DESIGN CONFORMITY ASSESSMENT OVERVIEW: OUTCOMES FOR THE BRAZILIAN LAUNCHERS PROGRAM

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Abstract. *Since the creation of space activities program, in 1961, Brazil has experienced not only several launching successes but also some failures with mission loss, mainly in the last ten years, with the Satellite Launch Vehicle (VLS) program. In a similar circumstance, after a series of launch vehicle failures, in 1998 and 1999, NASA (National Aeronautics and Space Administration) conducted an assessment of the situation and concluded that the success rate could be improved through the implementation of launcher design independent analysis and verification. The purpose of this paper is to present a design conformity assessment process overview, by building up a general panorama of methods and principles used by some major organizations around the world with high level of success in this area. It is expected that the outcome of this review might support the Brazilian space organizations to formulate a vehicle design conformity assessment process, as part of the space qualification assessment system. This work intends to extract the best practices related to vehicle design life cycle, control gates and verification methods made available in the literature by NASA, USAF (United States Air Force) and ESA (European Space Agency). The main focus of the research is on design conformity assessment system with special emphasis on the activities related to verification and validation process. With this information properly collected and analyzed, a preliminary framework of a design conformity assessment process might be drawn in order to enable Brazilian space organizations (developers, industries, operators and certification office), to improve the strategic decision for structuring their own systems for design conformity assessment within each competence area of the launchers program.*

***Keywords**: management, space program, launch vehicle, design, conformity assessment.*

1. INTRODUCTION

Since the creation of National Space Activities Commission Organization Group (GOCNAE) in 1961, and the Aerospace Activities Institute (IAE), in 1971, Brazil has been engaged in the research and development efforts on Launchers Programs and several sounding rockets were successfully developed and launched. In the end of 1997, the final validation of first Brazilian Satellite Launch Vehicle (VLS) prototype - V01 was initiated. In December of 1999, the second prototype - V02 and finally, in August of 2003, the third one - V03 were tested. All of them have no success. (IAE, 2007).

The investigation report (DEPED, 2004) has indicated several improvement needs, among them, the effective implementation of the project management system during product development activities, to be carried out by the development organization, and as strongly recommended, the implementation of an independent design conformity qualification assessment procedure to be carried out by an independent organization. This paper addresses the second improvement listed above, starting up right from its conceptual stage. Thus, a preliminary framework of a design conformity assessment to be applied for an independent assessment organization is drawn in order to assist the space launchers and its players (development organizations, industries, operators), to make the strategic decisions for structuring their own systems. To derive such a framework, a extensive research has been carried out to extract the best practices related to vehicle design life cycle, verification methods and control gates with special emphasis on the activities related to design conformity assessment (verification and validation) process used by NASA (National Aeronautics and Space Administration), ESA (European Space Agency) and USAF (United States Air Force).

2. DESIGN CONFORMITY ASSESSMENT OVERVIEW

2.1. Activities during development life cycle

The key to ultimate success of aerospace projects in the early 1960s was the implementation of project management and system engineering processes with development of procedures based on design best practices. As a consequence a more formalized design process took place within the organizations (DoD 1986).

One traditional approach view for design development and its conformity assessment can be represented as technical aspects of the design cycle and assessment layers (or “Vee” diagram) as shown in Fig. 1 (Stevens 1998; NASA 1995; USAF 2005). This depiction is requirements-driven, and starts with identification of the stakeholders needs. When these are understood and agreed to, they are placed under design control, and through the deployment into system requirements, the concepts and specification are developed. The deployment and definition process is repeated over and over again until, ultimately, the parts (components) are identified and specified.

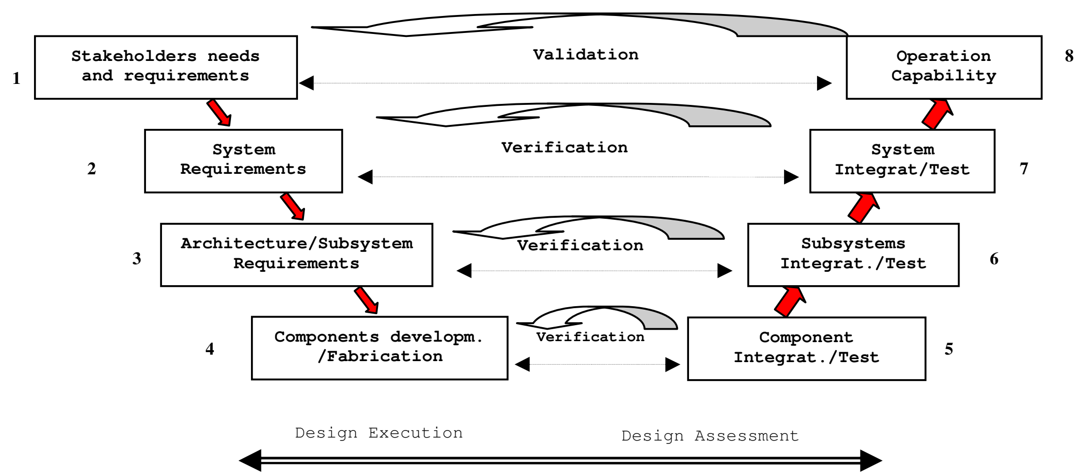

Figure 1. Design execution and assessment (verification/validation) layers

The process of capturing the stakeholders needs and establishing their requirements is the first activity aiming at the development of a product. The stakeholders are all those that own some relationship with the project, influence or are influenced by it, direct or indirectly. As such, they possess needs or specific necessities directed from its interests that must be converted into requirements (Hull *et al*, 2005). The main phases involved in this activity consist of the stakeholders definition, stakeholders requirements definition and the establishment of the results in a formal document.

The next step is the system requirements definition. In this phase, the transformation of the stakeholders needs into requirements to be fulfilled by the product occurs. The general model of the solution to be adopted is usually supplied without determining the system specific characteristics. Thus, in this stage, the key requirements must be established to characterize the main parameters that must be present in the system. Moreover, it should be defined the functional structure, performance characteristics, internal interfaces and non functional requirements or constraints. Non functional requirements are the constraints imposed to the product operation and complement those intended to meet its required functions. Thus, they are requirements that add quality to the system, taking care, for example, of its necessities of reliability, cost or safety. These requirements directly drive the system specifications and verification activities.(Stevens *et al*, 1998).

Then, the next project stages consist of the definition of its architecture and development of the components. In these phases, technical details are developed in all system levels until its configuration is established. The architectural design shows how the system will operate before its construction, and before defining the way how it will be built. After establishing the system architecture, the internal functionality of each component and its obligations in the interaction with other system components can be defined. As a consequence, other requirements might appear, for example, from the functionality that the components must supply, from the interfaces that they will use or supply and from the constraints which they will have to fulfill. The architectural design specifications might have portions of its content originated directly from the stakeholders requirements besides those originated from system requirements development. In this case, additional constraints imposed by relevant authorities may be reflected later in system qualification activities. At the end of the design execution phase (see Fig. 1), the system should be completely defined, including its interactions with the operational environment and the verification strategy to be adopted in the next development phases (Hull *et al*, 2005).

After the conclusion of design execution phases (left side of "V" diagram) the activities of design assessment (right side of "V" diagram) intend to verify the adherence of what has been specified to the established requirements according to the plans developed in the previous phases. So, the first activity is the component tests, developed in order to prove the accomplishment of the requirements specified to these items. According to Stevens *et al* (1998), high safety margins are required to balance the remaining uncertainties in a satisfactory way. In complex systems, the components are present in diverse system hierarchic levels and consequently, this activity will also be developed in other integration phases.

In the integration tests, the system control interfaces and the mechanisms are checked regarding the architectural design. Tests in this phase are concentrated in evaluating internal and external interfaces of the system, behavior of the main subsystems and interactions among the system and the external systems. The applied safety margins in this stage are considered intermediate. Elements of intermediate system levels are verified: these items consist of assemblies to subsystem level. Tests are performed in order to verify the requirements which demand integration level for assessing its fulfillment.

After concluding the subsystems verification, then the complete system integration and its consequent verification occur. Requirements verified in this phase are related directly to the same ones specified in the system requirements definition phase. Items that only can be tested with the system totally integrated are verified, as well as those involving the complete system behavior. The problems are more difficult to be identified; however, they produce more serious consequences to the system when they are exposed. Undesirable emergent properties among system elements can be identified and eliminated. Thus, system tests, even more complex, help to provide confidence in a good product operation.

After finishing all product verification stages in its manufacture place, the product is installed in the operational environment. The reception of the product assures that the stakeholders requirements have been met through system successful operation. In the case of launch vehicles this phase is performed during the product installation in its launch pad and finished after determined number of successful launchings. Tests on the ground are performed previously to launching and after concluding the revisions for launching release. In flight, the remaining requirements will be evaluated. After determined number of successful launchings when the system reliability could be proved, it gets the final acceptance and thus it reaches its validation

Analyzing the phases represented in "V" diagram and the description of the activities presented, a direct relationship of what is performed in both sides of the diagram can be observed. The left side of the V diagram (see Fig. 1) concentrates the planning activities of what must be verified ahead in the system and in the right side the verification activities regarding what has been planed previously are done. This approach allows a clear visualization of the location of any activity during the design and a better control of the reason and motivation of performing each step inside the process can be done.

In the projects that compose space programs developed by the organizations searched (USAF, NASA and ESA) the activities that are related to assessment are distinguished by several control gates present in design process layers with application of assessment methods. The activities, as a whole, are part of a context where systems engineering principles are followed to get, in this way, an objective confirmation that the requirements specified for the product have been met.

2.2. Assessment methods

The assessment methods are characterized by application of verification and validation processes. They assure that the products delivered for operation comply with the system requirements (NASA, 1995). In accordance with ESA (1998) the main objectives of these methods are: a) to characterize the project; b) to assure that the product is in compliance with the qualified project, free of manufacture defects and acceptable for use; c) to certify that the system will be able to take care of the requirements of the mission and, d) to confirm the integrity and the performance of the product in the diverse phases of project life cycle. Several methods are used to verify conformity with requirements. Within the searched organizations, there are some differences in its contents but the core of the methods are the same. These methods are presented and described below.

2.2.1. Testing

Testing consists of the verification of the whole system or part of it under a controlled condition, including data gathering and subsequent analysis in order to demonstrate the fulfillment of the defined requirements for the product. This approach, however, is selected as primary activity only when it can produce sufficient or necessary results for the conformity demonstration (USAF, 2005).

NASA divides this method in two categories: functional and environmental tests. ESA has a similar approach without, however, classifying test types. Moreover, it also enhances the importance of data analysis after tests, considering this activity as part of the same one (ESA, 1998).

2.2.2. Analysis, Simulation and Similarity

Analysis is the verification - thorough analytical techniques - whether the requirements are fulfilled by the system. Examples of such techniques are statistics, qualitative analyses, simulation or similarity analysis. Analysis activities are executed in those cases where the demonstration approaches like tests are or not capable to verify the cited requirement under all planned conditions, (ii) its accomplishment is not technically practicable or (iii) it's not cost-effective (USAF, 2005).

According to NASA, concepts relative to analysis are presented in a similar way to those adopted by USAF except by the fact that simulation and verification by similarity be presented as other verification techniques. ESA also has a similar approach; however, it poses verification by similarity as a subdivision of analysis. It also emphasizes that characteristics of the new part or component must be within the qualification margin of the previous project whose analysis has been based upon (ESA, 2004).

2.2.3. Demonstration

Demonstration is applied to determine if the design or performance qualitative requirements have been fulfilled. It takes place through the observation of system operation or part of it under controlled conditions, or through qualitative determination of properties of a testing article.

It intends to verify characteristics such as transportability or accessibility, i.e. requirements that are presented in a qualitative or conditional manner. The results of the demonstration can be obtained in test programs or even from activities set up exclusively for this proposal (USAF, 2005). USAF and NASA show this activity as a proper method of verification. Conversely, according to ESA principles, demonstration belongs to testing activities.

2.2.4. Inspection, Record validation, Process control and Design review

In order to assess the construction features, workmanship and other physical attributes, the inspection method is used. It is characterized by the verification of equipment or manufacturing process control documentation related to the design parameters (NASA, 1995). In this method, the verification is executed through visual determination of product characteristics (ESA, 1998). According to USAF, process control is another way of verification, in which parameters of process control can evidence the conformity of requirements. However, process control by its own can not be used to demonstrate the requirements accomplishment. (USAF, 2005). According to NASA (1995), it's adopted the record validation to verify characteristics and processes of system construction through the manufacture registers of an item submitted to acceptance. Another method adopted by ESA is design review, where design approved documents or validated records are used to evidence that a requirement is met (ESA, 1998).

2.3. Design life cycle phases and control gates

Each organization analyzed has a distinct product design representation within the project lifecycle, although its phase division, the objectives and characteristics related to project management in phases are very similar. The division of a project in phases improves project progress visibility during its execution. The verification activities in development phases are previously included in the project life cycle. A panorama of the control gates representations, detailed on assessment activities - with some influence on the design verification and validation - is shown below.

2.3.1. Phase 0 (ESA) or pre-phase A (USAF and NASA)

This phase comprehends the initial project studies (block 1 of "V" diagram). The concepts and ideas in accordance to operational needs to be supplied by the system are elaborated. In this phase, some requirements could be formulated throughout the goals analysis and presentation of several possible system solutions. The USAF and NASA approaches detach for this stage, the initial development of plans and strategies to execute them later. ESA does not present any specific activity for this stage.

2.3.2. Phase A

This phase aims to determine the feasibility of the project derived from alternatives solutions analyzed (corresponds to block 2 of "V" diagram). The activities are still carried out in a preliminary way, but in a more detailed manner (NASA, 1995). Once the goals and objectives are presented in detail, it's possible to get refined answers to the needs imposed on the previous phase concerning the product, system requirements and the associated architecture (ESA, 1996).

2.3.3. Phase B

In phase B, preliminary design development is initiated (USAF, 2005) (corresponds to block 3 of the “V” diagram). It includes a formal definition of system requirements and design specifications for the product. It is also elaborated an engineering and management plan for the several design processes, including the verification process. At the end, preliminary design reviews in some levels of the system are executed in order to prove the conversion of requirements into engineering specifications (NASA, 1995). It is enhanced at this phase, the deployment of the requirements up to a level to make them verifiable and traceable (ESA, 1998).

For NASA, the configuration management process is initiated with the establishment of system requirements and a verification requirements matrix, using, as a reference, the existing design specification. The verifications are concentrated on definitions, requirements and system safety reviews as well as the establishment of acceptance criteria for final product.

2.3.4. Phase C

During this phase, it is expected that all design development activities are already completed, including engineering data (corresponds to block 4 of the “V” diagram), in order to support manufacturing, integration and formal verification activities. At the end, critical design reviews are done in the several levels of the system, in order to establish a frozen configuration to the system and, to support the initiation of product manufacture phases (NASA, 1995). For NASA, the verification plans are refined, including system interfaces, reflecting its maturity. System operation and integration plans are developed and completed, besides the monitoring of the planned design progress. With critical design review it’s assured that the product specifications go to manufacturing in a manner that all requirements will be met.

In accordance ESA (1998), this phase of development, the verification activities objectives to aspects of transportability, accessibility and testability, and to start verification activities by inspecting the lowest system level in conjunction with components manufacturing process.

2.3.5. Phase D

The activities in this phase include product manufacturing, verification and integration (corresponds blocks 5, 6 and 7 of the “V” diagram). The main result of this phase is the demonstration of the product capability to reach the proposal it has been designed for (NASA, 1995). The acceptance process is also performed through assessments process for the product to be delivered (ESA, 1996). NASA and USAF perform prelaunch verification activities in this phase, while ESA places these activities in the phase E.

2.3.6. Phase E (ESA)

In this phase, according to NASA and USAF, the product is already into operation and takes only periodic operational readiness reviews (corresponds to block 8 of the “V” diagram). For ESA, the prelaunch activities are developed in this phase, with prelaunch readiness and operation review.

The sequences of the assessment activities are equivalently executed by the organizations searched. NASA and USAF present a verification planning before the conceptual phase of the design, while preliminary studies about the system are still made. ESA always demonstrates the possibility of execution of these activities, although it does not present this concern in the initial phase,. An example is the accomplishment of qualification activities in lower levels of the system before the execution of critical design review for its higher levels.

The steps described in Fig.1 are placed in the design life cycle phases and, the control gates, in most of the cases, allow the project to get in subsequent phases. The control gates yield many verification activities represented by verification methods to assure that all activities performed are in conformity with the established goals (DoD 1999). The verification methods are applied in many cases in groups, for example when the analysis is applied with tests to demonstrate that requirements are met in all possible ranges, not only for those checked in tests. The activities of design execution described in the left side of the “V” are performed from phase 0 or pre phase A to phase C and the activities of design assessment described in the right side of the “V” are performed from phase D to phase E.

2.4. Preliminary framework of a design conformity assessment

A summary of the best practices related to assessment and control gates is presented in Tab.1. It can be thought as a preliminary framework of assessment activities for design conformity, in order to assure compliance of requirements related to safety and mission assurance. The framework could be used by all program players (development offices, industries, operators and certification office) in such a way that the verification activities developed can be compared with theirs major milestones. It’s considered that verification strategy, its plans, test and demonstration proposes and analysis made in system design execution phases can be assessed in these own phases.

These activities could begin in phase 0 or A and be refined along the following two phases until the critical design review. Then, in the subsequent phases, the assessment of test procedures joined with analysis and test reportings could be performed from component level to system level until the product can be considered ready to be installed into operational environment. Then, the assessment continues through integration activities at the launch site and, when it is successfully finished, readiness reviews are performed to release the flight. Thus, the evaluation process could be done with the last assessments performed in operation and the system, if meets all requirements imposed, can be considered validated.

Table 1: Framework of assessment activities for design conformity.

Design phases	Assessment Activities
0 or pre A Initial project studies: concepts and ideas in accordance to operational needs.	**Assessment on**: Initial plan and strategies of development.
A Determination of the feasibility of the project derived from alternatives solutions.	**Assessment on**: a) Design preliminary requirements; b) Mission definition and system design review; c) Verification approach development; d) Criteria, metrics development and testing master plan definition and e) Systems engineering plan with requirements definition.
B Preliminary development of the design: formal definition of system requirements; design specifications; engineering and management plan; verification process.	**Assessment on**: a) Acceptance of initial system requirements; b) Verification requirements matrix; c) verification and control plan and; d) Preliminary design reviews on system definition, system requirements and system safety
C Design development completed, including engineering data to support manufacturing, integration and verification activities.	**Assessment on:** a) Refinement of verification plans; b) Monitoring design progress related to planned; c) Product assurance planning d) Construction processes approval ➔ Qualification of system low levels and verification process through prototypes or testing articles and; e) Critical Design Reviews
D Product manufacturing and integration: demonstration of product capability to reach the proposal.	**Assessment on:** a) Product construction; b) Operational and Final product (at all levels) ➔ Product qualification and acceptance, including safety issue and; c) Flight readiness.
E Product ready to operation.	**Assessment on:** Launching readiness and operational readiness.

For more confidence in the results, an independent design assessment system has been used by USAF, NASA and ESA. The main differences are in the surveillance intensity applied by each organization. The independent assessment system consists in execution of design conformity assessment and related activities performed by an organization or commission that act in an independent way, other than, the design developer, industry and operator. The independent assessment becomes an important activity during the product development with application of no defective procedures and criteria for verification activities. Thus, possible deficiencies can be detected and corrections made before the product is put into operation, assuring operational safety and product reliability. The design team responsible for it can also participate in the project reviews and present its observations as a result of an assessment that provides elements to improvements in the product design.

3. CONCLUSION

With the presentation of design principle (design life-cycle "V" diagram), the assessment methods and control gates during design life-cycle phases, it was possible to establish a preliminary assessment activities framework for design conformity. The information collected and analyzed in this paper intends to be suggestions for Brazilian space players (development offices, industries, operators and certification office) and the "V" diagram could be adopted to discipline the design development activities. The assessment activities framework and assessment methods could be used to plan the necessary documentation and activities for verification and validation process, as control gates during design development. Thus, each one of the players could improve the strategic decision for structuring their systems for design conformity assessment, within its competence area inside the launchers program.

The major benefit for application of the "V" diagram and proposed assessment activities framework is the great increase in the likelihood of launch mission success with the system safety operation calculated. Besides, based on literature case studies, it leads to better product quality, low design life cycle cost, shorter development time and manageable complexity.

For government space program agency, the framework of assessment activities could also be adopted, as a part of design conformity assessment procedures, in order to be established the base for the adequate regulation, normalization and activities control for development offices, industries and operators. In addition, the visualization supplied by the "V" diagram allows the accomplishment by the system of all requirements imposed in a more practical way without the execution of any unnecessary activity.

It is expected that the usage of such assessment framework will propitiate an adequate technical data file that allow design revisions and service difficulties analysis and, also, enable Brazilian space players, to use such information in their strategic decisions in order to set up an adequate space product design conformity assessment system of each competence area of launchers program.

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