Functional Availability and Reliability Modelling in Platform Design and Manufacture

E.T. Senalp

BAE Systems, Maritime Services, Filton, Bristol, United Kingdom: erdem.senalp@baesystems.com

Abstract. Availability, Reliability and Maintainability (ARM) are three attributes that collectively affect the economic life-cycle costs of a platform (e.g. Ship, Aircraft). Whilst there are different approaches, this paper presents modelling of Intrinsic Availability and Reliability (Ai&R) of Key Platform Functions (KPF) and System Functions (SF) adopted as a modelling approach during the platform design and manufacture (D&M). Ai is a measure of the proportion of time, which required functions are successfully provided, when used in stated conditions. It is a useful indication of the potential availability that the platform offers separate from operational and logistics constraints. When high reliability is achieved and supportability optimised, corrective maintenance is minimised, hence in-service availability realised tends towards the Ai and a limited number of failures are expected that result in support / logistic delays. Ai&R modelling using increasingly mature data, during the D&M phases provides visibility of potential impacts on the Ai&R implicit in the design. Estimating the Ai&R at equipment, SF and KPF levels gives a consistent approach within a complex platform design and allows improved comparative analysis. This paper presents benefits and outcomes of the application of functional ARM for platform modelling and simulation.

1. Introduction

The Design and Manufacture (D&M) of a platform (e.g. Ship, Aircraft) has an expectation of high operational performance as well as a cost-effective and timely adherence to schedule for high quality outcomes. Considering Support function at each phase of a platform development programme helps in achieving these aims.

Availability, Reliability and Maintainability (ARM) are three Support attributes affecting the performance and economic life-cycle costs of a platform. These attributes help developing the platform right first time because estimating them helps analysing the Ai&R performance throughout the D&M of a platform and fixing the potential problems at key Ai&R performance drivers before the platform is in service.

There are three types of Availability Modelling:

- Operational Availability: It considers actual corrective / preventative maintenance as well as actual operational conditions (See MOD 2011).
- Inherent Availability: It considers ideal corrective / preventative maintenance and ideal operational conditions (See MOD 2011).
- Intrinsic Availability (Ai): It considers ideal corrective maintenance and ideal operational conditions only.

This paper does not intend to compare between the three types of availability modelling. Instead, it presents modelling of Intrinsic Availability and Reliability (Ai&R) of Key Platform Functions (KPF) and System Functions (SF) adopted as a modelling approach during the D&M of a platform.

The main aim is to check and maintain the design intent throughout the platform development. Neither modelling of the in-service operational parameters nor modelling of the preventative maintenance parameters are the aims of this work. Operational Availability modelling requires estimations for in-service operational parameters and conditions. These data and information are not mature or not available at early phases of the platform design and development. For instance, Operational Availability modelling requires logistics modelling, which is a separate activity, and it does not reflect the design intent. In addition, both Operational Availability and Inherent Availability modelling require additional preventative maintenance parameters that are not mature or not available at the early phases. These facts and the data availability justify the reasoning in selection of the type of the availability modelling, i.e. Ai. Thus, this paper presents the Ai&R modelling considering the corrective maintenance data, the reliability data and the platform information which are available starting from the early phases.

The Ai&R modelling approach can be applied at all phases of the platform development including the low maturity phases and the high maturity phases. Design intent can be checked and maintained throughout the platform development. Towards the end of the D phase, ARM functional modelling is used to measure and declare the Ai&R of the KPFs. During the M phase, the implications of design development, including design options/decisions, are monitored through periodic comparison of modelling and analysis results at SF level and KPF level.

ARM modelling has been a popular area in multiple disciplines in industry and academics with several important contributions over a considerable time frame.

RIAC (2005) presented the fundamentals of the reliability and maintainability theory. Reliability prediction of a component differs considering the operational environment. The reliability predictions can be converted from one environment to another considering the environmental conversion factors as presented in the RIAC (2005).

Trivedi and Bobbio (2017) presented the availability and reliability modelling approaches including the non-state-space models, as well as the state-space models. Reliability Block Diagrams (RBD) sit under the non-state-space models.

Kawazoe et al. (2018) presented an approach for weapon system acquisition programs to meet the requirements including reliability, availability, maintainability, safety, and cost. Windchill Quality Solutions (WQS) developed by Parametric Technology Corporation (PTC) including the Reliability Block Diagrams (RBDs) modelling and simulation tools was used in the process to model a single system in terms of reliability engineering. The importance of implementing the modeling and simulation early in a system's life cycle was highlighted stressing the fact that it maximizes return on investment.

McCollin and Disney (2007) showed an availability case study for a ground benign system using an Ai modelling approach. Ai modelling approach was selected in order to reduce the complexity in analysis due to lack of detailed data on failure distributions and lack of operational and logistics time data.

Calculating Ai at early phases can help estimating Operational Availability when other required operational, logistics and preventative maintenance information becomes available. Kwasinski (2020) discussed a quantitative approach on power distribution systems availability and resilience which allows improved planning and operation. Kwasinski (2020) expressed Operational Availability as a function of Ai.

Corvaro et al. (2017) presented an ARM study on compressor systems. ARM data at component level were used as inputs to simulation and life cycle assessment at system level. Criticality of the subsystems and components were assessed. The analysis results showed the major vulnerability and the key performance drivers.

RBD is a popular and common approach provided by the equipment suppliers or Original Equipment Manufacturers (OEM) in justifying the low-level equipment ARM Case.

In this work, the RBD analysis approach in high-level platform / system design and integration is employed considering the availability of the low-level equipment RBDs. Thus, KPF / SF RBD development and analysis are presented as the Ai&R modelling approach.

In this approach, a capability in determining the key performance drivers for KPF and SF Ai&R at early phases of the platform development is introduced. In addition, the Ai&R modelling results and the capability are illustrated in a sample (mocked-up) case study.

2. Scope and Definitions

The Ai&R modelling approach takes into account corrective maintenance downtime including disassembly, interchange, reassembly, alignment, checkout and commissioning activities. It does not consider spares modelling, preventative maintenance downtime, work in way, fault isolation, replacement of work in way or logistic delays.

The defined scope and assumptions could have led to implications (e.g. uncertainty due to lack of information) if the main aim was estimating the Operational Availability but the main aim of this work is to check and maintain the design intent or the Ai. Operational scenarios and logistics modelling cannot improve the design intent or Ai. Thus, considering the main aim, defined scope and assumptions, the Ai&R modelling approach is sufficient. Operational scenario modelling and logistics modelling can be performed separately

when information on operational, logistics and preventative maintenance becomes mature. Later, when all information is available, Operational Availability can also be estimated.

RBDs are developed for Ai&R modelling and analysis. MOD (2011), BSI (1993), MOD (2009) and MOD (2012) are considered when undertaking the RBD analysis.

SF RBDs consist of equipment or sub-system blocks. Each equipment or sub-system in a SF RBD is represented by a Repairable on Platform (RP) block and a Non-Repairable on Platform (NRP) block. Each RP block in a SF RBD consists of a reliability and a corrective maintenance parameter, i.e. Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR). Each NRP block in a SF RBD has a reliability parameter, i.e. Mean Time To Failure (MTTF).

Ai is a function of Uptime and Downtime as in (1).

$$Ai = \text{Uptime} / (\text{Uptime} + \text{Downtime}) \quad (1)$$

If all the equipment blocks were RP only, then Ai could be expressed using MTBF and MTTR as in (2) considering ideal operational conditions and ideal corrective maintenance with infinite spares.

$$Ai = \text{MTBF} / (\text{MTBF} + \text{MTTR}) \quad (2)$$

On the other hand, if there are NRP equipment blocks as well as the RP ones then the Ai can be estimated using simulation techniques. Thus, Ai&R modelling and analysis of complex platform systems are performed using simulation tools. WQS developed by PTC is one of the simulation tools with Prediction and RBD toolsets. These tools provide capability to perform Monte-Carlo simulation iterations on the system RBDs developed. The number of simulations is a configurable simulation parameter. Choosing a high number of iterations in the simulations helps increasing the representativeness of the simulation sample population and generalising the analysis results.

Ai depends on the reliability parameters, the corrective maintenance parameter and the simulated mission time in each simulation iteration. To achieve high Ai over a long simulated mission time, an equipment should be designed to and demonstrate high RP MTBF and high NRP MTTF as well as low RP MTTR parameter values.

There are a number of important assumptions and exclusions which underpin the Ai&R modelling approach presented in this paper. The assumptions and exclusions are mainly due to the limited amount of mature reliability and maintainability data at early phases of the platform development and also to simplify the complex engineering problem. For instance, the following assumptions and exclusions are considered:

- Maturity of reliability data is dependent upon the availability of verified data, library data and engineering judgement.
- All failure rates are assumed to remain constant over the duration of the simulated mission.
- The effect of wear-in aging is not represented within the model.
- Equipment MTBF values are not factored within the model to reflect utilisation, as a result all systems have an equal weighting of importance.
- Each RP equipment is repaired to a good as new state without delay.
- For systems including NRP equipment, separate NRP and RP blocks are represented in the model.

Employing low maturity reliability and maintainability data can have implications like optimistic or pessimistic estimations leading to some uncertainty in the Ai&R models. In order to highlight this risk, the maturity levels of the input data are quantified and recorded, i.e. maturity levels of the reliability and maintainability information of the equipments.

Three different equipment reliability and maintainability maturity levels are defined:

- Level 1: Data from open-source libraries, e.g. NPRD, data from engineering judgement or experience.
- Level 2: Data from systems in previous platforms, data from ARM requirements.
- Level 3: Data from equipment supplier, OEM data, ARM Case Report data.

The maturity level of each system is assigned considering the lowest maturity level of the equipments involved in. The Ai&R modelling results are presented together with the system level maturity in order to address any improvement in increasing the information maturity level if required.

3. Ai&R Modelling

Figure 1 provides an illustration of the structure and relationship of key elements of the ARM modelling.

Figure 1. Structure and relationship of key elements of the ARM modelling.

Firstly, RBDs representing SFs are developed, comprising elements representing sub-systems and equipment, based on the range of information available such as Functional Block Diagrams and system schematics produced by the Design Team.

Then, KPFs are identified. Functional Criticality Matrix (FCM) defines the contributing SFs to each KPF. If a contributing SF is important for the KPF then it is defined as Required otherwise it is assumed 100% Available. KPF Ai&R are calculated using the Required SFs only. The SFs, which are assumed 100% available, are not included in the estimated KPF Ai&R. This helps quantification of the key Ai&R drivers because non-crucial information is filtered out. Although a SF can be assumed 100% available in a KPF, the same SF is defined as Required in another KPF. Thus, the modelling approach takes into account every SF in the totality of the whole platform analysis.

KPF RBDs are developed in collaboration with platform systems design teams and comprise the SFs required in series, based on the agreed FCM. Figure 2 provides a sample KPF RBD illustrating the relationship of SFs of the KPF.

Figure 2. Sample KPF RBD level of Ai&R modelling with the corresponding SFs.

In this approach, the KPF RBDs level of Ai&R modelling does not include any SF redundancy. The equipment redundancies are expressed in the SF RBDs level of the modelling.

4. Sample (Mocked-up) Ai&R Model

This section presents a sample (mocked-up) Ai&R modelling process and the results. The sample platform consists of five KPFs and ten SFs. The sample FCM defines the Required (R), assumed 100% Available (A) and Not-required (N) SFs for each KPF as in Table 1.

Table 1. Sample (mocked-up) FCM

	SF1	SF2	SF3	SF4	SF5	SF6	SF7	SF8	SF9	SF10
KPF1	R	N	A	N	A	R	N	A	N	A
KPF2	A	R	A	R	R	N	R	R	R	R
KPF3	A	N	R	A	A	R	N	R	A	N
KPF4	R	N	A	A	R	N	N	N	N	N
KPF5	N	N	N	N	N	R	A	A	N	A

First, the SF RBDs are developed with the MTBF and MTTR values of the equipments required by each SF. Then, using the FCM, the KPF RBDs are developed with the SFs required by each KPF. The SF RBDs and the KPF RBDs are simulated for 30 days of simulation time and with 10,000 Monte-Carlo simulation iterations in order to estimate the SF Ai&R modelling results and the KPF Ai&R modelling results.

The analysis results for two consecutive platform development phases are visualised using radar diagrams. To illustrate, at Phase D, the equipment reliability maturity and the maintainability maturity are at Level 1. Then, at Phase M, the maturities improve to Level 3.

Figure 3 shows the KPF Ai estimates, and the SF Ai estimates required by one of the KPFs, i.e. SF Ai estimates required by the KPF2, at Phase D and Phase M.

Figure 3. Sample (mocked-up) Ai analysis results diagrams

Considering the KPF Ai analysis results at Phase D, one of the KPFs has low Ai, i.e. KPF2 Ai estimation is 0.6. The key performance driver can be determined considering the KPF2 SF Ai analysis results at Phase D, i.e. SF4 with Ai estimation 0.65.

Low Ai estimation for SF4 at Phase D brings in a requirement to implement a design change in SF4 in order to improve the Ai, e.g. redundancies are introduced to the low reliability equipments in SF4.

At Phase M, the design changes are implemented, the design gets mature and the reliability and maintainability maturity level improves. As a result, the SF4 Ai estimation improves to 0.95 and the KPF2 Ai estimation improves to 0.9 at Phase M.

To the best knowledge of the author, the Ai&R modelling process and the sample modelling results presented and illustrated in this section introduce the capability in determining the key performance drivers at early phases of the platform development by applying the FCM.

5. Discussion

The Ai&R modelling brings in a systematic approach to analysis at Equipment, SF and KPF levels. Key performance drivers in the Ai&R models can be identified easily by tracing the analysis results at different levels because the approach provides high visibility of the analysis results.

To illustrate, comparative analysis results can be presented using comparative visualisation techniques such as spider or radar diagrams to identify the key performance drivers in the Ai&R modelling results.

Firstly, Ai&R simulation results of the KPFs are plotted on a spider diagram. The KPFs with low Ai&R performance are identified.

Secondly, for each KPF, the Ai&R simulation results of the required SFs are plotted on a spider diagram. The SFs with low Ai&R performance are identified.

Thirdly, for each SF, the reliability and maintainability parameters of the required equipments are plotted on a spider diagram. The equipments with low MTBF and MTTF and high MTTR parameters are identified.

High SF MTBF figures can be obtained by using reliable RP equipments and by introducing built-in-redundancies in the SFs. If an equipment has low NRP MTTF value and has no redundancy, and if it fails during a long simulated mission, then the rest of the simulated mission time is added to the Downtime decreasing the Ai. In this case, the MTTF becomes a key Ai driver.

Finally, for each identified equipment, the possibility to improve the reliability and maintainability parameters are investigated. This can include change in component selection, update in design and maintainability or introduction of equipment redundancies. After an equipment parameter or a RBD structure is updated, the simulations are run again.

This iterative approach provides benefits of identifying the key performance drivers and fixing them as the design and model data matures during the D&M phases of a platform development programme.

5. Conclusion

The application of functional availability and reliability modelling in platform D&M brings development of modular SF RBDs in multiple KPFs. This improves identification of the key Ai&R performance drivers in analysis and provides a process to escalate the effects of the updates in an equipment to the SF and KPF levels. Thus, Ai&R modelling using increasingly mature data, during the D&M phases provides early visibility of potential impacts on the Ai&R implicit in the design.

Estimating the Ai&R at equipment, SF and KPF levels provides a consistent approach within a complex platform design and allows improved comparative analysis between these different levels and between different phases of the platform development. This provides support to D&M decision making process. It can also assist in establishing a baseline as a comparator for a future project / programme.

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