Determining a Methodology for Effective Reliability Program Plans

Görkem Sarıkaya
Space Systems, Turkish Aerospace Industries
Technology Faculty, Gazi University
Ankara, Türkiye
gorkem.sarikaya@tai.com.tr

Şevki Demirbaş
Electrical and Electronic Engineering
Technology Faculty, Gazi University
Ankara, Türkiye
demirbas@gazi.edu.tr

***Abstract*—Reliability is one of the drivers in the design development projects and main objective of this engineering branch is to find methods to assess reliability of equipment or system. Reliability analyses such as Reliability Prediction Analysis, Failure Modes and Effects Analysis (FMEA), Derating (Part Stress) Analysis and Worst Case Circuit Analysis (WCCA) to verify the convenient operation of circuit design are conducted in various Research and Development Projects.**

The point that requires attention is that all studies or all projects directly focus on Reliability Prediction Analysis, FMEA, WCCA or Derating Analysis separately. This study aims to evaluate all analyses together in a comprehensive manner within a reliability program plan or strategy and to determine overall risk for design project. In addition, with this strategy, the goal of study also is to determine whether the WCCA is required to be applied or not and an algorithm in which cases it will be applied has been established.

With this motivation, a new methodology in reliability program plan with a novel understanding of reliability has been implemented and conducted on an example circuit. This implementation has showed that the circuit, which would not be accepted and guaranteed by the analyzes applied by the industry and the literature under normal conditions, was accepted thanks to the proposed unique reliability approach. Possible calendar delay, budget increase or design complexity increase have been prevented.

***Keywords*—reliability, worst case, circuit, prediction.**

I. Introduction

Reliability is a key topic of specialty engineering which affects the design decisions of systems. Today, the expectation is from equipment or systems in varied complexity is not only working properly at beginning of lifecycle (the time when they will start to operation), but also expectation from them is to perform the intended function without any failure or unacceptable degradation for the defined time interval till end of lifecycle [1]. Even in case of any failure, system needs to be kept as operational for that stated time interval with several ways and this is called as "Reliability". In long lifetime programs or in other words for systems that require long usage durations, reliability is the one of the prime considerations in assuring a successful achievement of the strict design goals.

Reliability is impacted by stress parameters that are applied to design, part selection within project, environmental factors like radiation, vacuum etc. and so on. These all affecting points imply that it is one of the main drivers on design. Besides, while mass, cost and configuration are important trade of parameters in design, the results of reliability analyses should be given required priority in trade off for the selection of design solutions since other performance parameters do not mean anything if system fails once [2].

To verify high reliable and robust design, there are various analyses such as Reliability Prediction Analysis, Failure Modes and Effects Analysis (FMEA), Derating (Part Stress) Analysis and Worst Case Circuit Analysis (WCCA). These analyses show that the design is in appropriate level of robustness. In the related literature, studies generally focus on the individual analyses separately instead of comprehensive program plan which presents how these analyses, as reliability tasks, are used together. For instance, the study which can be counted as a guidance in reliability for power electronic converters not only addresses useful life model to predict life of equipment but also addresses wear out life model for structural parts in reliability prediction analysis [3]. There are also some studies that investigate the existing methodologies' efficiency for reliability prediction analysis. One of these studies focuses on the calculation of a system's reliability using real failure cases recorded from life instead of well-known failure rate data bases and models. The study aims to evaluate the efficiency of existing failure rate databases by comparing with real life observed failures to find the probability of failure [4]. On the other hand, an example in qualitative side is a study which conducts FMEA for T-56 Turboprop Engine Turbine by using MIL-STD-1629A. In this study, major failure modes and causes to lead these failure modes have been investigated [5] and just takes into account only application of FMEA. However; It is obvious that there should be a reliability program plan which covers all analyzes from a single source. The design for dependability strategy must be applied from the very beginning of the process, from the concept stage to the end product, and must be integrated into every step. At the beginning of the program, targets must be established, and then an agenda must be created with the intention of achieving those targets. As a result, to run the program, designers adhere to a reliability program plan with all reliability analyses [6]. Besides, there are also some studies give attention to reliability program plan effectiveness but not for all the analyses as a whole. For instance, in a study which examines how execution of reliability program plan can be tracked focuses on a key performance indicator which is called as "Reliability Confidence Indicator". However, this indicator is dealing with only reliability target compliance as quantitatively [7]. Another study from literature also presents a critique for reliability area. The proposition that defended by study is calculations of reliability prediction based on MIL-HDBK-217F is deceptive and insufficient and instead of this, physics of failure methodology which examines varied failure modes or prognostics modeling can be preferred [8]. This could be seen another study revealing a single reliability task, as reliability prediction analysis, is not adequate.

It is apparently seen that there is no study that comprises all analyses together in a comprehensive manner within a reliability program plan or strategy to determine overall risk for design project. Furthermore, existing plan programs and tasks are deemed as not efficient as projects require and also this evaluation can be observed from survey study which is implemented by 494 professionals [9]. According to another study which considers integrity of reliability tasks, the requirements of the program plan are not shaped according to the analyzes included in the program. For instance, study gives an example for this statement. According to this example, an organization which is implementing FMEA also has to apply same test procedures compared to the another organization which doesn't implement FMEA [10]. This implies that tasks are not handled in same roof. The activities of reliability engineering should be chosen and customized in accordance with the goals of the particular project. During the selection process, variables including technology maturity, complexity, life cycle stage, and failure consequence should be taken into account. The wrong activities which will undoubtedly be chosen and be carried out or true activities which are conducted with wrong timing, could result in an increase in waste. As an example to this, there is a necessity to find a way for determining whether the WCCA is required to be applied or not. This should be based on a rationale in which cases it will be applied. Otherwise, it would be waste of time and sources. In literature, all studies focus on how WCCA is implemented instead of when it is implemented as it can be seen from a study which conducts WCAA of balancing voltage circuit of a satellite [11].

Considering both points, it becomes necessary to apply a new methodology in reliability program plan with a novel understanding of reliability. The circuits to which WCCA will be applied are decided by an algorithm with this new reliability plan approach, which evaluates all analyses comprehensively and in the same direction to see whether design can be acceptable or not.

II. Reliability analyses

There are common reliability analyses which are conducted to ensure proper operation of system or equipment in design phases within the elaborately prepared Reliability Program in the Project. These analyses can be implemented in a quantitative or qualitative way to determine the reliability of equipment/system or failure modes with compensation provisions at various levels. Main ones of these analyses are counted as Reliability Prediction Analysis, Failure Modes and Effects Analysis (FMEA), Part Stress Analysis (PSA). On the other hand, there is a tolerance based analysis which is called as Worst Case Analysis (WCA). This analysis takes into account the variance of part parameter and evaluate whether the circuit operates within specification or not in lieu of these variations, for the worst case conditions, with the most unfavorable operating and environmental conditions.

A. Reliability Prediction Analysis

The aim of the reliability prediction is to calculate the failure rate of an electronic system which is analyzed. Failure rate is defined as the calculation of the rate at which failures happen. Constant failure rate model is used by industry to address the issue of reliability prediction of electronic equipment or system with some assumptions. Typical failure rate versus time characteristic for an electronic part is given as presented in Fig. 1 [12]. This figure is called as Bathtub curve. At the beginning of lifetime, infant mortality is the phase that failures are observed while the part or equipment is tested. Products which are recently designed without heritage can come across failures at this phase since there can be wrong material choice, design issues, manufacturing and assembly process deficiency. Therefore, it is vital to implement a test process especially for new designs. In the useful life period or in other words "normal life" period, it is considered that part or equipment has constant failure rate and this failure rate is used in the analyses. On the other hand, "Wear out" period is a consequence of fatigue, environmental stresses such as radiation and temperature or material degradation. At this phase, occurrence of failures is increasing very rapidly. However, parts or equipment are chosen according to life limits so this wear out period can be ignored [1].

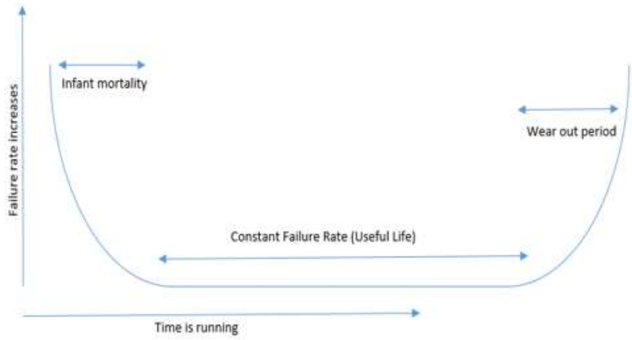

Fig. 1. Constant failure rate in bathtub curve

The reliability analysis is implemented according to guidelines which are shown in database handbooks such as MIL-HDBK-217F, Telcordia, Fides and 217 Plus. These databases provide constant failure rate models with several factors that have effect on reliability for all kind of components that composes the equipment or system [13]. The main theory is based on sum of failure rates for components that composes the system, however this is valid for the reliability of system that has no-redundancy. While adding failure rates, another aspect is to take into account redundancy scheme of design since this can affect failure rate of system significantly compared with a series system. There are 2 main kind of redundancy schemes: Active (hot) and standby (cold). These options can be preferred according to design requirements. However, it should be noted that standby redundancy is advantageous from reliability point of view since redundant unit is not always used and failure rate is fixed to zero or 1/10 of failure rate of main unit (1/100 dormancy factor also can be used for only passive mechanical units). Redundancy scheme models of two units which are non - redundant, active (hot) redundant and passive (cold) redundant are given respectively as simplest examples below in Fig. 2 [1]. All after the drawing reliability block diagram and calculations, at the end of the day, reliability which is estimated should be higher that one determined by project requirement.

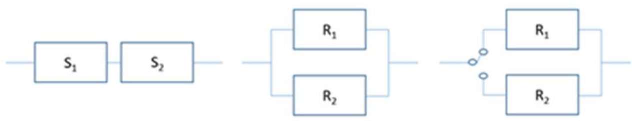

Fig. 2. a) Non - redundant system. b) Active (hot) redundant system. c) Passive (cold) redundant system.

B. Failure Modes and Effects Analysis

Failure modes and effects analysis (FMEA) is another valuable analysis method used as a reliability analysis. Along all phases before freezing of design, FMEA contributes to improvement of product design by determining potential failure modes and reducing their end effects. Equipment/system design's potential failure modes have been defined and local effects implying consequences at the level of the item under investigation and end effects implying consequences at the level of the end product under analysis are determined. Then, the single point failures which have catastrophic and critical end effects leading to loss of the mission or loss of satellite are specified and recorded [14]. Severity categories are determined according to related authority standard. For instance, table 1 refers to European Cooperation for Space Standardization (ECSS) severity classification [15]. This classification should be tailored according to level under investigation to get how analysis' end effects are evaluated. Another aim of this analysis is to highlight observable symptoms associated to failures in order to give input to Failure Detection Isolation and Recovery (FDIR) analysis which defines how failures are recovered autonomously. At last but most important part is to identify compensation or corrective action capabilities to mitigate effects of failure modes. To sum up, this analysis is an opportunity to verify why we are designing system in this way.

TABLE I. SEVERITY CATEGORIES

Severity	**Failure Effects**	
	ECSS Definition	**Subsystem Level Definition**
1	Risk of failure propagation	Risk of failure propagation towards another SS
2	Loss of mission	Loss of all communication capability
3	Major mission degradation	Major Degradation on communication capability
4	Minor mission degradation or any other effect	Minor Degradation on communication capability (e.g. Reduction of redundancy)

C. Derating (Part Stress Analysis)

The stress values which are applied to parts through design of equipment should be followed accurately to enhance reliability since most affecting factors to reliability are stresses that seen on equipment. Therefore, proper derating of electronic parts' stress values is a valuable tool to enhance reliability of equipment. Electronic equipment reliability is strongly dependent on both electrical and thermal stresses [16]. For this reason, electrical stress and thermal stress values of EEE parts are reduced to a specified derated value as compared with their maximum ratings to increase reliability. This analysis is called as Part Stress (Derating) Analysis. In this analysis, components are used with lower electrical and thermal stress values instead of their maximum ratings which are specified in their datasheets. Derating rule of a ceramic capacitor can be given as an example from space derating standard, "ECSS-Q-ST-30-11C Derating - EEE Components" [17]. In this instance, it is required to apply voltage stress to capacitor as %60 of rating maximum voltage which is written in datasheet till 85 centigrade. After this temperature, %40 of maximum voltage can be applied between 85 and 110 centigrade and component cannot be operated above 110 centigrade.

D. Worst Case Circuit Analysis

Another reliability analysis at circuit level is Worst Case Analysis (WCA). In some sources, it can be called as Worst Case Circuit Analysis (WCCA) since it is implemented for critical circuits in an equipment. WCA is a powerful tool determining whether circuit under analysis works as designed or not, although each component of circuit is subject to variations along its planned life because of initial tolerance, temperature, radiation and aging. The main goal with WCCA is to prove that the circuit still meet its performance requirements over the life, even if all parameters of all components change to their maximum or minimum values at same time [18].

E. Determining Critical Circuits

Another aspect in reliability domain is to determine critical circuits of equipment design since WCCA is implemented for critical circuits. Reliability Prediction Analysis, FMEA and Derating Analysis are main factors to identify the critical circuits which will be subject to WCA. Circuits that have very high failure rate which can be a weakness indicator and this is detected by Reliability Prediction Analysis. These circuits can be one of the candidates. The ones which are defined as single-point failure on a failure mode whose severity is evaluated as "failure propagating", "mission critical" or "major degradation" and the ones that have failure modes whose severity are classified as "failure propagating" in result of FMEA are another candidate for critical circuit. Single point failure here refers to parts that do not have redundancy. Circuits that have non-compliant components with respect to derated stress levels according to Derating Analysis are also candidates to be critical and therefore to be analyzed by WCA [19]. However, how all these conditions will be integrated is missing point. Therefore, in this new approach, this point should be clarified and should be incorporated in an algorithm with a rationale.

III. NEW ALGORITHM

In the relevant sectors of the industry, the reliability is managed from one dimension in any system design project. Reliability Prediction Analysis, FMEA, Derating and WCCA are applied separately and their compliance with project requirements is evaluated separately from concept to detailed design stages. For example, if a system is expected to be 99% successful in a given time period, which means that the reliability of the system is 0.99. It is expected that the reliability prediction analysis of the system will be performed and reliability will be above the target requirement value of 0.99. FMEA is performed in parallel at the same time interval and possible failures of the design and how tolerant it is against these failures are analyzed. Likewise, Derating and WCCA analyzes are performed at the equipment level and their compatibility is evaluated separately. Although all of these analyzes seem to be separated analyzes on their own, there is necessity to conduct an integrated evaluation of them within the well-organized Reliability Program Plan.

Besides, there is a study which implements a survey with 494 reliability professionals. According to this survey, while almost half of participants have evaluated the overall effectiveness of top 5 tasks/analyses as a part of Reliability Program Plan as not good, the same number of people have found execution of Reliability Program Plan average and below average. When all this study results are examined, they point out to one conclusion: There is a need for enhancement in the efficiency, implementation and value of Reliability Program Plan Tasks [9].

The most important thing is to decide how, when, and under what circumstances these analyses as reliability will be conducted. Determining how much flexibility can be offered while the design system's reliability is guaranteed is another crucial consideration. Due to the fact that reliability must be balanced together with a number of other factors, including cost, complexity of the design and timeline, a way giving this balance should be followed. Otherwise, it is simple to design a system that is very reliable, but it can result in budget items going over budget or the calendar getting prolonged. Determining the amount of flexibility that can be offered in the dependability domain is crucial for this reason.

As can be seen in Fig. 3, Reliability Prediction Analysis, FMEA, Derating Analysis and WCCA are considered in a single framework and it is stated which circuits should be applied WCCA with a real rationale. According to the algorithm, in some cases (marked with 1 in Fig. 3), the algorithm decision mechanism cannot lead to any result other than the design change, while in some cases it indicates that it is not necessary to apply WCCA, and in other cases it shows the necessity of applying WCCA.

Cases where there is no other way than a design change are listed below:

1- The difference between the result of the reliability prediction analysis and the assigned target requirement is more than 10%.

2- The related circuit of the relevant equipment has a failure mode that may cause failure propagation and the compensation method is not provided.

3- Presence of failure modes which are SPF that may cause loss of mission or major loss of function of the related circuit of the relevant equipment without any mitigation method.

4- As a result of Derating Analysis, the number of incompatible components of the equipment or the relevant circuit according to the level to which it is applied is more than 5% of the total number of components.

If all analyzes are passed with full compatibility as specified in the algorithm (marked with 2 in Fig. 3), then there is no need to apply WCCA.

On the other hand, other situations that necessitate the application of WCCA (marked as 3 in Fig. 3) are as follows:

1- The difference between the result of the reliability prediction analysis and the assigned target requirement is less than 10%.

2- The relevant circuit of the relevant equipment only has SPF failure modes that can cause major loss of function.

3- As a result of Derating Analysis, the number of incompatible components is less than 5% of the total number of components.

If the circuit contains 10 or less components in total, 1 component incompatibility in result of derating analysis requires WCCA, while more than 1 incompatibility leads to design change.

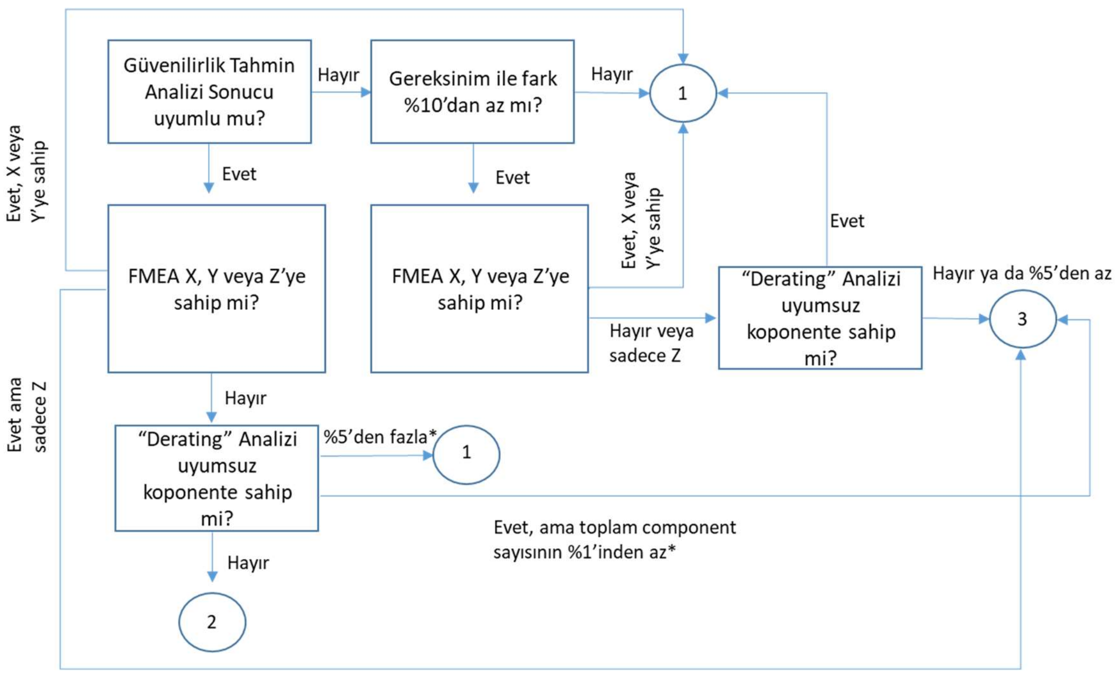

Fig. 3. Novel Reliability Approach Algorithm

IV. DISCUSSION AND RESULTS

In this study, the new methodology within a new algorithm has been conducted on a signal triggering circuit. This circuit aims to trigger a signal for the Latch Protections sub circuit whenever the voltage at the output of the Inductor Current Measure block exceeds a threshold. The Inductor Current Measure block senses the current through the transformer of each Push-Pull converter.

Reliability Prediction Analysis and WCCA is conducted on this circuit. Firstly, it has been seen that circuit reliability result is not complied with requirement, even if not inside 10 percent margin as a result of Parts Count methodology as Reliability Prediction Analysis. Therefore, analysis has been repeated with Part Stress methodology which is less conservative for Reliability Prediction Analysis. Then, it has been observed that reliability of circuit is equal to 4,442 FIT (Failure in Time). This value is still not complied with requirement which is 4,2 FIT. However, difference with requirement has been less than %10. Therefore, WCCA has been applied to circuit as new algorithm proposes to understand the design margins. The table 2 which shows these differences can be found below:

TABLE II. COMPARISON OF RELIABILITY PREDICTION RESULTS AND CONSEQUENCES ACCORDING TO ALGORITHM

	Failure Rate Result	Requirement	Difference	Consequence
Parts Count	4,96 FIT	4,2 FIT	%15,3	Design change is required.
Parts Stress	4.442 FIT4	4,2 FIT	%5,4	WCCA implementation is required.

WCCA has been applied according to -25°C to +85°C temperature range, 15 years life cycle and 30 krad total ionized radiation dose. Component variations at different temperature peaks have been determined and simulations have been conducted according to these variations. As a result of this analysis (could be seen Table 5), it has been observed that tolerance is not affecting the functions of the circuit to work properly and the tolerance margin is not more than what is expected. At a result of ultimate evaluation, over current detection measure ranges from 3.46 V to 3.38 V as maximum and it seems that the circuit can trigger the signal in the required range.

TABLE III. RESULTS ON TEMPERATURE PEAKS

Temperature	Result on Upper Limit	Result on Lower Limit	Nominal
-25 Centigrade	3.44 V	3.40 V	3.41 V
+85 Centigrade	3.46 V	3.38 V	3.41 V

If all which has done it is evaluated here with Fig. 4 that represents the simplification of Fig. 3. It is obvious that the circuit has confirmed even if it has not complied with requirement. Because it has been within the %10 margin and WCCA has been conducted and the circuit has been assured since it is in the range as a result of WCCA.

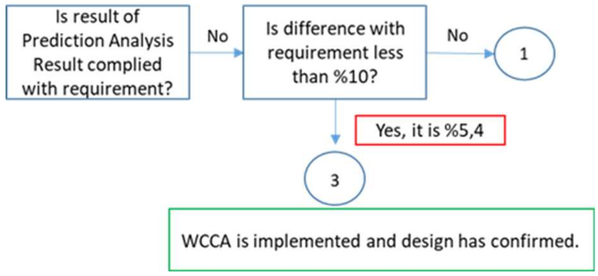

Fig. 4. Simplified Algorithm for the example given

V. CONCLUSION

Reliability analyzes are qualitative and quantitative tools that show how much we can trust to a designed system. It is an opportunity for us to see how accurate results our designs will yield. In this content, Reliability Prediction Analysis, Failure Mode and Effects Analysis, Derating Analysis and Worst Case Circuit Analysis (WCCA) are explained in the study. The crucial point is to decide in what order, to what extent and with what plan these analyzes will take place. Another important point is to determine how much flexibility can be provided while the reliability of the designed system is assured. Due to the fact that reliability is part of a collection that also contains other characteristics, such as cost, design complexity and schedule, all of these parameters must be balanced. Otherwise, it is easy to build a very reliable system, but it can increase the budget items much more than expected or cause the calendar to be extended. For this reason, it is important to determine the measure of flexibility that can be provided in the domain of dependability.

In addition, there is a necessity to determine whether the WCCA is applied and in which cases it will be applied. With this unique reliability methodology which is presented by this study, all analyzes are evaluated in the same direction, and which circuits WCCA will be applied to is determined by an algorithm.

This circuit in study, which would not be accepted and guaranteed by the analyzes applied by the industry and the literature under normal conditions, was accepted thanks to the proposed unique reliability approach and possible calendar delay, budget item increase or design complexity increase was prevented. This study showed that the novel reliability concept is the flexibility given to the system design and plays an important role in determining this flexibility.

REFERENCES

[1] Prof. Dr. Birolini A, Reliability Engineering Theory and Practice, Springer-Verlag, 2007.

[2] W. Wang, Y. Li, Q. Zhang, W. Feng, H. Liu and P. Liu, “Reliability Implementation and Cost Trade-off of Product during the Development Process”, MATEC Web of Conferences 221, 02003, 2018.

[3] S. Peyghami, Z. Wang and F. Blaabjerg, “A Guideline for Reliability Prediction in Power Electronic Converters. IEEE Transactions on Power Electronics”, Vol. 35, no. 10, pp. 10958-10968, 2020.

[4] S. D. Güreş, İ. Ulusoy and B. Durmaz, “Satellite Failure Estimation vs. Reliability Prediction Analysis”, Annual Reliability and Maintainability Symposium (RAMS), pp. 1-5, 2019.

[5] N. A. Qattan, A. M. Al-Bahi and B. Kada, “Failure Modes and Effects Analysis of T-56 Turboprop Engine Turbine”, Annual Reliability and Maintainability Symposium (RAMS), pp. 1-5, 2021.

[6] Vieira, D., Rebaiaia, M. and Chain, M, "The Application of Reliability Methods for Aircraft Design Project Management". American Journal of Industrial and Business Management, Vol 6, 967-992, 2016.

[7] I. Cacipu and S. Voiculescu, "Reliability Confidence Indicator", Annual Reliability and Maintainability Symposium (RAMS), Palm Springs, pp. 1-6, 2020.

[8] G. P. Pandian, D. Das, C. Li, E. Zio, M. Pecht, "A critique of reliability prediction techniques for avionics applications. Chinese Journal of Aeronautics", Volume 31, Issue 1, pp. 10-20, 2018.

[9] C. Carlson, G. Sarakakis, D. J. Groebel and A. Mettas, "Best practices for effective reliability program plans", Annual Reliability and Maintainability Symposium (RAMS), pp. 1-7, 2021.

[10] S. P. Brady, A. A. Thompson and J. L. Cook, "Motivating the Program – An Improved Reliability Case Approach", Annual Reliability and Maintainability Symposium (RAMS), pp. 1-6, 2019.

[11] R. Sugathan, Ananda S, V. Ramdas, P. Satyanarayana, Sankaran M and Ekkundi R, "Worst case circuit analysis of a new balancing circuit for spacecraft application", International Conference on Power and Advanced Control Engineering (ICPACE), pp. 327-332, 2015.

[12] Pham H, Handbook of Reliability Engineering, Springer, 2003.

[13] K. Choudhary and P. Sidharthan, "Reliability prediction of Electronic Power Conditioner (EPC) using MIL-HDBK-217 based parts count method", International Conference on Computer, Communication and Control (IC4), pp. 1-4, 2015.

[14] F. Mozaffari, A. Eidi, L. Mohammadi and Z. Alavi, "Implementation of FMEA to improve the reliability of GEO satellite payload", *Proceedings Annual Reliability and Maintainability Symposium (RAMS)*, pp. 1-6, 2013.

[15] European Coordination for Space Standardization, Space Product Assurance Failure modes, effects (and criticality) analysis (FMEA/FMECA), European Space Agency, 2019.

[16] Department of Defense, Electronic Reliability Design Handbook (MIL-HNDBK-338B), United States of America, 1998.

[17] European Coordination for Space Standardization, Space Product Assurance Derating - EEE Components, European Space Agency, 2021.

[18] Aerospace Space Systems Group, Electrical Design Worst-Case Circuit Analysis: Guidelines and Draft Standard (TOR-2013-00297), Space and Missile Systems Center, Air Force Space Command, 2013.

[19] Z. Guofu, Z. Yuege, Y. Xuerong, H. Bo, "A method of multi-objective reliability tolerance design for electronic circuits", School of Electrical Engineering and Automation, Chinese Journal of Aeronautics, pp. 161-170, 2013.