloads to space. Its development was stated as a cost-driven process which involves the important aspects in anticipation of the requirements to the initial stages of the development (Fulindi, 2011). The VLM-1 is a three-stage solid propelled rocket, which provides the necessary energy to reach low equatorial orbits. This project is developed in cooperation with the National Aeronautics and Space Research Centre of the Federal Republic of Germany (DLR), and the first flight of the VLM-1 will be able to put in low orbit the German payload called Shefex III.

In space projects, different fields of research and engineering, as materials, mechanics, electronics, control and others, are involved. In each conception model of the project, analyses of the functional aspects, with materials to be adopted, mechanical stresses, equipment assembly and preliminary actions are taken in order to integrate such a multifunctional group. This group aims at performing the integrated product team. From the Design for Manufacture and Assembly method (DFMA) analysis, more efficient actions are taken to anticipate requirements for the beginning of the product development. This leads to reduced problems in the assembly, better ideas to prepare the manufacture process, and the decision on materials is taken in the same time when the process is under analysis. Furthermore, all impacts are analyzed in the conception stage of the project. In this work, DFMA is applied aiming at developing the VLM-1 Fins Module.

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Based on DFMA arising from Concurrent Engineering methodology, it was possible to achieve a balanced solution for the VLM-1 Fins Module, which considered organizational aspects, manufacture techniques and assembly strategies. As the main result, one can outstand a Fins Module conceptual design, considering real needs from stakeholders and adapted for the Brazilian technological scenario.

PRODUCT DEVELOPMENT PROCESS AND CONCURRENT ENGINEERING

Product Development Process (PDP) consists of applying a set of activities aiming at reaching the design specifications and its production process. So that, manufacture is able to produce it, from the needs of the market, possibilities and technological constraints, considering the competitive and company's product strategy.

On the other side, as stated by Huang (1996), Concurrent Engineering (CE) improves quality, reduces costs, compresses cycle times, increases flexibility, raises productivity and efficiency, and improves the social image, making an ideal environment for product development.

The practice of CE has applied methodologies during the product development aiming at integrating engineering tools in order to help in decision-making, such as Design for X (DFX), DFMA (Design for Manufacture and Assembly), Computer Aided Design (CAD), Computer Aided Engineering (CAE), Computer Aided Manufacturing (CAM), among others.

Design for X

DFX is one of the most effective approaches to implement CE. The called X can be quality, manufacture, assembly, cost, among other features related to the product life cycle process (Huang, 1996).

DFX has become a powerful tool for project analysis of products, promoting the practice of CE in a prediction error process of subsequent processes. In other words, DFX assists in raising the largest number of project related information, in view of facilitating decisions in the preliminary stages, which generally have less information than in future phases. Since the 1960s, efforts have been made in the study of conceptual and detailed design of products, aiming at manufacture and assembly analysis. Among the various methodologies that compose the DFX, there are some that are already being more strongly applied, having a wider literature and well-structured implementation methods, such as Design for Manufacture and Design for Assembly methodology (Iwaya, 2010).

Design for Manufacture

In Design for Manufacture, or DFM, the product is developed for production, aiming at facilitating and reducing the production cost.

According to Xie (2003), DFM is the method that considers the limitations related to manufacture in the initial phase of the project. Thus, the project engineer can make the selection between different materials and technologies in order to estimate the manufacture time and the product cost quantitatively and to quickly choose between different project plans. The project team compares all types of project plans and technology, and revisions are carried out in the initial phase of the project according to the feedback information. Therefore, the most satisfactory configuration for the product can be determined. There are three objectives in DFM:

- Improving the quality of new products during the development period, including project, technology, manufacture, service and so on.
- Decreasing the cost, including the design cost, technology, manufacture, delivery, technical support, disposal, and so on.
- Shortening the development cycle, including project time, preparation for manufacture, and calculation of repeatability.

Currently, DFM is widely applied with CAD/CAM systems, where the designer can extract the features of a modeled part in order to predict spending and determine manufacture processes. This allows project modifications for the choice of the best product engineering solutions.

Design for Assembly

As stated by Redford (1983), through Design for Assembly (DFA) application in a development early phase, a significantly cost reduction can be achieved during the final integration and assembly stage. The mentioned cost reduction could be attained accomplishing the project of parts that can be easily handled and products that can be easily assembled manually or by machine. In general, improvements can be typically achieved through DFA implementation, resulting in cost reduction. This fact occurs because there are not ideal attention in assembly strategies and time spending to execute this step of development.

According to Boothroyd *et al.* (1994), in order to provide guidance to the designer in reducing the number of parts, the DFA methodology provides three criteria by which each part should be examined as well as how it is added to the product during assembly:

- During the operation of the product, the part moves in relation to all other parts already assembled? Only overall motion should be considered — small movements that can be accommodated by integral elastic elements, for example, are not sufficient for a positive response.
- The part must be of a different material or be isolated from other parts already assembled? Only fundamental reasons related to the material properties are acceptable.
- A piece must be separated from all other parts already assembled because, otherwise, required assembly or disassembly of other separate parts would be impossible.

Design for Manufacture and Assembly

Huang (1996) defines a better alternative in a project by the optimization of the manufacture and assembly process, applying DFMA approach. This approach is a systematic analysis used in the preliminary phases or in the project review, when problems of product manufacture and assembly appear and when a product is losing its market.

This approach is the basis for CE studies, providing guidance to the design team, simplifying the product manufacture and assembly, reducing costs — as a benchmarking tool that aims at studying competitors — and quantifying manufacture and assembly difficulties, as a should-cost tool, helping negotiate suppliers' contracts.

As stated by Boothroyd *et al.* (1994), "to manufacture" refers to the manufacture of the individual component parts of a product or assembly and "to assemble" refers to the addition or joining of parts to form the completed product. Assembly will not be considered a manufacture process in the same sense that machining, molding etc., which are manufacture processes. Hence, the term Design for Assembly (or DFA) means the design for ease of assembly. Thus, Design for Manufacture and Assembly (DFMA) is a combination of DFA and DFM.

The DFMA concerns to anticipate the assembly and integration requirements for the development phase, reducing future problems in the project physical implementation.

METHODOLOGY

The methodology applied in this work is based on references, tools and approaches used in the VLM-1 Project. It is characterized as a qualitative research, according to Silva and Menezes (2001); the interpretation of the phenomena and the attribution of the meanings are basics in the qualitative research process. It does not require the use of methods and statistical techniques. The process and its meaning are the principal focus of the approach.

In order to collect and understand the methods and tools, a line of reasoning considering a framework for the execution of the project can be built, where they are used, starting from the highest to the lowest level. As a result, one has a broader approach as it reaches the final objective (Fig. 1). This approach aims at involving development scenarios to obtain the best design solution.

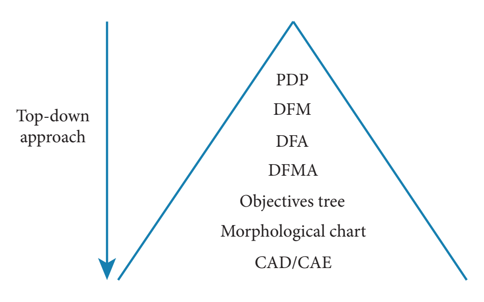


Figure 1. Framework for project of fins module.

The Product Development Process (PDP) model considers, from the beginning, the organization requirements, which, together with the product requirements, guide the process of product development (Fulindi, 2011). Following this model, there is the flow chart shown in Fig. 2. The stages of integrated development are presented, showing the interaction that the DFMA approach provides between the design phases.

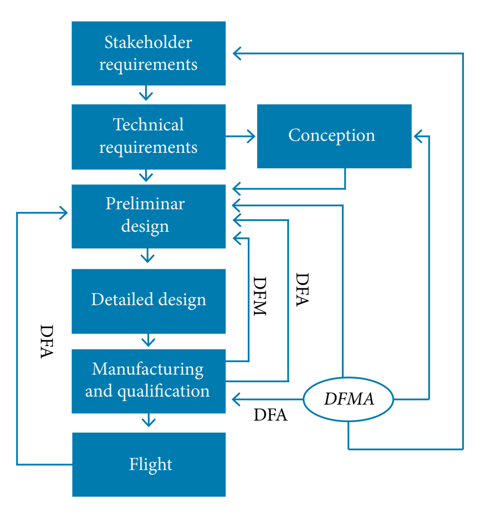


Figure 2. Project flowchart of Design for Manufacture and Assembly method.

From the stakeholders' requirements, the technical requirements that will feed the product conception are defined. The preliminary design is developed based on the requirements anticipation of the manufacture and qualification phase through the DFA and DFM analysis tools, in which the physical elements that will compose the final assembly can be identified as well as how they will be performed. For the processes used in manufacture, materials and types of tools for the visualization and analysis of these elements are used, with CAD and CAE software to validate the concepts generated from the requirements. In this phase, the requirements to the module integration in the vehicle main structure and to aid the launch pad are identified. This analysis looks to the type of the module fixation with the bottom vehicle in the launch pad. In the same time, the question "how to integrate?" the equipment distributed in the vehicle and distributed in the integration tower is analyzed. Though DFA analysis, it is possible to detail and planning all the integration process of the vehicle to the flight phase.

For the VLM-1 Project, a cluster of four fins coupled to a cylindrical membrane structure is required, denominated here Fins Module. The types of manufacture studied attending the project are: carbon, aluminum, fiberglass, and sandwich type in core and aluminum, or core and foam.

The Fins Module also integrates the fins in the vehicle body and aids to protect the equipment inside of the vehicle. Knowing the mechanical and aerodynamics characteristics of the VLM-1, as static margin, the main functions and objectives are identified. These objectives are organized and deployed as an objective tree, which drives to the goals and the metrics that determine the guidelines to the project's physical implementation (Palmerio, 2008).

As stated by Summers (2000), objective trees are used to model the hierarchical nature of the requirements, or objectives, of a design problem. This tool has been used for problem definition and clarification in the early stages of design, though it should be reviewed to ensure that design team is kept on task. Questions about how to measure as well its impact and importance in the design development must be raised, if the objective was achieved. The first question will derive metrics (it means a word as cost, schedule, fuel economy, productivity that encompasses a set of measures). The metrics are deployed to the measures (objectives and quantifiable). Cross (2008) stated that in order to identify the product objectives, the questions "why?", "how?" and "what?" are used to expand and clarify the objectives. Afterwards, the objectives are hierarchically drawn in the tree diagram. In this way, the importance of each objective is analyzed aiming at establishing which one should be achieved first.

Figure 3 shows the objective tree for the VLM Fins Module. The main objectives are deployed towards the lower levels. From these objectives the functions will be attained.

When the objectives unfold, one can identify the features that have become the principal functions of the Fins Module. These functions were represented by physical elements, which, through a morphological chart, allowed building the first physical conceptions.

According to Cross (2008), the morphological chart method exploits all possibilities of combination and encourages the designer to identify novel combinations of elements

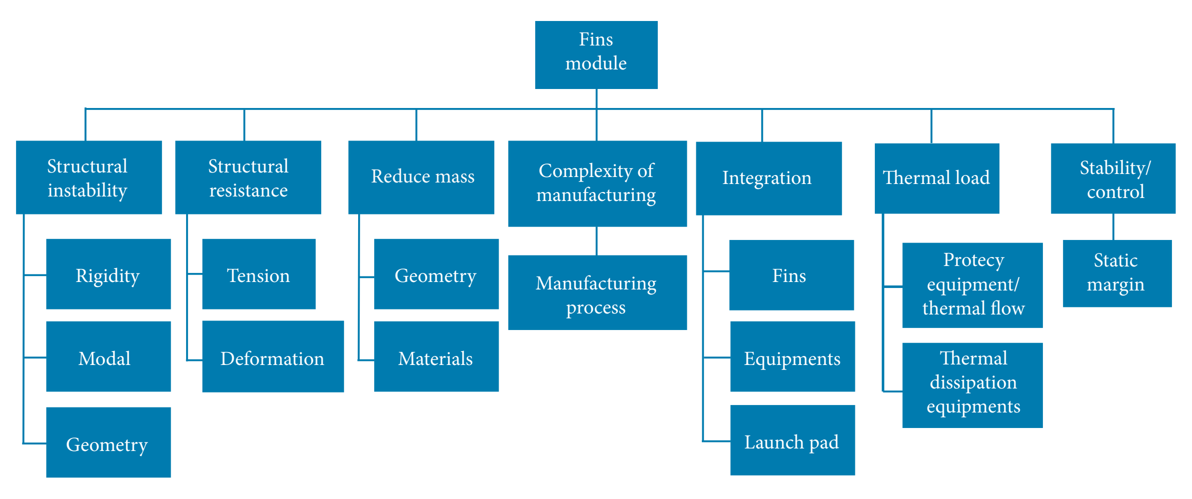


Figure 3. Objective tree of fins module.

or components. The chart sets out the complete range of elements, components or sub-solutions that can be combined together to make a solution. The number of possible combinations is usually very high, and includes not only existing conventional solutions but also a wide range of variations and completely novel solutions.

By analyzing the Fins Module objective tree, the following characteristic were raised: being rigid, resistant, and light, reducing manufacture complexity, enabling integration, allowing thermal dissipation and the vehicle's controllability. The physical elements that meet the Fins Module are known and their dimensions are defined by relevant calculations to other studies.

Table 1 shows the Fins Module Morphological Chart, which can permit a comparison between different solutions for the same requirements arising from the objective tree. The conception defined is about carbon fins and also carbon monolithic membrane based on the principal functions for the system, as mass, stiffness and structural strength.

The carbon was chosen based on the fins material characteristics. Carbon fins are more rigid and resistant, which is one of the most important requirements of the Fins Module. The low carbon density compared to aluminum and the glass fiber make the fins lighter and, as result, it implements the mass reduction requirement. The rigidity and resistance characteristics impacted in the choice of the carbon monolithic membrane. When compared to other materials, it is more adequate for the manufacture, where the performed process reduce the manufacture time.

The choice of the best solution is made based on the manufacture procedures of the module, as well as the integration in the vehicle, taking into consideration the three more relevant scenarios to the system (Fig. 4), chosen from several ones. An analysis with all deployment of the possible scenarios from the life cycle processes is not represented in this work. The scenarios are environments that involve the process of life cycle of the product. In other words, each scenario presents the project elements needed for the development, which are related to the system when subjected to DFMA analysis.

The three scenarios illustrated in Fig. 4 provide the elements that exchange material, energy and information about the system when submitted to the DFMA analysis. These elements for the "Development Organization" are the impacts of the international relationship in this project. Through IAE and DLR interactions, the relevant flows of information to the project conception occur. In the AIT scenario, the resources to implement the assembly, integration and tests are identified. In this scenario, the material types, the processes and the necessary tools to the physical implementation of the project are also identified. Finally, in the Product Operation scenario, the behavior of the system in flight is considered. In this scenario, the geometry and mass of the fins as well as the gravity center of the module are

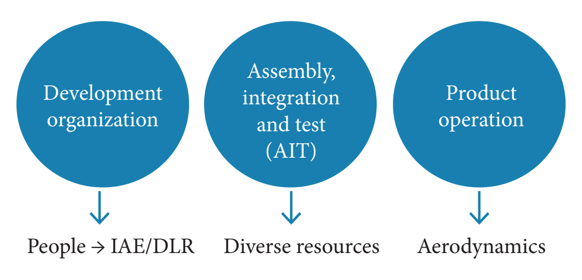


Figure 4. Scenarios from the life cycle process.

Table 1. Morphological chart of fins module.

Function	Physical elements						
	Fin				Membrane		
	Carbon	Aluminium	Fiberglass	Aluminium	Carbon monolithic	Core/Al sandwich	Core/Foam sandwich
Be rigid	x				x		x
Be resistant	x				x		
Be light	x		x			x	x
Reduce manufacturing complexity					x		
Allow integration	x	x	x	x	x	x	x
Allow thermal dissipation		x		x			
Allow controlability	x	x	x	x	x	x	x

identified. All these parameters influence in the aerodynamics and the vehicle's trajectory.

RESULTS

Based on the analysis of the main functions raised and the obtained results using the applied tools, it was possible to describe the first manufacture and assembly for the Fins Module. It is worth to highlight that the number of integration hours and mass limit value for the module derived from calculations belong to other stages of Project VLM-1 development.

The following list presents the first requirements of the Fins Module:

- The Fins Module shall permit the integration of the launch pad.
- The Fins Module shall have mechanical interface to the fins.
- The Fins Module shall have vehicle electrical interface with the launching tower.
- The Fins Module shall be integrated in 3 hours.
- The Fins Module shall have a mass less than 90 kg.
- The Fins Module shall have at most 10 elements for integration.
- The Fins Module shall not allow structural instability.

Table 2 describes each requirement that was allocated for each physical element defined for analysis and studies. Figures 5 and 6 present the first CAD conception of these elements.

Figure 7 shows the physical dimensions of the Fins Module, in a sectional view. These dimensions match with the requirements stated for this part of the vehicle.

Table 2. Allocation of the requirements.

Requirements	Physical element
1	Ring interface of the launch pad
2	Follow-up plans on the cylindrical structure to support the fins' base
3	Umbilical connector
4	Integration plan, environment, and tools
5	Structure and fins in carbon and aluminum rings
6	Fins module + 2 interface rings + fins
7	Monolithic module made of laminated carbon with compatible stiffness

The data of mass, center of gravity and moments of inertia are generated from a finite element model and in the CAD software as well (Table 3). The results show that conception is acceptable based on mass requirements.

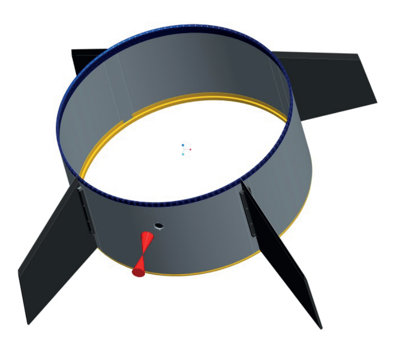


Figure 5. First conception of fins module in CAD.

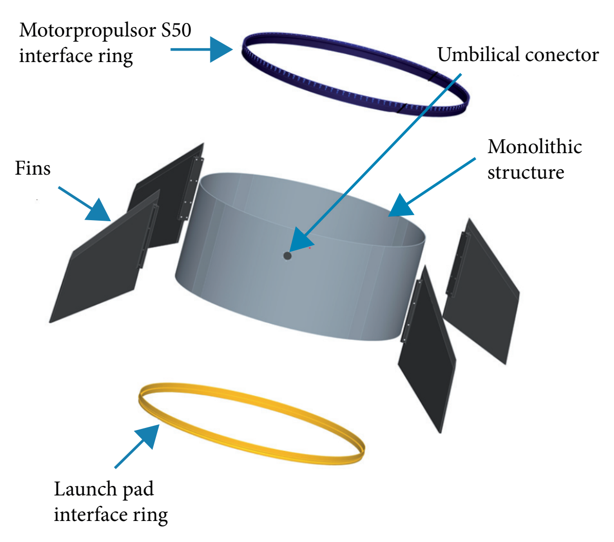


Figure 6. Explode view of fins module in CAD.

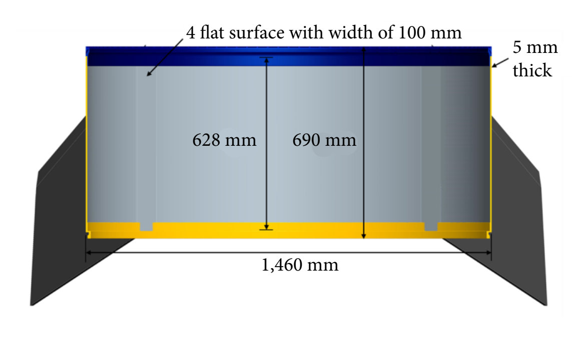


Figure 7. Physical dimensions of fins module.

Table 3. Results of the fins module model analysis.

Volume	3.3557712e-07 mm^3
Surface area	1.3335811e+07 mm^2
Average density	2.3960170e-04 kg/mm^3
Mass	8.0404848e+03 kg
Center of gravity: X	0.0000000e+00 mm
Center of gravity: Y	1.5783229e+00 mm
Center of gravity: Z	8.7176133e+02 mm
Inertia tensor: I_{zx}	0.0000000e+00 kg x mm^2
Inertia tensor: I_{zy}	0.0000000e+00 kg x mm^2
Inertia tensor: I_{zz}	2.0991524e+07 kg x mm^2

A structural CAE static analysis and modal analysis showed that results reached the main objectives proposed, approving the Fins Module conception for use in flight conditions expected for the VLM-1, without problems related to buckling effects and flutter, decoupling frequencies on the fins. Figure 8a shows the finite element method for structural response of the Fins Module, equipped with four fins; on the other side, one notices in Fig. 8b an example of membrane structure subjected to compression load. Therefore, it is concluded that there is a load distribution, which makes the module comply with the requirements of rigidity and resistance.

According to the Fins Module's physical and structural characteristics, and the adopted materials, a manufacture requirements proposal for the Fins Module was raised, following the guidelines of a DFM analysis:

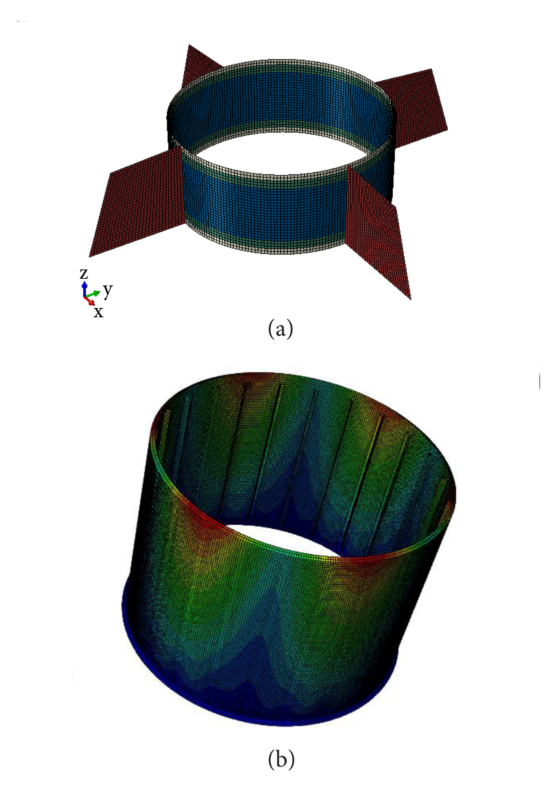
- Manufacture process of carbon structure: type filament winding (winding process of continuous fibers on a rotating mandrel in predetermined pattern).
- Manufacture process of the rings: machining of aluminum plate.

The type filament winding process reduces direct labor in lamination and, consequently, there is a cost reduction of the product. The machining of the rings will follow the profiles drawn in CAD, respecting the DFM guidelines for machining process.

From the conception generated in CAD and their characteristics, it is presented a proposal of components integration of the Fins Module. This was carried out following the guidelines of a DFA analysis, as well as it was taken into account handling the module during transport and integration.

The logical order of the sequence of events was respected:

- Assembly of the rings in the module structure before the launch site transportation.



(a)

(b)

Figure 8. Structural analysis in CAE software with fins (a), and with isolated structure (b).

- Transport of the rings integrated to the module structure with security and protection against impacts.
- Transport of the fins separately to the structure with security and protection against impacts.
- Integration of the Thrust Vector Assembly (TVA) module to the first stage motor case in the horizontal position.
- Integration of the fins to the module structure in the horizontal position.
- Integration of the first stage to the launch pad by the launch pad interface ring.
- Integration of the other modules and stages of the vehicle.
- Integration of the electrical interfaces between the vehicle and the launch pad through the umbilical connector modules present in the vehicle.

From the mentioned integration sequence, it is possible to deploy the Vehicle Integration Plan. In this plan, all steps are detailed, respecting all safety and time requirements. In this work, it will not be showed due to the complexity of the plan and the publishing restrictions. The product conception is carried out simultaneously with the development process in the preliminary phase of the project, considering all the requirements identified using DFMA analysis. Then, the physical implementation of the product was done, with all needed attributes aiming at avoiding rework in future phases of project. This optimizes the time and cost of the manufacture and integration phases.

CONCLUSIONS

The design for manufacture and assembly analysis was presented to the VLM-1 Fins Module conception. A CAD model was developed from the study of the methodology and application of the tools. The DFMA analysis derived the requirements to the physical implementation. From these requirements and the knowledge gained using the DFMA analysis, it was possible to take into account the anticipation of the elements that impact generally in the manufacture, assembly and test phases. This guides to avoid material loss, rework, wasting time to assembly and integration, over engineering and unnecessary engineering throughout the life cycle process.

Thus, describing a framework propose, created from the methodologies analyzed and definitions from VLM-1 project, it was possible to apply the concepts of the DFMA method aiming at defining the characteristics of the Fins Module.

The presented results emerged due to the implemented application, when the guidelines were used aiming at the conception of a CAD model and the survey of the first DFM and DFA requirements for the Fins Module.

Also falls the importance of applying DFMA method throughout the VLM-1 project, as in the case of a low-cost project, where new technologies are approached and used; this method helps in raising the requirements for manufacture and integration present in the development phases in order to minimize the possible errors that may occur in implementation and vehicle's flight.

PROPOSALS FOR FUTURE WORKS

As this work is a part of the current studies on the development of the VLM-1 project, it will serve as the principle for the next related studies, using the presented methods for the development of other subsystems conceptions of the vehicle.

Based on the framework presentation for the product development, this work can be used as a basis for studies of other product development methods as well.

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